# Chapter 8
# Hemodynamic Assessment in the CCU by Echocardiography

**Yuvrajsinh J. Parmar, Craig Basman, and Itzhak Kronzon**

**Abstract** Cardiac hemodynamics and intracardiac pressures can be assessed noninvasively with echocardiography. The simplified Bernoulli equation can be used for the majority of calculation for inter-chamber gradients. These measurements can aid in the assessment and management of patients in the cardiac intensive care unit. This chapter will focus on the hemodynamic assessment of the cardiac intensive care patient using Doppler and other echocardiographic techniques.

**Keywords** Doppler · Cardiac output · Intra cardiac gradients

## Introduction

Cardiac hemodynamics and intracardiac pressures can be assessed noninvasively with echocardiography. The simplified Bernoulli equation can be used for the majority of calculation for inter-chamber gradients. These measurements can aid in the assessment and management of patients in the cardiac intensive care unit. This chapter will focus on the hemodynamic assessment of the cardiac intensive care patient using Doppler and other echocardiographic techniques.

## Evaluation of Right Atrial Pressure

The inferior vena cava size and change with respiration can be used to evaluate right atrial pressures. The inferior vena cava can be visualized with the transducer in the subxiphoid position traveling through the liver into the right atrium. The ultrasound transducer is placed perpendicular to the inferior vena cava. Normally, the inferior vena cava is <2.1 cm when measured 1–2 cm prior to entering the right atrium, and

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**Table 8.1** Inferior vena cava (IVC) size and respiratory variation in the evaluation of right atrial (RA) pressure

| Inferior vena cava size and collapsibility | Estimate of right atrial pressure |
|---|---|
| Dilated (>2.1 cm) and little collapsibility (<50%) | Elevated (10–20 mmHg) |
| Normal (<2.1 cm) but little collapsibility (<50%)<br>Dilated (>2.1 cm) but collapsible (>50%) | Intermediate (5–10 mmHg) |
| Normal (<2.1 cm) and collapsible (>50%) | Normal/low (0–5 mmHg) |

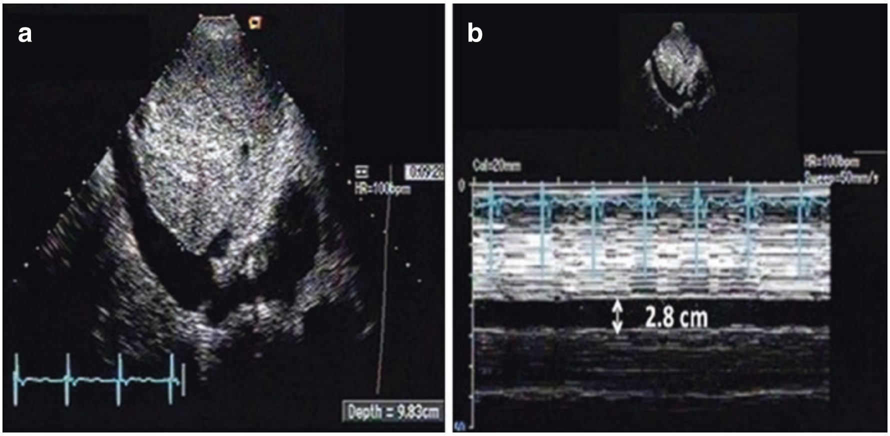


**Fig. 8.1** Assessment of right atrial pressure (RAP). (**a**) The inferior vena cava (IVC) is markedly dilated at its entrance to the right atrium (2.8 cm). (**b**) The M-mode recorded demonstrates lack of respiratory variations in diameter. RAP is estimated to be 15–20 mmHg

there is a decrease of 50% or more in its diameter with inspiration. A dilated inferior vena cava and failure to collapse with respiration and the “sniff test” suggests elevated right atrial pressures [1–3]. M-mode echocardiography can be particularly helpful to measure the size and changes of its diameter during inspiration. Table 8.1 displays inferior vena cava characteristics (diameter and respiratory changes) and estimated right atrial pressure. Figure 8.1 shows a two-dimensional image and M-mode echocardiogram of a patient with a markedly elevated right atrial pressure.

