Chapter 12
Echocardiographic Assessment of Pulmonary Artery Pressure, Tips and Tricks

Anthonie L. Duijnhouwer and Arie P.J. van Dijk

Abstract Pulmonary hypertension (PHT) is often observed in the presence of left side heart disease and lung disease, it is rare in the presence of all other possible causes, like PHT associated with atrial septal defect. Regardless of the cause of PHT it is always a sign of poorer prognosis. Echocardiography can help making the diagnosis of PHT, keeping in mind that only invasive pressure measurements can confirm the diagnosis of pulmonary hypertension (PHT). Echocardiography plays an important role in the screening and can simultaneously determine the possible cardiac cause of the PHT.

Tricuspid regurgitation velocity is the most used method to assess the systolic right ventricular pressure. This is only possible in absence of an outflow obstruction of the right ventricle (like pulmonary valve stenosis or infundibular obstruction). Other features of PHT should be evaluated like right ventricle deformation (dilatation, loss of banana shape) and function, the later being important for the prognosis. Doppler interrogation of pulmonary regurgitation can give an estimation of the existing mean and diastolic pulmonary artery pressures. Patterns of the pulsed wave Doppler of the right ventricular outflow can also be used to estimate the existing pulmonary artery pressures.

Keywords Pulmonary hypertension • Right ventricular pressure estimation • Pulmonary pressure estimation

Abbreviations

PHT	Pulmonary hypertension
PAH	Pulmonary arterial hypertension
RV	Right ventricle
RA	Right atrium

A.L. Duijnhouwer, M.D. (✉) • A.P.J. van Dijk, M.D., Ph.D.
Department of Cardiology, Radboud University Medical Center, Nijmegen, The Netherlands
e-mail: Toon.Duijnhouwer@radboudumc.nl

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IVC	Inferior vena cava
RVOT	Right ventricle outflow tract
PA	Pulmonary artery

Introduction

Echocardiography plays an important role in the screening for PHT, because estimation of the blood pressure in the pulmonary artery is possible in a variety of ways.

Echocardiography is non-invasive, easy applicable and almost everywhere accessible. Several Causes of pulmonary hypertension can be differentiated using echocardiography, especially in left sided heart diseases and congenital heart defects. The presence of an increased pressure load in PHT causes remodeling of the right ventricle, which can easily be assessed by looking for changes in anatomy and function. Right ventricular function has an important role in determining prognosis in all patients with some form of PHT [1]. To understand the lung circulation, not only pulmonary artery pressure, left atrial pressure and the right ventricle function need to be known, but pulmonary blood flow is important as well. Both pressures and flow can be estimated by echocardiography.

To understand the pulmonary circulation the analogy with Ohm's law for electrical circuits can be used.

Ohm's Law: $V = I \times R$

(V = voltage difference between two points, I = current, R = resistance)

Ohm's law can be rewritten for a hemodynamic circuit, i.e. the pulmonary circulation as:

$(MPAP-LAP) = Qp \times PVR$

(Qp = pulmonary blood flow (L/min), MPAP = mean pulmonary arterial pressure (mmHg), LAP = left atrial pressure (mmHg), PVR = pulmonary vascular resistance (Wu)

Case

Mrs. K, a 65 years old woman complains of chest pain and dyspnea during moderate physical effort as walking stairs. She had hypothyroidism for which she uses substitution therapy. At the emergency department of a regional hospital she had elevated cardiac troponin, but on coronary angiography no significant stenosis were present.

For further evaluation of the dyspnea, she was referred to the outpatient pulmonary hypertension clinic.

All images shown in this chapter were obtained from Mrs. K's echocardiography.

The Anatomy of the Right Ventricle and the Effects of Elevated Pulmonary Arterial Pressures

Due to the limitations of two-dimensional echocardiography, the anatomy of the right ventricle is difficult to analyze. Ideally, three-dimensional echocardiography could resolve this problem, but in practice the retrosternal location of the right ventricle in the thorax makes it difficult to image the entire right ventricle. Especially imaging of the anterior right ventricular wall is troublesome [2]. To get a full picture using two-dimensional echocardiography, it is necessary to assess the right ventricle form multiple directions and views.

The right ventricle is a low-pressure volume pump and therefore has only thin myocardial wall and is wrapped around the thick walled spherical left ventricle. As shown in Fig. 12.1, the right ventricle has a more banana-shaped configuration.

In PHT, as a consequence of increased afterload, right ventricular hypertrophy develops in order to keep wall stress as low as possible and to increase contractility. To maintain stroke volume the right ventricle dilates, which also includes dilation of the tricuspid annulus. Eventually, with chronically increased afterload, right ventricular systolic and diastolic failure ensues leading to more dilation and tricuspid regurgitation.

To evaluate the anatomy of the right ventricle and pulmonary valve a minimal number of images should be made.

