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Critical care echocardiography in shock: A comprehensive review

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ABSTRACT:

Bedside transthoracic echocardiography is a valuable tool for assessing cardiac morphology and function in critically ill patients. It provides real-time information and aids in making prompt clinical decisions. This article aims to explore the role of critical care echocardiography, especially during shock resuscitation, focusing on basic image acquisition and interpretation. The review discusses the evaluation of left ventricular function, right ventricular function, preload responsiveness, the presence of pericardial effusion, and tamponade.

Keywords: Critical care echocardiography; Shock; Left ventricular function; Right ventricular function; Pericardial effusion; Preload responsiveness

INTRODUCTION

Critical care echocardiography (CCE) is a valuable tool in the management of critically ill patients, providing detailed information on cardiac morphology and function. As a point-of-care ultrasonography (POCUS), it usually consists of a limited set of findings, is less time-consuming, and is highly feasible, even for less experienced physicians, when compared to standard comprehensive transthoracic echocardiography (TTE), which requires extensive training [1]. CCE is particularly useful in answering specific questions, such as determining the type of shock or guiding appropriate management strategies, such as the use of a fluid bolus, vasopressor, or inotropic drugs [2]. For example, in cardiogenic shock, CCE reveals evidence of reduced left ventricular (LV) function. In hypovolemic shock, the inferior vena cava (IVC) may collapse, indicating low intravascular volume. In obstructive shock, the presence of pericardial effusion or right ventricular (RV) overload signs might raise suspicion of cardiac tamponade or acute pulmonary embolism, respectively. In distributive shock, there may be evidence of preserved cardiac function with or without hypovolemia. Recent data have shown a beneficial effect of CCE on changes in clinical management and improved mortality [3, 4, 5].

Presently, there are many multi-organ POCUS protocols aiming for circulatory failure management. These protocols share a commonality in utilizing a limited set of basic echocardiography findings as integral components [6]. The current guidelines for CCE also recommend utilizing these examinations for bedside evaluation of critically ill patients, specifically addressing four vital questions: 1) LV function, 2) RV function, 3) presence of pericardial effusion and tamponade, and 4) preload responsiveness [7, 8]. This review excludes cardiac valvular assessment because its details generally fall beyond the scope of CCE. However, in the setting of cardiogenic shock, it is essential for screening for acute severe regurgitation, as it can lead to specific management. In cases necessitating valvular evaluation, such as infective endocarditis, comprehensive echocardiography is still necessary, even if POCUS TTE shows a negative result.

BASIC ECHOCARDIOGRAPHIC VIEWS

To evaluate cardiac morphology and function, basic TTE views should be performed as follows (Figure 1) [9]:

Parasternal long axis (PLAX) view: The probe should be placed at the 3rd or 4th left intercostal space with the marker pointing toward the patient's right shoulder. This allows assessment of left ventricular ejection fraction (LVEF), wall motions, and mitral and aortic valvular structure, including measuring the LV outflow tract diameter.

Parasternal short axis (PSAX) view: To obtain this view, clockwise rotate the probe from the PLAX position to point the marker towards the left shoulder. This provides information about the LV and RV sizes, LVEF, and LV wall motions.

Apical four-chamber (A4C) view: The probe should be placed at the LV apex with the marker pointing toward the right side of the patient. This view provides a comprehensive assessment of all four cardiac chambers. It allows the evaluation of chamber size, LV ejection fraction, LV diastolic function, wall motion, mitral and tricuspid valvular structure and function, and the presence of any intracardiac shunts. To evaluate the left ventricular outflow tract (LVOT), tilt the probe anteriorly to obtain the apical five-chamber (A5C) view or rotate the probe clockwise to obtain the apical long axis view.

Subcostal view: This view is obtained from the subcostal region and is particularly useful in patients with poor acoustic windows or those on mechanical ventilation. It provides information about the right atrium, right ventricle, and pericardial effusion.

IVC longitudinal axis view: This view focuses on the IVC and is used to assess its changes during respiration. It is a useful parameter to evaluate the right atrial pressure, fluid status, and volume responsiveness.

Before image interpretation, appropriate image acquisition is crucial. During the examination, the physician mobilizes the probe to obtain the optimal view and adjusts depth, gain, and other settings to ensure image quality before obtaining qualitative assessments and measurements of various cardiac parameters.

ASSESSMENT OF LEFT VENTRICULAR FUNCTION

This assessment involves a comprehensive evaluation of both systolic and diastolic function. Accurate assessment of LV function is essential in managing various conditions, including shock, congestive heart failure, or acute coronary syndrome, as it helps guide appropriate treatment strategies and provides valuable prognostic information. LVEF is a commonly used quantitative parameter to assess LV systolic function, while parameters such as the E/A wave and the E/Ea ratio are utilized to evaluate LV diastolic function.

KEY MESSAGES:

- Echocardiography plays a crucial role in determining the cause of circulatory shock by assessing cardiac function, identifying clues for obstructive shock, and evaluating preload and fluid responsiveness. This helps determine the appropriate hemodynamic support or guides further investigations.
- Knowing the limitations of each measurement is crucial. Always remember that accurate image interpretation relies on obtaining optimal image acquisition.

