



# Hemodynamic Focused Echocardiography

# 10

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## Contents

10.1	<b>Introduction</b> .....	88
10.2	<b>Imaging Views</b> .....	88
10.2.1	Transthoracic Echocardiography: Parasternal Long and Short Axis, Apical or Subcostal Four-Chamber View with Subcostal View of the Inferior Vena Cava.....	89
10.2.2	Transesophageal Echocardiography: Midesophageal Four-Chamber view, Midesophageal View of the Superior Vena Cava, Transgastric Short Axis View.....	90
10.3	<b>Hemodynamic Assessment</b> .....	91
10.4	<b>Step 1: Cardiac Filling Impairment</b> .....	92
10.5	<b>Step 2: Volume Status</b> .....	92
10.6	<b>Step 3: Right Ventricle Function</b> .....	93
10.7	<b>Step 4: Left Ventricle Function</b> .....	94
10.8	<b>Step 5: Valve Function</b> .....	95
10.9	<b>Step 6: Cardiac Output Estimation</b> .....	95
10.10	<b>Conclusion</b> .....	96
	<b>References</b> .....	96

## Abbreviations

4C	Four-chamber view
AS	Aortic stenosis
AV	Aortic valve
CO	Cardiac output
DO <sub>2</sub>	Oxygen delivery
FAST	Focused Assessment with Sonography in Trauma

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HFpEF	Heart failure with preserved ejection fraction
IAS	Interatrial septum
ICU	Intensive care unit
IVC	Inferior vena cava
LA	Left atrium
LV	Left ventricle
LVEDD	End-diastolic left ventricular diameter
LVEF	Left ventricular ejection fraction
LVOT	Left ventricular outflow tract
ME	Midesophageal
PLAX	Parasternal long axis
PPV	Pulse pressure variation
PSAX	Parasternal short axis
RV	Right ventricle
S4C	Subcostal four-chamber view
SAX	Short axis
SIVC	Subcostal view of the inferior vena cava
SIVC-DI	SIVC-distensibility index
SV	Stroke volume
SVC	Superior vena cava
SVC-CI	SVC collapse index
TAPSE	Tricuspid annular plane systolic excursion
TEE	Transesophageal echocardiography
TGSAX	Transgastric short axis
TTE	Transthoracic echocardiography
VTI	Velocity time integral

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## 10.1 Introduction

Adequate oxygen delivery ( $DO_2$ ) is critical for the maintenance of physiological homeostasis and organ function and is significantly dependent upon cardiac stroke volume (SV). The determinants of SV are pre- and afterload, intrinsic contractility, heart rate/rhythm, and valve function. A critically reduced  $DO_2$  due to a compromised SV in the perioperative setting can worsen outcome especially in high-risk patients with preexisting cardiovascular risk factors [1–3].

In this context, hemodynamic focused echocardiography provides a real-time pathophysi-

ologically oriented approach, which allows guiding cardiovascular therapy [4–12]. It has been shown that the use of an echocardiography-based hemodynamic optimization protocol improved outcomes among septic patients in an intensive care unit (ICU) setting [13–15]. In hemodynamically unstable patients unresponsive to initial treatment, there exists a class I indication for performing a timely echocardiographic examination in order to accurately assess and implement interventions aimed at maintaining hemodynamic stability [12, 16–19]. In order to adequately interpret and evaluate echocardiographic findings, however, a standardized curricular training and continuously available supervision is inevitable [20, 21]. In addition, “focused examiners” have the responsibility to *seek expert help* whenever needed.

In this chapter, a practical six-step approach toward a perioperative echocardiographic-based hemodynamic optimization is presented. It should be noted that the proposed algorithm may be used “as needed” in the case of hemodynamic instability or “as a predefined monitoring tool” within a goal-directed treatment strategy with monitoring intervals appropriately addressing the patient’s hemodynamic risk. It may also be beneficial to be able to compare perioperative echocardiographic findings with a preoperative baseline exam. Nevertheless, it is of importance that echocardiographic findings must always be interpreted in the context of the clinical situation along with the patients’ medical background. For instance, fluid substitution will be indicated in a trauma patient with low blood pressure, overall small heart chambers and a small inferior vena cava on echocardiography.