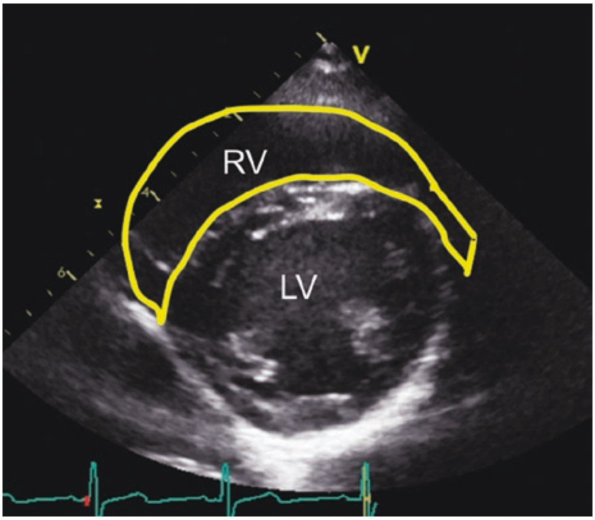

Fig. 12.1 Parasternal short axis view at the height of the papillary muscle

Parasternal Long Axis View of the Left Ventricle

One should keep in mind that the right ventricle consists of 3 parts, the inflow, the outflow and the trabecular part, that all parts should be visualized. The *outflow part* is best seen in the parasternal long axis view. In this view the abnormal position of the interventricular septum can be seen. The left ventricle, aortic valve and mitral valve can be evaluated (Fig. 12.2a).

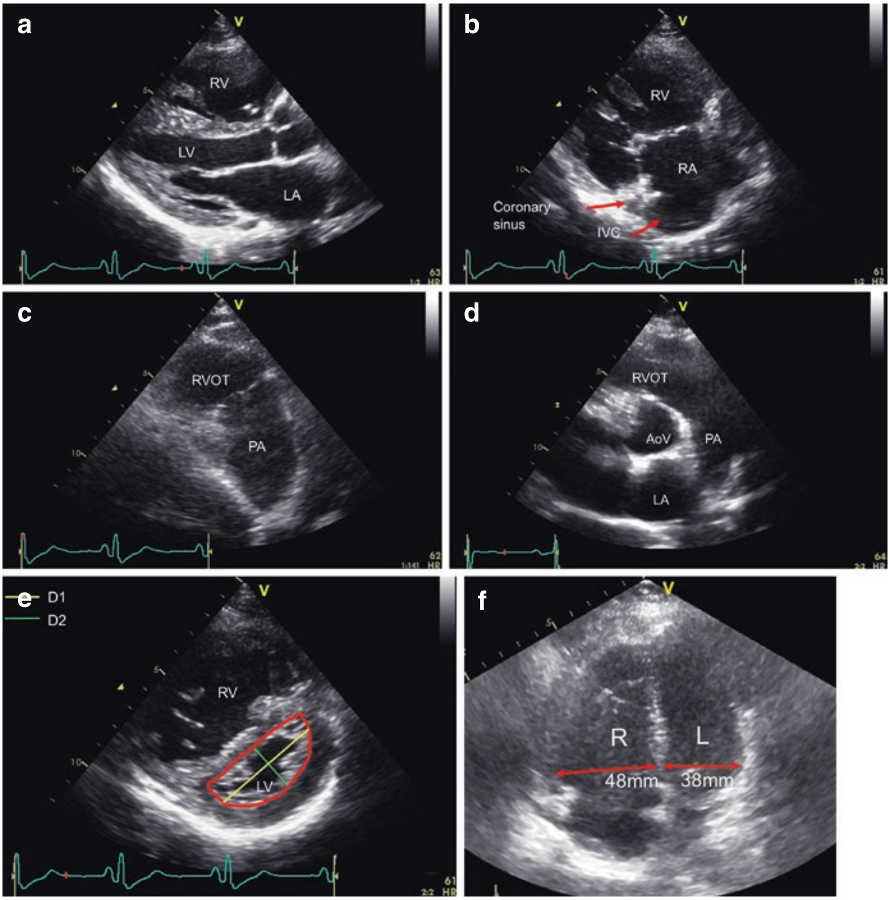

Fig. 12.2 (**a**) Parasternal long axis view. (**b**) Parasternal long axis view of the right ventricle. (**c**) Parasternal long axis view of pulmonary artery and right ventricle outflow tract. (**d**) Parasternal short axis view at the level of the aortic valve. (**e**) Parasternal short axis view at the level of the papillary muscles. (**f**) Apical 4-chamber view

Parasternal Long Axis of the Right Ventricle

This view can be obtained by tilting the probe to scan more anteriorly. The right ventricle *inflow part* can be visualized. This is the only view in which the right anterior (free) wall can be visualized completely, in order to assess the hypertrophic right anterior free wall and its systolic function. (Fig. 12.2b). The diaphragmatic, inferior right ventricular wall can also be seen.

Parasternal Long and Short Axis Views of the Pulmonary Valve and Main Pulmonary Artery

In order to evaluate the pulmonary valve the two most used views are the parasternal long axis view and short axis view. The long-axis view (Fig. 12.2c) is obtained by tilting the probe more cranial. In the parasternal short axis view (Fig. 12.2d), the infundibular portion or *outflow portion* of the right ventricle can be evaluated to assess whether a right ventricular outflow obstruction or pulmonary valve stenosis is present. Quantification of the severity of the obstruction can be done using continuous wave Doppler.