## Evaluation of Right Ventricular Systolic Pressure

The tricuspid valve during systole can be used to estimate the right ventricular systolic pressure. During systole, the tricuspid valve is closed, and there is a pressure gradient between the right ventricle and right atrium. Approximately 80% of adults have some degree (usually trace to mild) of tricuspid regurgitation. Continuous wave Doppler can be used to measure the peak velocity of this tricuspid regurgitant

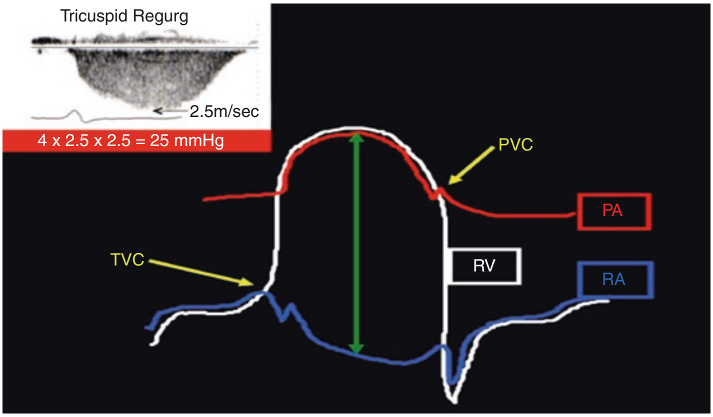


**Fig. 8.2** Assessment of right ventricular (RV) systolic pressure (see text). The diagram shows normal right-sided pressures with no significant systolic gradient across the pulmonic valve and no significant diastolic gradient across the tricuspid valve. The gradient across the tricuspid valve in systole (*green arrow*) is responsible for the tricuspid regurgitation velocity seen in the *upper left corner*. With a peak regurgitant velocity of 2.5 m/s, the gradient between the right ventricle and right atrium is 25 mmHg. Other abbreviations: *PA* Pulmonary artery pressure, *PVC* Pulmonic valve closure, *RA* Right atrial pressure, *TVC* Tricuspid valve closure

jet. In the absence of pulmonic stenosis, the right ventricular systolic pressure can be used to estimate pulmonary artery systolic pressure. Figure 8.2 shows the superimposed pressure curves of the right atrium, right ventricular, and pulmonary artery pressure. This peak velocity can be used to estimate the gradient between the right ventricle and right atrium by using the simplified Bernoulli equation. The right ventricular systolic pressure (RVSP) therefore will equal the tricuspid regurgitant (TR) gradient plus the right atrial pressure (RAP).

$$\mathrm{RVSP} = \mathrm{TR\ gradient} + \mathrm{RAP}$$

In a patient with ventricular septal defect (VSD) with a left-to-right shunt, the right ventricular systolic pressure can be calculated after measuring the gradient across the VSD in systole. In the absence of aortic stenosis, the systolic pressure in the left ventricle equals the systemic systolic blood pressure. Thus, the right ventricular systolic pressure (RVSP) equals systolic blood pressure (SBP) minus the systolic ventricular septal defect (SVSD) gradient.

$$\mathrm{RVSP} = \mathrm{SBP} - \mathrm{SVSD\ gradient}$$

Figure 8.3 shows an example of calculating right ventricular systolic pressure in a patient after a myocardial infarction that developed a VSD with a left-to-right shunt.

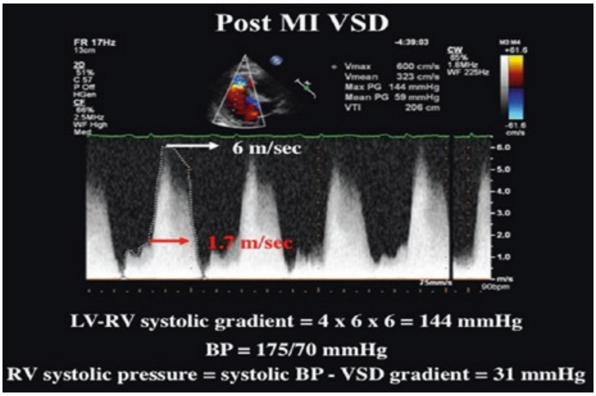


**Fig. 8.3** Assessment of right ventricular systolic pressure in a patient with a ventricular septal defect after myocardial infarction. Note that there is flow in both systole (*white arrow*) and diastole (*red arrow*). Other abbreviations: *LV* Left ventricle, *RV* Right ventricle