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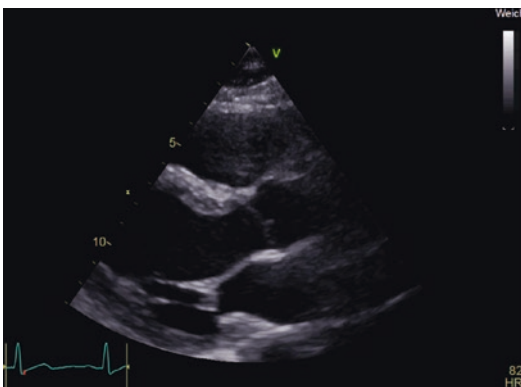
## 10.2 Imaging Views

The following views should be used within a hemodynamic focused transthoracic (TTE) or transesophageal (TEE) echocardiography:

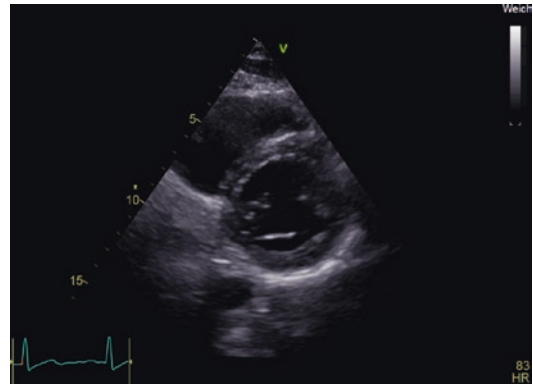
### 10.2.1 Transthoracic Echocardiography: Parasternal Long and Short Axis, Apical or Subcostal Four-Chamber View with Subcostal View of the Inferior Vena Cava

In order to obtain a parasternal long-axis (PLAX) view (Fig. 10.1), the cardiac ultrasound probe needs to be placed on the thorax in the left parasternal position, with the marker pointing toward the right shoulder. An optimal view should be gained *via* carefully moving the probe between the intercostal spaces (ICS), starting from the second ICS to the fifth ICS. Once the most optimal view has been obtained, the following structures should be apparent in the PLAX: the right ventricular outflow tract, the interventricular septum with the upper aortic wall, the aortic valve, the left atrium, the mitral valve, the left ventricle without the cardiac apex, and the posterior wall of the left ventricle. With the PLAX view, a global assessment of major cardiac structures, as well as volume status, myocardial morphology, and valve status can be assessed. Next, the parasternal short-axis (PSAX) view (Fig. 10.2) can be obtained by simply rotating the probe clockwise 90°, so that the marker on the probe is in the direction of the left shoulder.

Once the optimal view has been obtained, the following structures should become apparent: the cross-shaped left ventricle with the anterior, inferior, septal, and lateral wall segments. Adjacent



**Fig. 10.1** Parasternal long-axis view



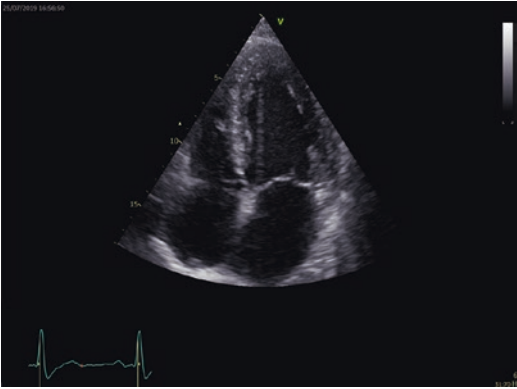
**Fig. 10.2** Parasternal short-axis view

to this is the crescent-shaped right ventricle. The cardiac apex, the cross-shaped aortic, and mitral valves, as well as the anterolateral and posteromedial papillary muscles, can be obtained *via* angulating the probe from cranial to caudal. Additionally, the pulmonary valve, the main pulmonary artery trunk, its associated branches, and the right and left pulmonary arteries can be visualized at the level of the aortic valve, normally seen on the right-hand side of the monitor. On the opposite side of the monitor, additional cardiac structures such as the aortic valve, right atrium, tricuspid valve, and right ventricle can be visualized.