Parasternal Short Axis at the Level of the Papillary Muscles

The parasternal short axis at the level of the papillary muscles evaluates the mid segments of the left and right ventricle (Fig. 12.2e).

Progression of right ventricle pressure causes thickening of the wall and dilation of the lumen.

The pressure loaded right ventricle loses its crescent, banana-shape, configuration and becomes more spherical and dilated. The wall is thickened. The interventricular septum shows systolic flattening, which causes the left ventricle to get a typical D-shape in this view. This septal flattening can be quantified by the eccentricity index, which is the ratio of the left ventricular diameter perpendicular to the septum and the orthogonal diameter of the left ventricle at the same level. This index changes from 1 (normal) to >1 in elevated right ventricular systolic pressures. An index >1.0 is therefore one of the secondary echocardiographic signs of pulmonary hypertension. An index >1.7 denotes a poor prognosis.

Diastolic interventricular septal flatting can be seen in severe tricuspid valve regurgitation as a sign of volume overload.

Eccentricity index = D1/D2

Apical 4 Chamber View

The inflow of the right and left ventricle can be evaluated in the 4-chamber view, which further allows the comparison of the right and left ventricular dimensions. The ratio of the basal right to left ventricular diameters. >1.0 is a secondary sign of PHT (Fig. 12.2f). For a realistic measurement of these diameters one should avoid foreshortened images by placing the ultrasound probe on the apex of the heart. In some cases this can be challenging and difficult to accomplish.

Right atrial dilation is often present in the presence of PHT. In the apical 4-chamber view the maximal right atrial area (mid-systole) can be measured. A right atrial area >18 cm^2 is indicative of right atrial dilatation and >27 cm^2 indicates a poorer prognosis.

Beware of foreshortening with the consequence of measuring a larger right to left ventricular diameter ratio, due to oblique imaging of the right ventricle.

Tricuspid Valve Anatomy and Effect of High Pulmonary Artery Pressures and Right Ventricle Dilatation

The tricuspid valve is an anatomical structure belonging to the right ventricle. It consists of 3 valve leaflets which are kept in place by chordae, which on their part are mostly attached to the anterior papillary muscle. Chordae are also attached directly to the septum and to many smaller medial and inferior papillary muscles. The normal tricuspid valve annulus is an oval structure, with its largest diameter in the anterior to posterior direction. The tricuspid valve does not lie in one plane: the septal part is more cranially displaced in the perimembraneus region and the postero-septal region near the opening of the coronary sinus is lying more apically. During the cardiac cycle the annular area changes with a maximum area change during mid-diastole with the largest change in the septal to lateral axis. In diastole the annular plane is round and flat, while in systole the annulus becomes more oval and the curvature increases [3].

In the setting of right ventricular remodeling by pressure overload in PHT the morphology of the tricuspid valve changes. Dilation of the annulus is dominantly in the septal to lateral axis making the annular area larger, more round, and more planar during systole. As a consequence, a loss of leaflet coaptation area occurs. Additionally, right ventricle dilatation leads to a change in the geometry of the subvalvular apparatus causing tenting of the valve leaflets. In Fig. 12.3a, b schematic drawing shows these changes.