## Evaluation of Right Ventricular Diastolic Pressure

The right ventricular diastolic pressure is similar to the right atrial pressure in the absence of tricuspid stenosis. Therefore, the right ventricular diastolic pressure (RVDP) equals right atrial pressure (RAP). One can use the IVC dimensions to estimate the RAP and substitute that number for RVDP.

$$\text{RVDP} = \text{RAP}$$

The RVDP can also be calculated in the presence of a ventricular septal defect with left-to-right shunt. If the left ventricular diastolic pressure is higher than the right ventricular diastolic pressure, then there is continuous diastolic flow from left ventricle to right ventricle. If the left ventricular diastolic pressure is known, then the RVDP can be calculated as the left ventricular diastolic pressure (LVDP) minus the ventricular septal defect (VSD) diastolic gradient.

$$\text{RVDP} = \text{LVDP} - \text{VSD diastolic gradient}$$

## Evaluation of Pulmonary Artery Systolic Pressure

It can be assumed that the pulmonary artery systolic pressure equals the right ventricular systolic pressure in the absence of pulmonic stenosis. Therefore, the pulmonary artery systolic pressure (PASP) equals the tricuspid regurgitation (TR) gradient plus the right atrial pressure (RAP).

$$\text{PASP} = \text{TR gradient} + \text{RAP}$$

However, in the presence of pulmonic stenosis, the gradient across the pulmonic valve must be accounted for. It is still possible to calculate the PASP by first calculating the pulmonic stenosis gradient. In these patients, the pulmonary artery systolic pressure (PASP) equals the right ventricular systolic pressure (RVSP) minus the pulmonic stenosis (PS) gradient.

$$\text{PASP} = \text{RVSP} - \text{PS gradient}$$

## Evaluation of Pulmonary Artery Diastolic Pressure

The velocity of pulmonic regurgitation can be used to calculate the gradient between the pulmonary artery and the right ventricle. The majority of patients normally have some degree (trace to mild) of pulmonic regurgitation. Thus, the pulmonary artery diastolic pressure (PADP) equals the end pulmonary regurgitation gradient plus the right ventricular diastolic pressure (RVDP).

$$\text{PADP} = \text{PR gradient} + \text{RVDP}$$

Since the right atrial pressure is approximately equal to the right ventricular diastolic pressure, this equation can be simplified to the pulmonary artery diastolic pressure (PADP) equaling the pulmonic regurgitation (PR) gradient plus right atrial pressure (RAP).

$$\text{PADP} = \text{PR gradient} + \text{RAP}$$

The ability to measure the pulmonic regurgitation velocity may be particularly helpful in the evaluation of the pulmonary artery pressure in patients who do not have a sufficient tricuspid regurgitation jet. Figure 8.4 shows a continuous wave Doppler tracing of pulmonic valve flow in a patient evaluated for significant pulmonary

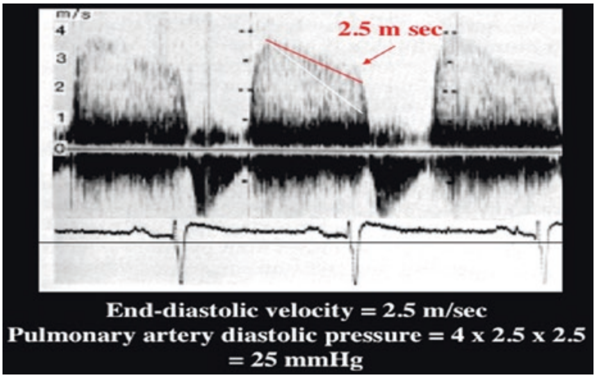


**Fig. 8.4** Assessment of pulmonary artery diastolic pressure in a patient with pulmonary hypertension. The continuous wave Doppler of the pulmonic valve shows an end-diastolic velocity of 2.5 m/s. This indicates an end-diastolic gradient of 25 mmHg between the pulmonary artery and the right ventricle

hypertension who did not have tricuspid regurgitation. The end-diastolic velocity of the pulmonic regurgitant flow is 2.5 m/s, which indicates an end-diastolic gradient of 25 mmHg across the pulmonic valve. Therefore, the diastolic pulmonary artery pressure is at least 25 mmHg (25 mmHg plus the right ventricular diastolic pressure or right atrial pressure).