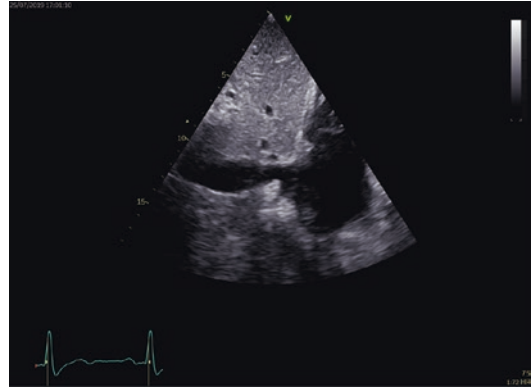
The next view which should be acquired is the apical four-chamber (4C) view (Fig. 10.3), which is best visualized by probe placement in the fifth ICS, between the medioclavicular and posterior axillary line, while the probe marker is pointing to the direction of the left shoulder.

Similarly to the PLAX view, the 4C view requires the movement of the probe between the ICS in order to obtain the best examination window.

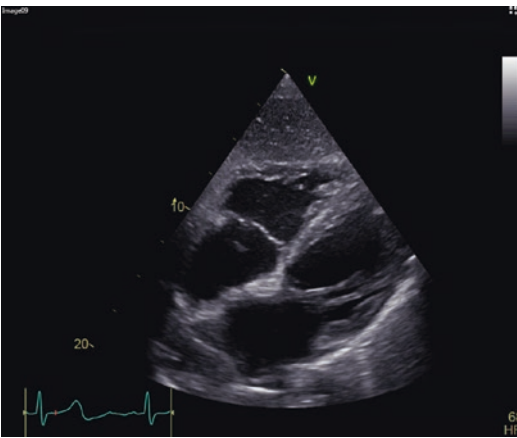
Upon obtainment of the 4C view, both the atria and ventricles, along with the tricuspid and mitral valves become apparent. In the middle of the sonographic window, the interventricular septum should be present. In order to prevent the underestimation of left ventricular, as well as the overestimation of the right ventricular dimensions, the lowest ICS 4C view should be used. This prevents the so-called “foreshortening.”



**Fig. 10.3** Apical four-chamber view



**Fig. 10.5** Subcostal view of the inferior vena cava



**Fig. 10.4** Subcostal four-chamber view

Additionally, the 4C view allows for the visualization of the left ventricular wall, which includes the inferior septal wall, and the anterior-lateral wall on the opposite side. Furthermore, a five-chamber (5C) view, which includes the left ventricular outflow tract and aortic valve, can be observed *via* probe angulation cranially. To round out the TTE, a final view should be obtained, aptly termed the subcostal four-chamber (S4C) view (Fig. 10.4). This is performed by placing the probe inferior to the xiphoid process, with the marker pointing to the patients' left side.

In this view, a four-chamber view along with the tricuspid and mitral valves is seen. The last structure which needs to be obtained for a comprehensive hemodynamic is the inferior vena cava (IVC) (Fig. 10.5), which can be visualized

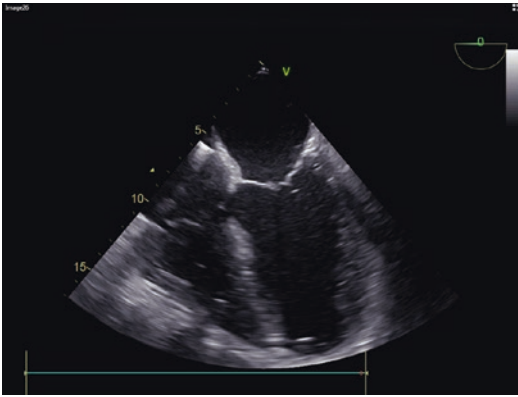
by rotating the marker toward the head of the patient. This step-by-step method rounds out the TTE assessment.