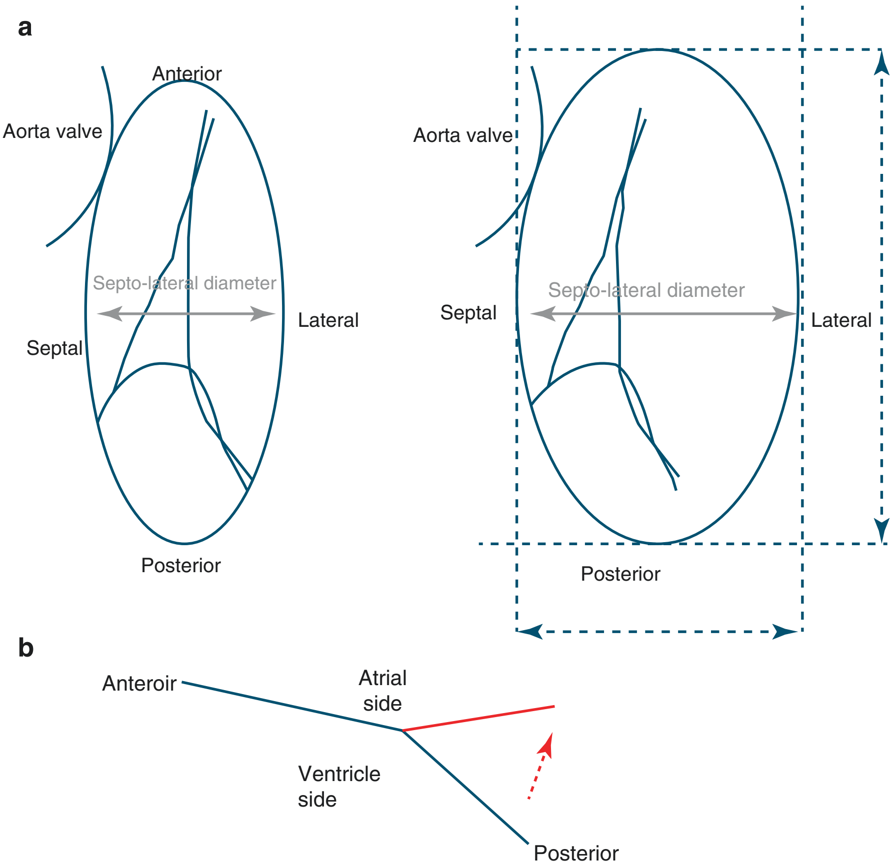

Fig. 12.3 (**a**) Change in tricuspid annulus geometry due to pressure overload of the right ventricle, the cranial view from atrium to right ventricle. (**b**) Change in tricuspid annulus geometry in the lateral view, due to pressure overload of the right ventricle

Pulmonary Pressure Estimation

As stated before it is important to realize that pulmonary artery pressure is dependent on left atrial pressure, pulmonary vascular resistance and pulmonary blood flow (cardiac output created by the right ventricular pump). During echocardiography, focus should lie on these parameters in order to understand and report the state of the pulmonary circulation completely.

In case of right ventricular outflow tract obstruction or pulmonary valve stenosis the estimated

> A common mistake is to overlook the fact that pulmonary artery pressure is not equal to systolic right ventricular pressure in the presence of right ventricle outflow obstruction (on whatever level).

systolic right ventricular pressure is not equal to the systolic pulmonary artery pressure.

Pulmonary Artery Pressure Estimation Using Tricuspid Valve Regurgitation

Almost every tricuspid valve has some regurgitation, although sometimes hard to capture with Doppler interrogation. The regurgitation jet velocity can be used to estimate the systolic pressure differences between the right ventricle and the right atrium by using the simplified Bernoulli law equation (Fig. 12.4):

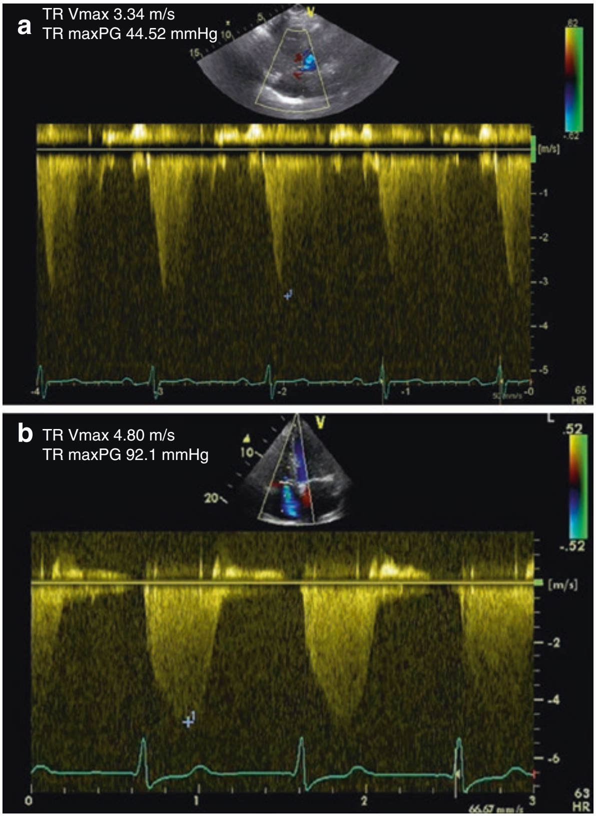

Fig. 12.4 (**a**) Continuous wave Doppler regurgitation velocity of the tricuspid valve. (**b**) Continuous wave Doppler regurgitation of the tricuspid valve of another pulmonary hypertension patient

Table 12.1 Right atrial pressure estimation

Right atrial pressure	3 mmHg (0–5 mmHg)	8 mmHg (5–10 mmHg)		> 15 mmHg
IVC diameter	≤ 21 mm	≤ 21 mm	> 21 mm	> 21 mm
IVC collapse after sniff	> 50%	< 50%	> 50%	< 50%

ΔP = 4 V2

In case of tricuspid regurgitation:

ΔP = 4 TR-Vmax2

RV systolic pressure−RA pressure = 4 TR-Vmax2

RV systolic pressure = 4 TR-Vmax2+ RA pressure

RV systolic pressure = systolic PA pressure IF no right ventricular outflow tract obstruction.

ΔP = pressure differences; V = maximal velocity assessed with continuous wave Doppler. PA = pulmonary artery, RV = right ventricle, TR-Vmax = maximal tricuspid regurgitation velocity.

To estimate right atrial pressure (see Table 12.1), the diameter of the inferior vena cava is measures either by 2D-mode or by M-mode and the variation induced by spontaneous breathing or sniff testing. This measurement should be taken just proximal of the right hepatic vein (Fig. 12.5).

So, for our patient it means that the estimated systolic pulmonary arterial pressure is 50 mmHg (pressure gradient accross tricuspid valve 45 mmHg + right atrial pressure 5 mmHg), as no right ventricular outflow tract obstruction exists (Fig. 12.2c).