## Evaluation of Mean Pulmonary Arterial Pressure

An estimation of pulmonary artery (PA) pressures in the absence of tricuspid or pulmonic regurgitation can be obtained with M-mode echocardiography and pulse wave Doppler. Normally atrial contraction produces a premature opening movement of the pulmonic valve, since the diastolic pressure is lower in the pulmonary artery than the right atrial/ventricular pressure after atrial contraction. In severe pulmonary hypertension, the elevated pulmonary pressures do not allow the atrial contraction to cause movement of the pulmonary leaflet. The characteristic M-mode pattern of the pulmonic valve in patients with severe pulmonary HTN includes an absence of "a" deflection during atrial contraction. The elevated pulmonary pressures can cause premature closure of the pulmonary valve during systole, which appears as the "flying W" on M-mode echocardiography (Fig. 8.5).

Mean PA pressures can be obtained by measuring the systolic acceleration time of the antegrade flow velocity measured by pulse wave Doppler just proximal to the pulmonic valve. The acceleration time is inversely proportional to the mean PA pressure [4]. The equation used for this estimation is:

$$\text{PAMP} = 79 - (0.45 \times \text{AcT})$$

where PAMP is mean PA pressure in mmHg and AcT is acceleration time in milliseconds.

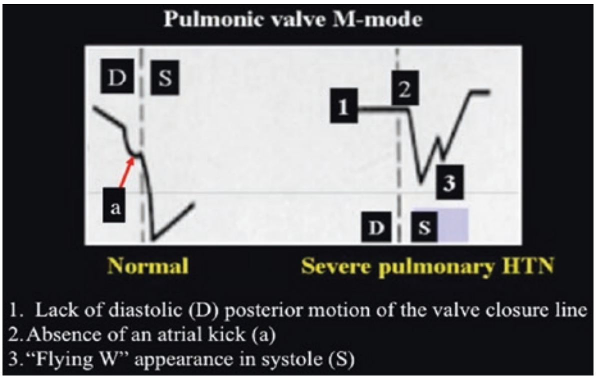


**Fig. 8.5** A comparison M-mode echocardiography of the pulmonic valve in individuals with and without severe pulmonary hypertension

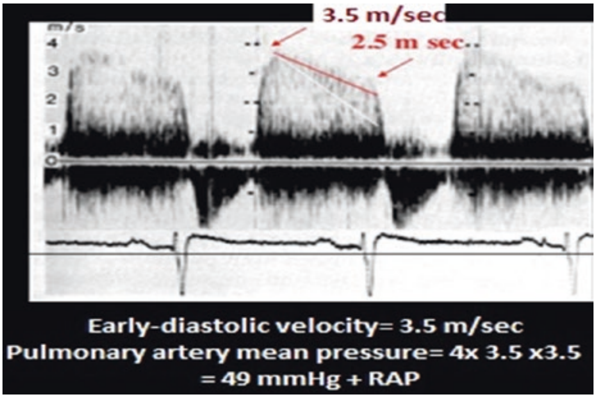


**Fig. 8.6** Assessment of pulmonary artery mean pressure in a patient with pulmonary hypertension. The continuous wave Doppler of the pulmonic valve shows an early diastolic velocity of 3.5 m/s. This indicates an early diastolic gradient of 49 mmHg between the pulmonary artery and the right ventricle

A normal acceleration time is greater than 120 ms, and values less than 90 ms are associated with a PA mean pressure greater than 40 mmHg.

Mean PA pressure can also be estimated from the pulmonic regurgitation jet. Figure 8.6 shows a continuous wave Doppler tracing of pulmonic valve flow in a patient evaluated for significant pulmonary hypertension who did not have tricuspid regurgitation. The early diastolic velocity of the pulmonic regurgitant flow is 3.5 m/s, which indicates an early diastolic gradient of 49 mmHg across the pulmonic valve. Therefore, the mean pulmonary artery pressure is at least 49 mmHg (49 mmHg plus the right ventricular diastolic pressure or right atrial pressure).