#### Practical Advice

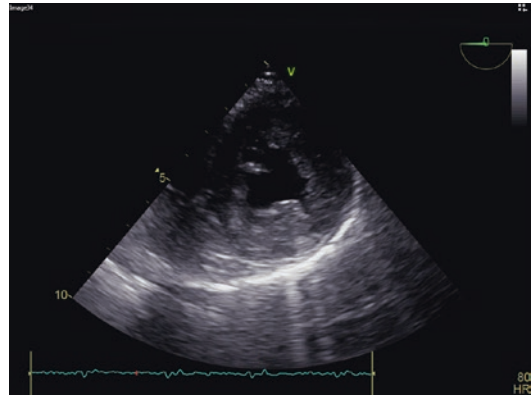
In the PLAX view, the highest intercostal view that yields a sufficient image should be used, whereas in the 4C view, the lowest intercostal space as lateral as possible should be used to prevent foreshortening.

### 10.2.2 Transesophageal Echocardiography: Midesophageal Four-Chamber view, Midesophageal View of the Superior Vena Cava, Transgastric Short Axis View [22]

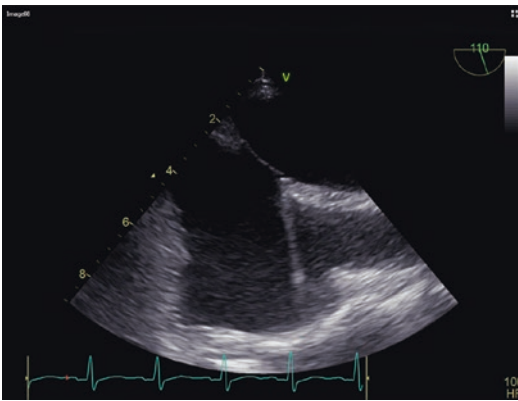
The first step is passing the probe through the upper esophageal sphincter until the first image of the left atrium is obtained. Usually, this occurs upon a 30-cm depth from the dental arch. Upon obtaining the view of the left atrium, the probe is described as being in the transesophageal position. From this position, the midesophageal four-chamber (ME4C) view (Fig. 10.6) can be obtained. By rotating the image, the left ventricular axis and the apex should become apparent in the sectional image. Similar to the 4C view of the TTE, the foreshortening of the left ventricle



**Fig. 10.6** Midesophageal four-chamber view



**Fig. 10.8** Transgastric short-axis view



**Fig. 10.7** Bicaval view

should be kept in mind. The annulus diameter of both atrioventricular valves should be acquired, while attempting to maximize the views of these valves in order to assess valve function and morphology. This can be achieved by retroflexing the probe and rotating the probe by 0–20°.

The next structures to be visualized are the right ventricle and the tricuspid valve, which should be directly in the center of the monitor. This is done by tilting the probe to the right. In order to obtain the optimal views of the great caval veins entering into the right atrium, interatrial septum, and the fossa ovalis area, the probe should be rotated 100°, thereby acquiring the bicaval view (Fig. 10.7) and the midesophageal view of the SVC.

By increasing the depth of the probe approximately 40–45 cm from the dental arch, with the probe in the “0” position of flexion and rotation

without applying force, the image is momentarily lost. Upon this loss of image, the probe should be placed in the anteflexion position and retracted until the cross-sections of the left and right ventricles are observable. The probe should then be rotated until the cross-sections of both papillary muscles are obtained and the entire symmetric left ventricle is acquired. Thereby the transgastric short-axis (TGSAX) view (Fig. 10.8) is obtained. This is an excellent position to assess the left ventricle at the midpapillary level as well as wall motion of all coronary regions. Also, this view can be reliably utilized to assess cardiac volume status and contractility.

#### Practical Advice

If the insertion of the TEE probe is difficult, the performance of an Esmarch (jaw thrust) maneuver as well as the usage of a laryngoscope can be helpful.

### 10.3 Hemodynamic Assessment

The next section details a step-by-step algorithmic approach for rapid hemodynamic assessment in order to optimize SV function in the high-risk surgical patient. All steps encompass the TTE and TEE approach.