A common mistake is to presume that high right ventricular pressures are accompanied by severe tricuspid valve regurgitation. But severity of tricuspid regurgitation tells us little about the existing pressure difference between right atrium and the right ventricle.

According to current guidelines (ESC guidelines 2015) the probability of the presence of pulmonary hypertension is primarily based on the maximal velocity of the tricuspid valve regurgitation jet, although other characteristics are taken into account [4]. The height of right atrial pressure is not included in the ESC guideline for pulmonary artery pressure estimation, but it is important to reckon with it. In the presence of a reduced right ventricle function or more severe tricuspid valve regurgitation right atrial pressure will be elevated, which leads to underestimation of pulmonary pressures. The guideline-based probability determination of the presence of PHT is only valid in the absence of elevated right atrial pressures (as high right atrial pressure will reduce the pressure gradient across the tricuspid valve).

Care has to be taken to measure the proper maximal velocity. Not only Doppler angle should be kept as low as possible, blurred or faint Doppler signal should be

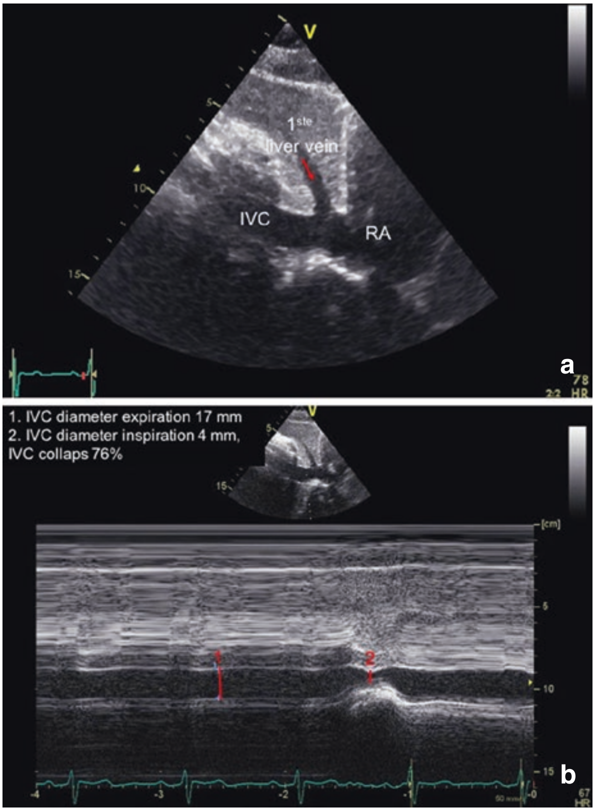

Fig. 12.5 (**a**) 2D subcostal view of the inferior vena cava. (**b**) M-mode during sniff-testing of the inferior vena cava

optimized in order to prevent over- or underestimation of velocity. Incomplete signals should not be used at all. Discrepancies in right atrial pressure estimation might lead to inaccurate pressure estimation too [5] (Fig. 12.6).

Be careful with the use of the maximal tricuspid valve regurgitation jet velocity method for the estimation of systolic pulmonary arterial pressure in the presence of severe tricuspid regurgitation, in which the pressure in the right atrium is elevated, antegrade flow through the pulmonary artery might be diminished and the simplified Bernoulli equation does not work.

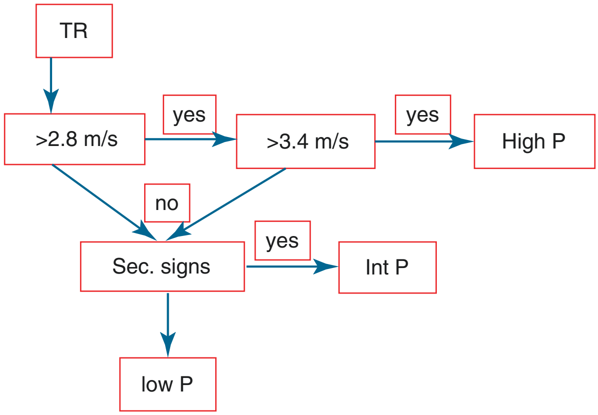

Fig. 12.6 Flow diagram of probability of pulmonary hypertension based on tricuspid valve regurgitation. *TR* tricuspid valve regurgitation, *high P* high probability of pulmonary hypertension, *int P* intermediate probability of pulmonary hypertension, *low P* low probability of pulmonary hypertension, *sec. signs* secondary signs of pulmonary hypertension

Pulmonary Artery Pressure Estimation Using Pulmonary Valve Regurgitation

The pulsed wave or continuous wave Doppler of the pulmonary valve regurgitation jet entails a lot of information about the gradient between pulmonary artery and right ventricle. In the same way as explained in paragraph 1.4.1 the Bernoulli equation can be used to calculate pressure difference between the pulmonary artery and the right ventricle in diastole. The calculated pressure gradient by using peak regurgitation velocity, occurring directly after closure of the pulmonary valve added to estimated right atrial pressure, nicely corresponds with the mean pulmonary artery pressure. In the ESC guidelines an early diastolic pulmonary regurgitation velocity > 2.2 m/s is seen as evidence for the presence of pulmonary hypertension. Care has to be taken to measure only the maximal regurgitation velocity just after pulmonary valve closure. In many patients the early pulmonary regurgitation velocity, i.e. the pressure difference between pulmonary artery and right ventricle is influenced by the early passive filling of the right ventricle through the tricuspid valve leading to loss or diminishing of the velocity signal. In the example case (Fig. 12.7a) the maximal regurgitation jet is difficult to establish, but was measured at 3.3 m/s corresponding to an estimated mean pulmonary artery pressure of 50 mmHg in case of adding a 5 mmHg right atrial pressure.