## Evaluation of Left Ventricular Systolic Pressure

In patients without aortic valve or left ventricular outflow obstruction, the gradient between the left ventricle and the aorta during systole is negligible. Therefore, left ventricular systolic pressure (LVSP) is equal to the systolic blood pressure (SBP).

$$\text{LVSP} = \text{SBP}$$

In patients with outflow obstruction (i.e., aortic valve, subvalvular or supravalvular stenosis), there is a gradient between the left ventricle and the ascending aorta. Since the systolic ascending aortic pressure equals the systolic blood pressure, the left ventricular systolic pressure (LVSP) equals the systolic blood pressure (SBP) plus the systolic pressure gradient across the aortic valve (or other subvalvular or supravalvular sites).

$$\text{LVSP} = \text{SBP} + \text{aortic valve gradient}$$

The gradient across the aortic valve can be measured with continuous wave Doppler. While cardiac catheterization records the peak-to-peak gradient (P2P), which is the gradient between peak aortic systolic pressure and peak left ventricular systolic pressure, Doppler echocardiography measures the maximum instantaneous gradient (MIG). The value of the MIG is typically higher than the P2P (Fig. 8.7). In most cases of severe aortic stenosis, the P2P is approximately 70% of the MIG. After the mean pressure gradient is calculated with Doppler echocardiography, the P2P can be estimated by taking 70% of the MIG. This number is then added to systolic blood pressure to calculate left ventricular systolic pressure.

$$\mathrm{LVSP} = \mathrm{SBP} + 70\%\mathrm{MIG}$$

The mitral regurgitant jet can be used to help estimate LVSP and gradients across the aortic valve. Continuous wave Doppler of the mitral regurgitant jet is used to estimate the gradient between the left ventricle and left atrium. The left ventricular systolic pressure (LVSP) equals the mitral regurgitation gradient plus the left atrial pressure.

$$\mathrm{LVSP} = \mathrm{MR\ systolic\ gradient} + \mathrm{LAP}.$$

The mitral regurgitant jet can also be used to estimate the gradient in a patient with aortic stenosis. Figure 8.8 shows the MR jet in a patient with aortic stenosis, with a

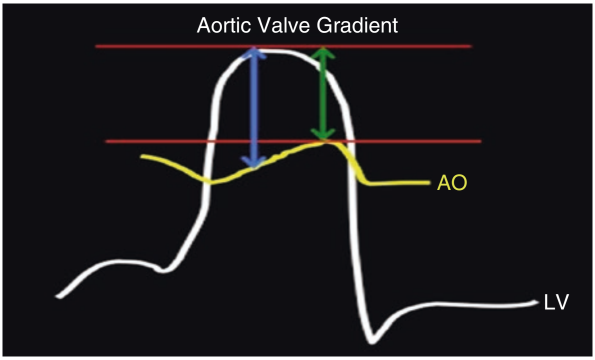


**Fig. 8.7** Left-sided pressure curves in aortic stenosis demonstrating maximum instantaneous gradient (*blue arrow*) and the peak-to-peak gradient (*green arrow*)

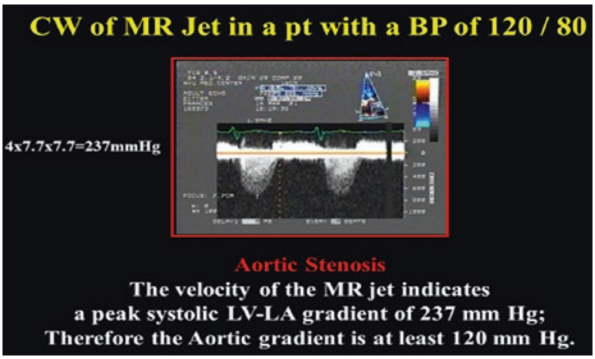


**Fig. 8.8** The velocity of the MR jet indicates a peak systolic LV-LA gradient of 237 mmHg. The aortic gradient is therefore 237 mmHg + LAP – 120 mmHg (SBP)

blood pressure of 120/80 mmHg. The LVSP can be calculated based on the MR jet (see above). Aortic gradient can be calculated from the LVSP and SBP.