The additional use of (color) Doppler modalities may allow for semiquantitative evaluation of

the heart valves [23]. Though TTE is noninvasive and may be the method of choice, TEE may offer better image quality, particularly in patients with morbid obesity or on mechanical ventilation [24]. Nevertheless, image acquisition will be impossible in some patients at all as well as in most patients in prone position.

## 10.4 Step 1: Cardiac Filling Impairment

The first step is to rule out cardiac filling impairment due to pericardial effusion or tamponade requiring immediate evacuation. Not only in the cardiac surgery setting but also due to trauma or due to chronic disease, a relevant accumulation of fluid in the pericardium can occur [25–28]. Echocardiographic signs of hemodynamically relevant pericardial effusions may include the existence of pericardial effusion with consecutive hypovolemia of all heart chambers, collapse of the right cardiac chambers, and/or dilatation of IVC. When using a TTE, the S4C view should be used, while for TEE, the ME4C should be used initially.

## 10.5 Step 2: Volume Status

The second step is to estimate the volume status of the patient, as both hypo- and hypervolemia can reduce SV and thus  $DO_2$ . The four-chamber (4C) views and the short-axis (SAX) views at the level of the papillary muscles are suitable for obtaining a quick overview.

Although resting diameters for cardiac chambers are gender and body surface area specific [29], the size of the left ventricle (LV) and the right ventricle (RV) should be measured. An end-diastolic left ventricular diameter (LVEDD) of 35–55 mm may reflect normal LV, and a basal RV diameter of  $\leq 41$  mm may reflect normal RV size. Qualitatively, hemodynamic-relevant hypovolemia may provoke a “kissing papillary muscle” sign: the opposite myocardial walls of the corresponding ventricle come in contact with one another during systole. Nevertheless, a preopera-

tive dilated LV (*e.g.*, LVEDD 65 mm) due to a reduced global systolic function may be interpreted as “hypovolemic” if the LVEDD is within normal range (*e.g.*, LVEDD 50 mm).

### Practical Advice

A pronounced concentric hypertrophy as evidenced by a myocardial wall thickness of  $>14$  mm (*i.e.*, due to severe aortic stenosis) must be excluded prior to the diagnosis of hypovolemia [30]!

The assessment of the interatrial septum (IAS) in the four-chamber (4C, ME4C) views can be used for qualitative estimation of atrial filling pressures. A hypermobile IAS is commonly observed during global hypovolemia. A sole increase in left atrial filling pressure will shift the IAS permanently convex to the right, whereas increased right atrial filling pressure shifts the IAS permanently convex to the left atrium in combination with the left cardiac hypovolemia [31]. Global hypervolemia may be identified with all heart chambers appearing “overfilled” or “stretched” and a in the middle-fixed IAS [32, 33].

Volume responsiveness can be estimated by interrogating the IVC *via* TTE or the SVC *via* TEE. The IVC diameter may be used to estimate the right atrial filling pressure [34]. In awake and spontaneously breathing patients, the normal diameter for the IVC is  $<21$  mm [35]. During mechanical inspiration, venous return is reduced due to the increased intrathoracic pressure and the IVC distends (“IVC-distensibility index, DI”) [36]. Thus, the more pronounced intravascular hypovolemia is present, the greater the IVC will distend [37]. An IVC-DI of  $>18\%$  in controlled ventilated septic patients may indicate a positive volume response resulting in an increased cardiac output (CO) after fluid resuscitation [38–42]. In patients with preserved spontaneous respiration, the patient is asked to inspire deeply once and expire passively afterward, while the variation in IVC diameter is recorded [43]. An IVC diameter

**Table 10.1** Qualitative echocardiographic evaluation of volume status/fluid responsiveness

Status	Respiratory modulation	Interpretation	Fluid response
IVC/SVC dilated ( <i>i.e.</i> , round in shape, stretched, visual aspect of overfilling)	No variation	Filling pressure $\uparrow$	Negative (“stop signal” for further fluid administration) <sup>a</sup>
IVC/SVC small/collapsed	Pronounced variation	Filling pressure $\downarrow$	Positive
IVC/SVC intermediate	Passive leg raising (PLR) and/or fluid challenge (FC) If stroke volume increases with unchanged systemic resistance, fluid substitution is clinically indicated		