Left ventricular systolic function

The echocardiographic finding used to determine LV systolic function is the LVEF, which can be assessed using quantitative or semi-quantitative (visual estimation) techniques. In critically ill patients, due to its time-sensitive nature and feasibility, the Teichholz method is commonly used as a quantitative approach. To measure LVEF using this method, first obtain the PLAX or PSAX view and identify the level of the mitral valve leaflet tip in PLAX or the level of the middle papillary muscle in PSAX. After that, measure the internal diameter of the left ventricle during systole (LVIDs) and diastole (LVIDd) at the same level using either 2D or M-mode. Finally, calculate the LVEF using the following formulas (Figure 2A):

$$\text{LVEF (\%)} = (\text{LVEDV} - \text{LVESV}) / \text{LVEDV} \times 100\%$$
$$\text{LVEDV} = [7 / (2.4 + \text{LVIDd})] \times \text{LVIDd}^3$$
$$\text{LVESV} = [7 / (2.4 + \text{LVIDs})] \times \text{LVIDs}^3$$

However, it is important to note that this method may be unreliable if corresponding regional wall motion abnormalities are present or if the wrong angle or cut is measured [10].

A finding of LVEF greater than 70% suggests hyperdynamic LVEF, which can be found in patients with a catecholamine surge, a hypovolemic state, or some patients with sepsis [11]. A finding of LVEF less than 50% suggests reduced systolic function, and less than 30% suggests severely reduced systolic function. Both reduced and hyperdynamic LVEF are associated with increased all-cause mortality [12]. The visual estimation method, in the hands of an experienced physician, is reliable and does not lead to different management compared to the quantitative method [13]. In addition to assessing LVEF, it is important to evaluate for either global or regional wall motion abnormalities. These abnormalities may indicate ischemia or infarction in specific areas of the myocardium. Wall motion abnormalities can be described as hypokinetic (reduced motion), akinetic (absence of motion), or dyskinetic (paradoxical motion). It's worth noting that the Simpson's biplane method is the recommended method to estimate LVEF according to the current guidelines, as it can provide more accurate assess-