$$\text{Aortic gradient} = \text{LVSP} - \text{SBP}$$

## Evaluation of Left Ventricular Diastolic Pressure

Similar to the right atrial and ventricular diastolic pressure, the gradient between the left atrium and the left ventricle during diastole is small and can be ignored in the absence of mitral stenosis. Therefore, the left atrial pressure (LAP) can be estimated and will approximate left ventricular diastolic pressure (LVDP).

$$\text{LVDP} = \text{LAP}$$

In patients who have aortic regurgitation, the regurgitant jet velocity is a function of the diastolic gradient between the aorta and the left ventricle. If the aortic diastolic pressure is known, then the left ventricular end-diastolic pressure (LVEDP) equals the diastolic blood pressure (DBP) minus the aortic regurgitation gradient (AR) at end diastole. In most patients, the aortic pressure equals the cuff pressure in the arm.

$$\text{LVEDP} = \text{DBP} - \text{end diastolic AR gradient}$$

In patients with VSD with a left-to-right shunt, the LVEDP can be calculated if the RA pressure (RAP), which estimates RV diastolic pressure (in the absence of tricuspid stenosis), is known. In these patients, the addition of the RAP and the VSD end-diastolic gradient equals the LVEDP.

$$\text{LVEDP} = \text{RAP} + \text{VSD end} - \text{diastolic gradient}$$

Figure 8.9 demonstrates a continuous wave Doppler tracing taken from a patient with both aortic stenosis and aortic regurgitation. The aortic stenosis peak velocity jet is 4 m/s, and aortic regurgitation end-diastolic velocity is also 4 m/s. The blood pressure during the examination was 150/80 mmHg. Therefore, the left ventricular systolic pressure equals the systolic blood pressure (150 mmHg) plus 70% of the aortic systolic gradient. Since the maximum instantaneous aortic gradient is 64 mmHg, the peak-to-peak gradient is 70% of 64 mmHg, which is 45 mmHg. The left ventricular systolic pressure is therefore 150 + 45 = 195 mmHg. The left ventricular diastolic pressure equals the diastolic blood pressure (80 mmHg) minus the aortic diastolic gradient (64 mmHg), which equals 16 mmHg. Therefore, this patient's left ventricular pressure is 195/16 mmHg.

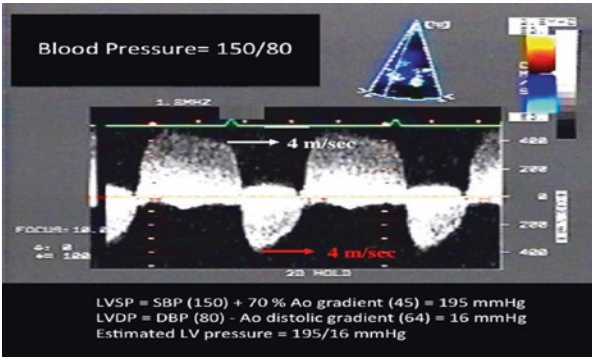


**Fig. 8.9** Continuous wave Doppler (CW) in the calculation of left ventricular (LV) pressures in a patient with aortic stenosis and insufficiency (see text). Aortic stenosis peak velocity (*red arrow*) and aortic regurgitation end-diastolic velocity (*white arrow*) both measure to be 4 m/s. Other abbreviations: *Ao* Aorta, *LVSP* Left ventricular systolic pressure, *LVDP* Left ventricular diastolic pressure, *SBP* Systolic blood pressure, *DBP* Diastolic blood pressure