<sup>a</sup>In the context of chronic cardiovascular disease, a positive volume responsiveness may occasionally be given despite a dilated vena cava without respiratory oscillation. Further evaluation may be done by means of PLR/FC

variability of  $\geq 48\%$  represents a positive volume response. The same is also possible with TEE using the SVC collapse index (SVC-CI) [44]. In contrast, the SVC will be compressed during mechanical inspiration due to its intrathoracic position: SVC collapse index (SVC-CI) [44]. A SVC-CI of  $>36\%$  measured with TEE indicates a positive volume response. Nonetheless, like many other methods, these easy-to-determine quantitative variables are subject to individual cut-off variations (*e.g.*, IVC-DI “gray zone” 8–30%) [42, 45–48]. Therefore, in extension to quantitative determinations, the approach shown in Table 10.1 may be helpful in deciphering the measurements taken from the IVC/SVC [49–51].

However, from a clinical point of view, one has to differentiate between (a) “relative” hypovolemia (*i.e.*, all heart chambers appeared to be “normally” filled; however, additional fluid substitution may cause an increase in SV—“volume responsiveness”), (b) “global” hypovolemia (*i.e.*, all heart chambers are reduced in size due to a significant reduction in the total circulating blood volume—additional fluid substitution will lead to an increase in SV), and (c) “partial” hypovolemia (*i.e.*, LV hypovolemia in the case of RV failure—fluid substitution will mostly not be effective in increasing left ventricular SV because of the incapability of the RV).

## 10.6 Step 3: Right Ventricle Function

A restricted RV function is associated with increased perioperative mortality [52–54]. Additionally, sufficient LV function depends on sufficient preload

provided by the RV [55]. The RV thus may be assessed prior to LV assessment [56].

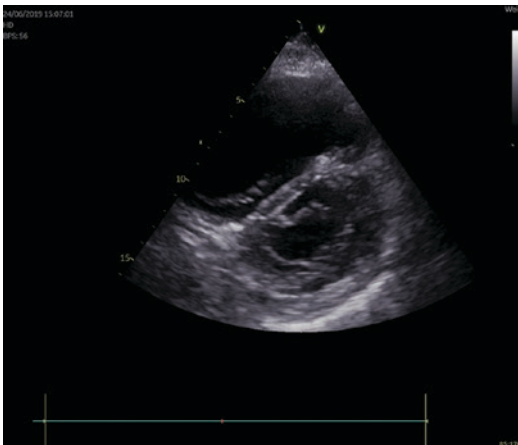
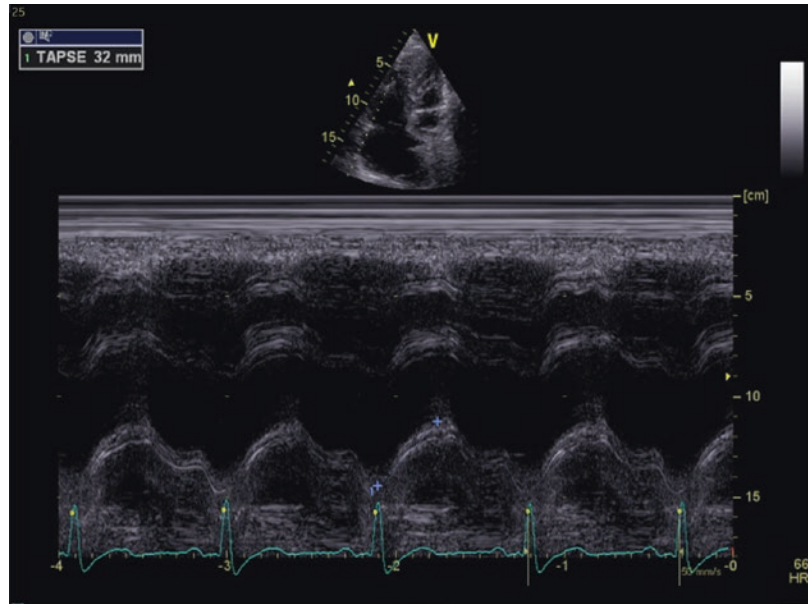
This is achieved by measuring RV diameter (Step 2) as well as the volume/diameter relation between the right and left ventricles, the “RV/LV index” ( $\leq 0.6$ ). A RV/LV index of  $\geq 1.0$  indicates a severe RV dilatation [57]. Hypertrophy of the free right ventricular wall ( $>5$  mm) may indicate a chronic disease process [58]. The thickness of the right ventricular wall is best measured from the subcostal at the level of the anterior tricuspid valve tip or alternatively in the PLAX [34].