The end diastolic velocity of the pulmonary regurgitation, measured at the beginning of the QRS-complex of the ECG, corresponds well with the end-diastolic

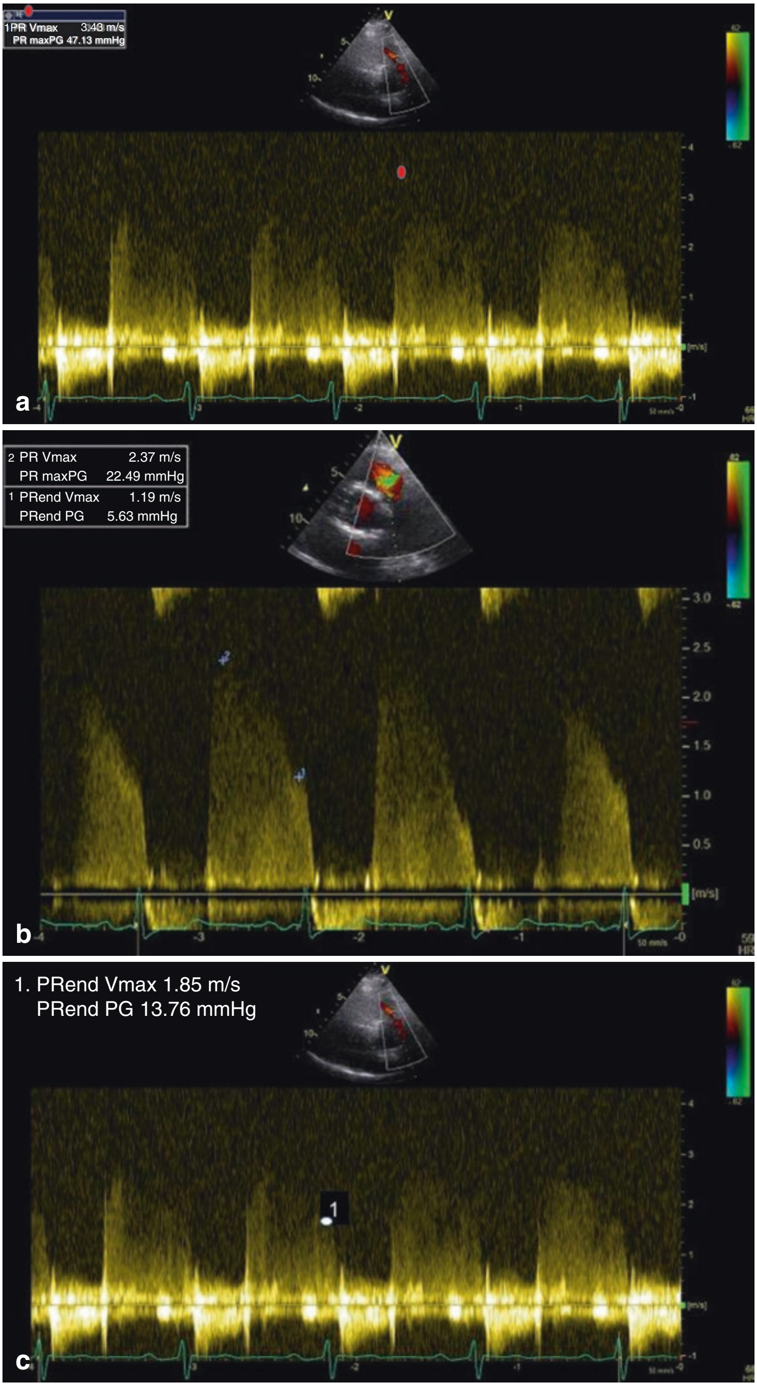

Fig. 12.7 (**a**) Continuous wave Doppler of the pulmonary valve regurgitation. (**b**) Shows another example of maximal regurgitation velocity and end diastolic regurgitation velocity. (**c**) End-diastolic velocity of pulmonary regurgitation

pulmonary arterial pressure. Right atrial pressure should be added to the calculated end-diastolic pulmonary to right ventricular pressure difference. (Fig. 12.7c).

The pulmonary regurgitation Doppler velocity is a good alternative for the tricuspid valve regurgitation Doppler velocity to estimate elevated pulmonary artery pressures.