## Evaluation of Left Atrial Pressure

Doppler echocardiography is useful to estimate left ventricular filling pressures. Pulse wave Doppler of the transmitral and pulmonary venous flow, along with tissue Doppler of the lateral and septal mitral annulus, allows for the estimation of LAP. Under normal flow patterns, the pressure in the left atrium is generally between 6 and 12 mmHg. Impaired relaxation results in a flow pattern with a low *E*-wave and high *A*-wave on pulse Doppler and corresponds to an atrial pressure of ~13–19 mmHg (minimal elevation left atrial pressure). In pseudonormalization of transmitral flow, the *E*–*A* ratio is between 9 and 14 with a low $E'$. This corresponds to an elevated left atrial pressure ranging from 20 to 24 mmHg. Lastly, a restrictive pattern with a high *E*-wave, low *A*-wave, and rapid transmitral deceleration time (<150 ms) occurs when the left atrial pressure is usually at least 25 mmHg. A simpler alternative to calculating left atrial pressure uses the ratio of the transmitral flow *E*-wave velocity and the tissue Doppler ($E'$). In general, as the left atrial pressure increases, *E*-wave becomes higher and the $E'$ becomes lower. An $E/E'$ ratio of less than 9 is associated with normal left atrial pressures, where as a ratio of greater than 14 is highly specific for elevated left atrial pressures (>14 mmHg). An equation reported by Nagueh et al. [5] describes the relation between LAP and $E/E'$.

$$\text{LAP} = 1.24\left[\left(E / E'\right) + 1.9\right]$$

The simplified equation that may be used is:

$$\text{LAP} = E / E' + 4\,\text{mmHg}$$

In patients with mitral regurgitation (without aortic stenosis), the left atrial pressure during ventricular systole (LAS) equals the systolic blood pressure (SBP) minus the mitral regurgitation (MR) gradient.

$$\text{LAS} = \text{SBP} - \text{MR gradient}$$

In patients with mitral stenosis, the left atrial pressure during ventricular diastole (LAD) equals the left ventricular end-diastolic pressure (LVEDP) plus the mean transmitral gradient.

$$\text{LAD} = \text{LVEDP} + \text{transmitral gradient}$$

Left atrial pressure can also be estimated with the use of flow propagation velocity ($V_p$) of the mitral inflow obtained by color M-Mode. The $V_p$ measures that rate at which red blood cells reach the LV apex from the mitral valve during early diastole. $V_p$ is an indirect measurement of LV relaxation rate. Therefore a lower $V_p$ means that LV relaxation is higher, which corresponds to elevated filling pressures.

$$\text{PAWP} = 4.6 + 5.27 \times E / V_p$$

where $V_p$ is the flow propagation velocity of the mitral inflow obtained by color M-Mode in cm/sec. $E$ is the peak blood flow velocity of the mitral inflow in cm/s.

It is important to note that for the use of Doppler echocardiography, the estimation of left atrial pressure assumes absence of atrial fibrillation, ventricular pacing, left bundle branch block, left ventricular assist device, or mitral valve disease.

## Calculation of Cardiac Output

Cardiac output (CO) may be calculated by measuring either pulmonary or systemic blood flow. In the absence of shunts, the pulmonary blood flow is equal to systemic blood flow (SBF). The left ventricular outflow tract blood flow is often used to calculate the stroke volume. The LVOT flow can be calculated by the cross-sectional area (CSA) times the velocity time integral (VTI) of the LVOT. The cardiac output can then be calculated by multiplying the stroke volume with the heart rate (HR) (Fig. 8.10).

$$\text{SV} = \text{CSA}_{\text{LVOT}} \times \text{VTI}_{\text{LVOT}}$$

$$\text{CO} = \text{SV} \times \text{HR}$$

Calculation of cardiac output can be done using the right ventricular outflow tract blood flow or the flow in the pulmonary artery as well.

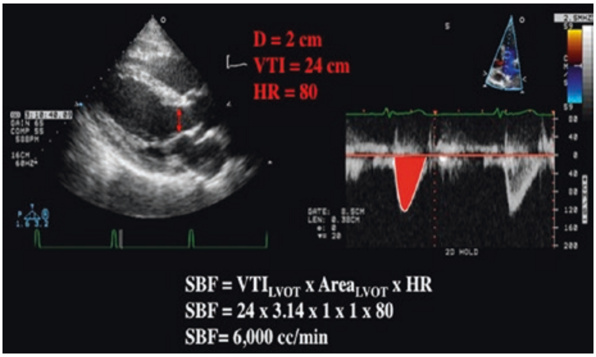


**Fig. 8.10** Calculation of systemic blood flow. The diameter (*D*) is measured at the LVOT in parasternal long-axis view (*left*), and the VTI (*right*) is determined by pulse wave Doppler at the LVOT

## Calculation of Shunt Flow

Calculating shunt flow in patients with atrial or ventricular septal defects can be performed by subtracting the systemic blood flow (SBF) from the pulmonary blood flow (PBF) (Fig. 8.11).