RV contractility is assessed in the four-chamber views. With a normal RV function, the free RV wall should move inward [34]. The systolic movement of the lateral tricuspid valve annulus toward the apex (tricuspid annular plane systolic excursion, TAPSE) (Fig. 10.9) can be used as a quantitative measurement. A TAPSE of  $\geq 17$  mm indicates a normal systolic RV function [34]. Hemodynamically relevant RV dysfunction may be suspected if the RV appears dilated with impaired systolic function. In addition, RV overloading can displace the interventricular septum toward the LV (“paradoxical septum shift”) (D-sign) (Fig. 10.10), thereby further restricting cardiac function.

### Practical Advice

The acuity of a right ventricular dysfunction can be differentiated based on the diameter of the right ventricular wall. A hypertrophy of the free right ventricular wall ( $>5$  mm) indicates a chronic disease process, whereas a normal right ventricular wall and signs of right ventricular dysfunction propose an acute pathology.

**Fig. 10.9** Tricuspid annular plane systolic excursion



**Fig. 10.10** Paradoxical septum shift in the right ventricular dysfunction seen in the parasternal short-axis view

## 10.7 Step 4: Left Ventricle Function

LV should be assessed in an analogous manner to the RV (see also Steps 2 and 3). The left ventricular ejection fraction (LVEF) is determined to quantify global systolic function. For normal clinical

concerns, however, a qualitative assessment of the LVEF (“eyeballing”) may be sufficient [59]. PSAX or TGSAX as well as four-chamber (4C or ME4C) views allow for a quick orientation [60].

Hemodynamic-relevant systolic LV dysfunction may be excluded if the LV appears nondilated with normal systolic function (LVEF >50%). However, isolated diastolic LV dysfunction (heart failure with preserved ejection fraction, HFpEF) may be present [61]. If diastolic dysfunction is suspected, an expert consultation should be made in order to guide further diagnostics and therapy [62]. However, a hypertrophied LV with normal systolic function in conjunction with a pronounced dilation of the left atrium (LA) may be related to HFpEF in a breathless patient with/without signs of pulmonary edema [63].

Finally, regional wall motion abnormalities—hypokinesia, akinesia, or dyskinesia [64]—may hint at specific cause such as myocardial infarction or takotsubo syndrome, which require a specific diagnostic testing (*e.g.*, electrocardiogram, cardiac enzymes, coronary angiography) and treatment.



**Practical Advice**

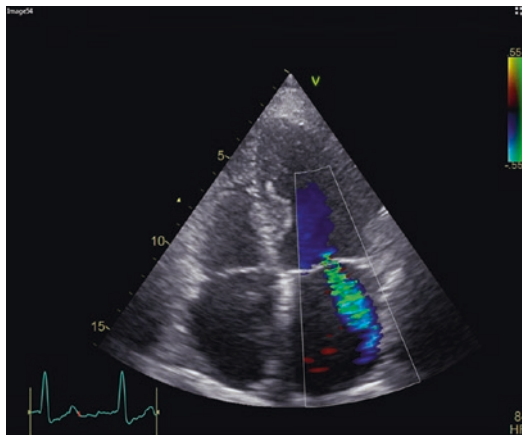
If the LV appears nondilated with normal systolic function, hemodynamic-relevant systolic LV dysfunction can be excluded. However, if the patient shows clinical signs of heart failure and echocardiography reveals a hypertrophied LV and a pronounced dilation of the LA, HFpEF should be considered.