Pulmonary Artery Pressure Estimation Using the Right Ventricle Outflow Pulsed Wave Doppler Velocity

According to ESC guideline, the acceleration time of the right ventricular outflow tract velocity as measured by pulsed wave Doppler <105 ms is a sign of PHT. The shape of the velocity curve is probably even more informative [6]. With advancing PHT the normally symmetrical parabolic shape of the curve becomes more triangular with shorter acceleration time and shorter ejection time as well. The ratio of acceleration to ejection time becomes lower meaning that acceleration time shortens more than ejection time. Eventually, by the influence of early returning reflected pressure waves in the case of elevated pulmonary vascular resistance, a notch will appear in the velocity curve. The presence of a notch is highly sensitive and predictive for the presence of elevated pulmonary vascular resistance.

Technically it can be difficult to obtain reliable Doppler signals. Placing the sample volume in the middle of the right ventricular outflow tract with a small Doppler angle can be a challenge or even impossible. Other factors as right ventricular dysfunction, the presence of tricuspid regurgitation and right bundle branch block influence the shape of the curve (Figs. 12.8 and 12.9).

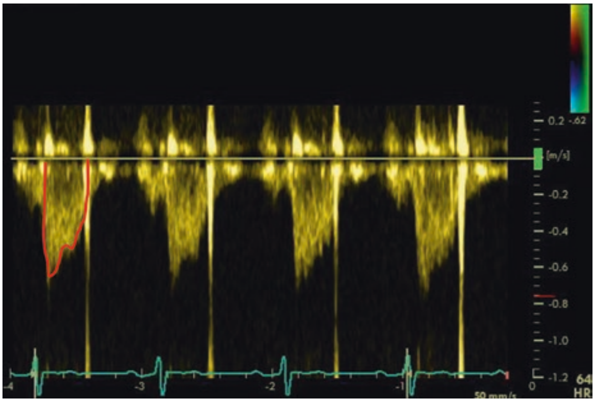

Fig. 12.8 Pulsed wave Doppler with sample in right ventricle outflow tract

According to López-Candales et al. pattern 1 can be seen in patients with a systolic pulmonary pressure up to 48 mmHg, pattern 2 in patients with a systolic pulmonary artery pressure between 48 and 68 mmHg, pattern 3 in patients with a systolic pulmonary artery pressure between 69 and 94 mmHg and pattern 4 in patients with a systolic pulmonary artery pressure above 95 mmHg [6].

Pulmonary Artery Diameter

Pulmonary artery dilatation can occur in many circumstances. The most common cause is high pulmonary pressures [7]. Measuring main pulmonary arterial diameter using echocardiography is, in our experience, inaccurate. The visibility of the pulmonary arterial wall is hindered by the fact the vessel wall runs parallel to the