$$\text{Shunt flow} = \text{PBF} - \text{SBF}$$

Alternatively, the shunt flow can be estimated by multiplying the defect orifice area (DOA) by the shunt velocity time integral (VTI) and heart rate (HR). Figure 8.10 is an example of the calculation of ASD flow with a left-to-right shunt with an orifice area of 1.2 (radius of 0.6 cm), a VTI of 80 cm, and HR of 80 bpm. Using the equation below, the shunt flow is calculated.

$$\text{Shunt flow} = \text{DOA} \times \text{VTI}_{\text{shunt}} \times \text{HR}$$

## Estimation of Pulmonary Vascular Resistance (PVR)

Pulmonary vascular resistance is defined as the ratio between the pressure gradient and the blood flow across the pulmonary vascular tree, measured in Wood's units. Invasively, PVR can be calculated using the following equation:

$$\text{PVR} = \left(\text{PAMP} - \text{LAMP}\right) / \text{PBF}$$

where PAMP = pulmonary artery mean pressure in mmHg, LAMP = left atrial mean pressure in mmHg, and PBF = pulmonary blood flow in L/min.

The PVR is directly related to the PA pressure (and therefore to the maximal TR jet velocity) and inversely related to the stroke volume in the RVOT (which can be measured noninvasively by pulse wave Doppler, using the VTI at the RVOT, just proximal to the pulmonic valve). PVR can therefore be calculated by Doppler using the following equation [6]:

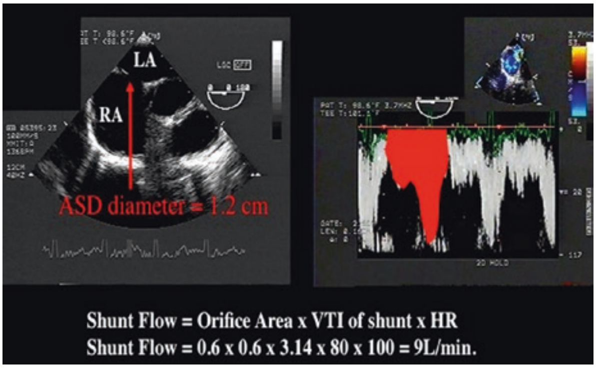


**Fig. 8.11** Calculation of ASD with left-to-right shunt flow. The *red arrow* marks the ASD orifice diameter (*left*). The VTI of the shunt flow is shown in the shaded red area (*right*)

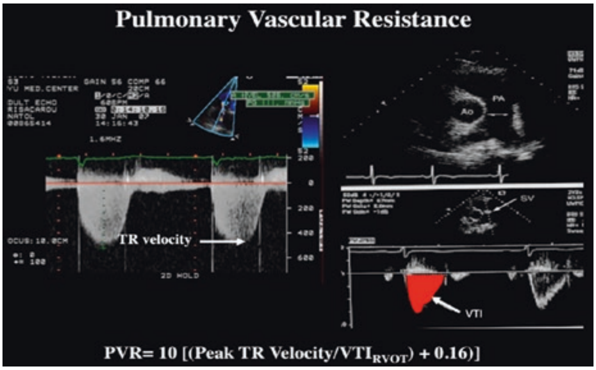


**Fig. 8.12** Noninvasive calculation of PVR in Wood's units using the peak TR velocity and VTI at the RVOT

$$\text{PVR} = 10\left[\left(\text{peak TR Velocity} / \text{VTI}_{\text{RVOT}}\right) + 0.16\right]$$

where PVR is expressed in Wood's units, TR = tricuspid regurgitation in m/s, and $\text{VTI}_{\text{RVOT}}$ = velocity time integral at the right ventricular outflow tract in centimeters (Fig. 8.12).

## Conclusion

With the use of Doppler Echocardiography, intracardiac pressures can be assessed noninvasively. The hemodynamic information obtained with the use of echocardiography can be comparable to invasive methods. It is therefore important to obtain a full echocardiographic exam in cardiac patients hospitalized in the cardiac critical care unit. This information can be especially helpful in the assessment and management of CCU patients without invasive hemodynamic monitoring.

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