**10.8 Step 5: Valve Function**

The visual and thus qualitative evaluation of valves in the hemodynamic focused examination is used to assess valve opening and closure as well as to recognize morphological abnormalities. Thin leaflets with a normal opening/closing and without turbulent flow in the color Doppler determined in  $\geq 2$  cross-sectional views may exclude hemodynamic-relevant valve dysfunction. Hemodynamic-relevant stenosis may be suspected in the case of a thickened or calcified valve with a restricted opening resulting in antegrade flow accelerations/turbulences in the color Doppler. On the other hand, hemodynamic-relevant regurgitation might be suspected if a visible coaptation defect and/or an exaggerated leaflet motion during valve closing in conjunction with a wide, turbulent, backward color jet (“vena contracta”) (Fig. 10.11) is observed [23]. In suspicion of a hemodynamically relevant valve abnormality, a comprehensive evaluation should be performed immediately by a certified examiner [65–67].

**Practical Advice**

Thin leaflets with normal opening and closing and without turbulent color flow exclude hemodynamic-relevant valve dysfunction.



**Fig. 10.11** Turbulent backward color jet in mitral valve insufficiency seen in the apical four-chamber view

**10.9 Step 6: Cardiac Output Estimation**

Transthoracic and transesophageal echocardiography are capable of estimating cardiac output, although discontinuously, using continuous-wave (cw) Doppler across the left ventricular outflow tract (LVOT)/aortic valve (AV) measuring the velocity time integral (VTI) [68]. A VTI of 18–22 cm indicates a normal stroke volume, whereas a VTI of <18 cm suspects decreased stroke volume and >22 cm an increased one [69]. Prior to this, a relevant aortic stenosis must be excluded. However, echocardiography may not be interchangeable with other cardiac output monitoring [70]. Thus, a continuous hemodynamic monitoring should be implemented in hemodynamic unstable patients to assess the therapeutic success after initial echocardiographic evaluation [71, 72].

**Practical Advice**

A VTI of 18–22 cm indicates normal, a VTI of <18 cm decreased, and >22 cm increased stroke volume.

## 10.10 Conclusion

Hemodynamic focused echocardiography as a rapid bedside diagnostic method can examine signs of filling impairment, volume status and volume responsiveness, right and left ventricular function, and heart valve function as well as estimate cardiac output. Using a stepwise approach, high-risk patients within the perioperative setting can be assessed in the case of hemodynamic instability to rapidly pinpoint pathophysiological causes. The summary of all echocardiographic findings, including clinical symptoms and patient history, allows a differentiated assessment of the patient's cardiovascular function and can thus help to guide a (patho)physiologically orientated and individualized hemodynamic therapy in order to optimize and maintain stroke volume.

### Keynotes

- Hemodynamic focused echocardiography allows to examine the signs of cardiac filling impairment, cardiac preload, myocardial contractility, and cardiac heart valve function.
- Echocardiographic signs of filling impairment are pericardial effusion with hypovolemia of all heart chambers, collapse of right cardiac chambers, and/or dilatation of the inferior vena cava.
- Volume status/responsiveness can be assessed by examining a potential kissing papillary muscle sign and the positioning and movement of the interatrial septum as well as the diameter and respiratory variation of the superior and inferior vena cava.
- The right ventricle is assessed by examining the volume/diameter relation between the right and left ventricles, the diameter of the right ventricular wall, the movement of the right ventricular free wall, and the lateral tricuspid valve annulus toward the apex as well as the position and movement of the interventricular septum.

- A qualitative assessment of the left ventricular ejection fraction with eyeballing may be equivalent to a quantitative one for normal clinical concerns in the context of a hemodynamically focused examination.
- Thin leaflets with a normal opening/closing and without turbulent flow in color Doppler exclude hemodynamically relevant valve dysfunction.
- A velocity time integral, measured with continuous-wave Doppler across the left ventricular outflow tract/aortic valve, of 18–22 cm indicates normal, whereas a VTI of <18 cm a decreased and >22 cm an increased stroke volume. Prior to this, aortic stenosis must be excluded.

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