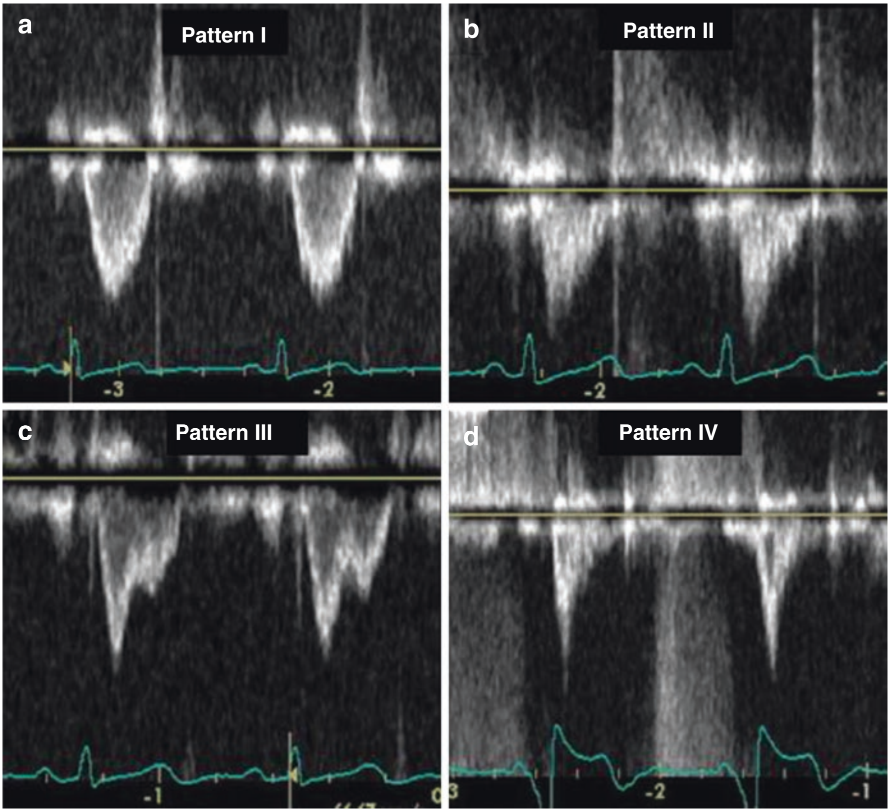

Fig. 12.9 Pulsed wave Doppler pattern of the right ventricle outflow

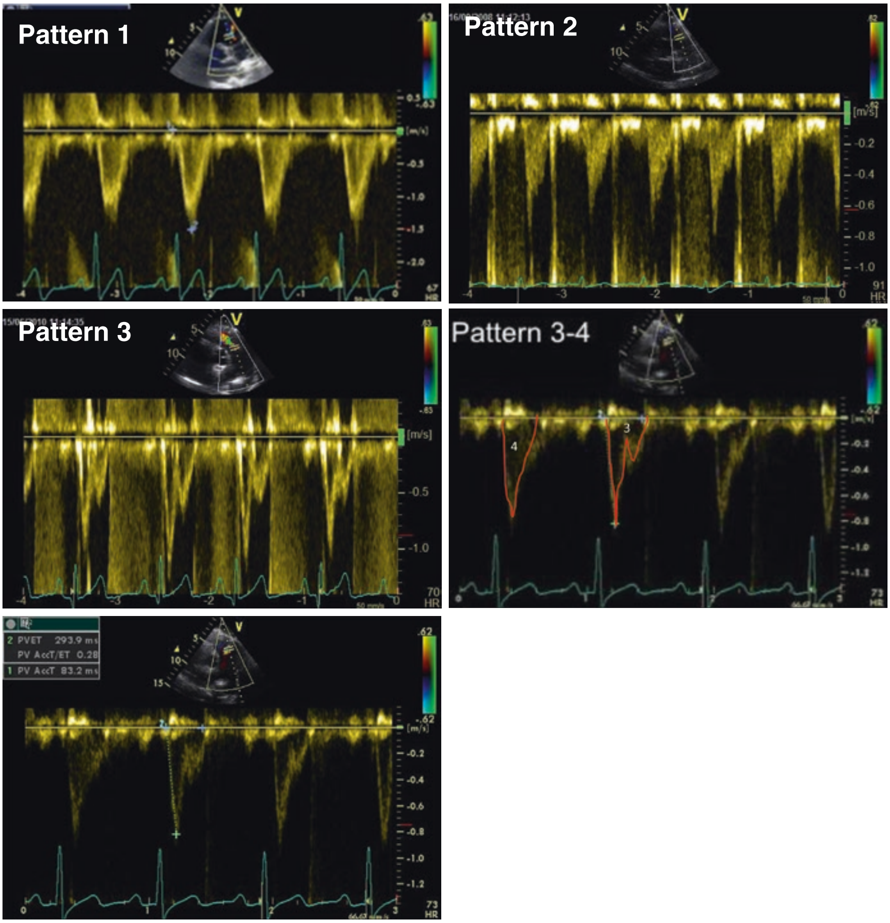

Fig. 12.9 (continued)

ultrasound beam. If well visualized a pulmonary arterial diameter > 25 mm is a secundary sign of PHT. The evidence for this recommendation is low and other conditions might lead to pulmonary arterial dilatation too, for example idiopathic pulmonary arterial dilatation or severe pulmonary regurgitation.

Key Points

1. Echocardiography can be used to screen for PHT. The diagnosis of PHT should be confirmed by invasive hemodynamic measurements.
2. Tricuspid valve regurgitation jet velocity is the best predictor of right ventricular pressure in the absence of right ventricular outflow obstruction and severe regurgitation.

3. Pulmonary valve regurgitation can be used to estimated mean and diastolic pulmonary artery pressure and is good alternative of tricuspid valve regurgitation Doppler velocity method
4. Right atrial pressure estimation should be added to the Doppler derived regurgitation jet velocity. Derived pressure difference between right ventricle and right atrium or between right ventricle and pulmonary artery, are more reliable when incorporating right atrial pressure, especially in circumstances in which an elevated right atrial pressures excised, like right ventricular failure or severe regurgitation.
5. Right ventricular outflow Doppler pulsed wave velocity signal can be used to evaluate the pulmonary artery pressure.

Questions

1. What is the effect of elevated high right ventricular pressure on the right ventricular shape?
2. What is the effect of elevated high right ventricular pressure on the annulus of tricuspid valve?
3. What condition(s) should be met to use the velocity of the tricuspid valve regurgitation to estimate systolic pulmonary artery pressure?
4. What could be the reason(s) to use right atrium pressure estimation in estimation pulmonary artery pressure?
5. Does the severity of tricuspid valve regurgitation tell us something about the height of the right ventricular pressure?
6. What does the maximal pulmonary valve regurgitation velocity tell us?
7. What does the end-diastolic pulmonary valve regurgitation velocity tell us?
8. What other parameters determine pulmonary artery pressure?

Review Questions

68. What is the effect of elevated high right ventricular pressure on the right ventricular shape?

    (a) RV hypertrophy
    (b) RV dilatation
    (c) RV hypertrophy and later on dilatation

69. What is the effect of elevated high right ventricular pressure on the annulus of tricuspid valve?

    (a) Dilatation of the anterior part only
    (b) Dilatation of the septoanterior portion
    (c) Dilatation of the anteroposterior portion
    (d) Dilatation of the posterior part only

70. What condition(s) should be met to use the velocity of the tricuspid valve regurgitation to estimate systolic pulmonary artery pressure?

    (a) Effect of respiration
    (b) Doppler alignment
    (c) Effect of loading conditions
    (d) All of the above

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