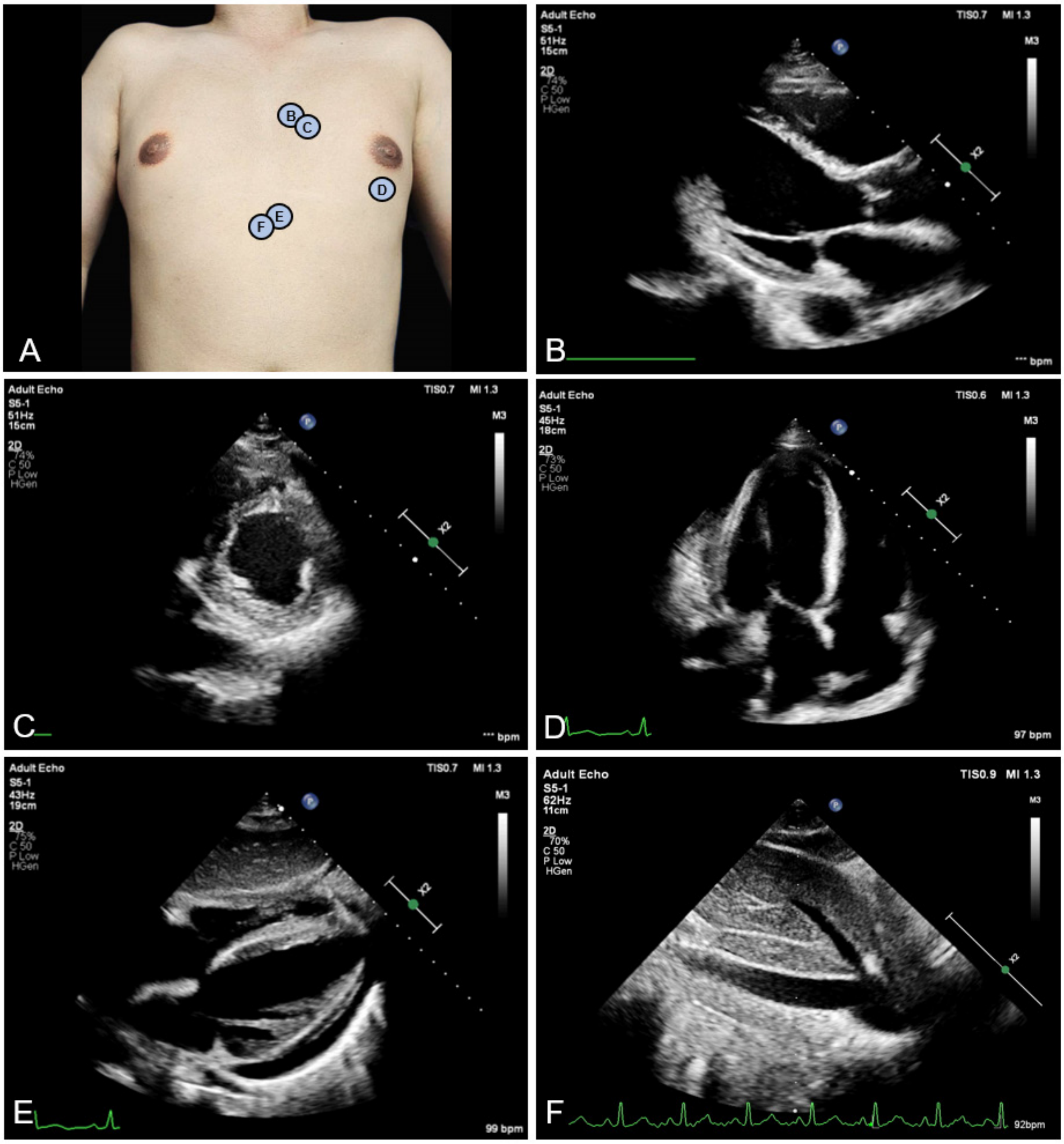


Figure 1. Standard views of transthoracic echocardiography. **1A**: Anatomical landmark of chest wall for probe positioning; **1B**: Parasternal long axis view; **C**: Parasternal short axis view; **1D**: Apical 4-chamber view; **1E**: Subcostal view; **1F**: Inferior vena cava longitudinal view.

ments of LVEF [10]. The choice of method depends on the expertise of the physician and the availability of advanced software for image analysis.

Overall cardiac function can be indirectly assessed by stroke volume (SV) and cardiac output (CO). The SV is the product of the LV outflow tract velocity-time integral (LVOTVTI) and the cross-sectional area of the LVOT. CO can then be calculated by multiplying the SV by the heart rate. Changes in CO, SV, or LVOTVTI after preload modification can also be used as tools for detecting fluid responsiveness. This will be described later in this review.

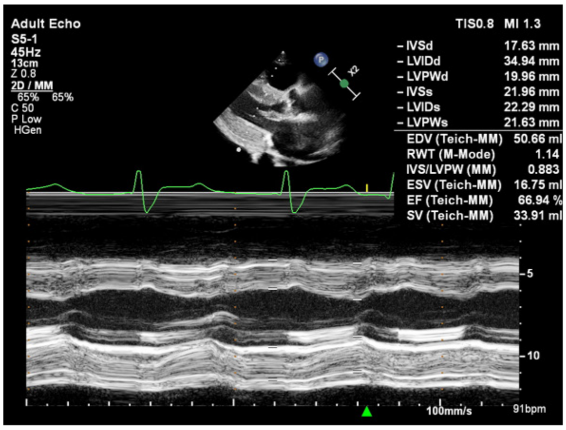
The LVOTVTI is a measurement of the forward blood flow obtained by calculating the area under the velocity-time integral curve of the flow. The LVOTVTI can be assessed by placing the sampling area of the pulse-wave doppler on the LVOT just proximal to the aortic valve in the A5C or apical long axis view (Figure 2B). Color flow doppler can be helpful in detecting the direction of blood flow, as the doppler beam-flow angle should not deviate more than 20 degrees to limit angle error. The cross-sectional area of the LVOT can be calculated from the LVOT diameter by measuring the maximum aortic root diameter during systole in the PLAX view (Figure 2C). Slight changes in measuring the LVOT diameter can have a significant effect on SV calculation; therefore, using zoom during the LVOT diameter measurement can yield more accurate results [14].

Left ventricular diastolic function

LV diastolic dysfunction is strongly associated with mortality in sepsis. Additionally, it increases the risk of pulmonary edema, either from fluid resuscitation or during weaning from positive pressure ventilation [15]. The assessment of left ventricular diastolic function in the ICU can be challenging due to various confounding conditions. Among these, the E/A ratio, Ea wave, and E/Ea ratio have been validated for reliable use in this clinical setting [16,17].

To obtain the E/A ratio, pulse wave doppler was performed in the A4C view with the sampling area placed at the tip of the mitral valve opening. The maximal flow velocities during early diastole (E wave) and atrial systole (A wave) were measured to compute the E/A ratio (Figure 3A). Subsequently, tissue doppler imaging (TDI) mode was then applied to record the maximal velocity of medial mitral valve annulus displacement during early diastole (Ea wave) for calculating the E/Ea ratio (Figure 3B). The E/A ratio is considered normal between 0.8 and 2, and the Ea wave has a normal cut-off at the medial annulus of over 8 cm/sec. For the E/Ea ratio, normal values are less than 8, borderline values are between 8 and 15, and high values are over 15. Notably, the Ea wave can also be measured at either the medial or septal site, or by using average values, which have different cut-offs for interpretation [18]. These parameters allow the categorization of diastolic function into normal, impaired relaxation, pseudo-normal, and restrictive patterns (Table 1) [16].

Moreover, the E/Ea ratio not only represents diastolic function but can also serve as a surrogate for LV fill-



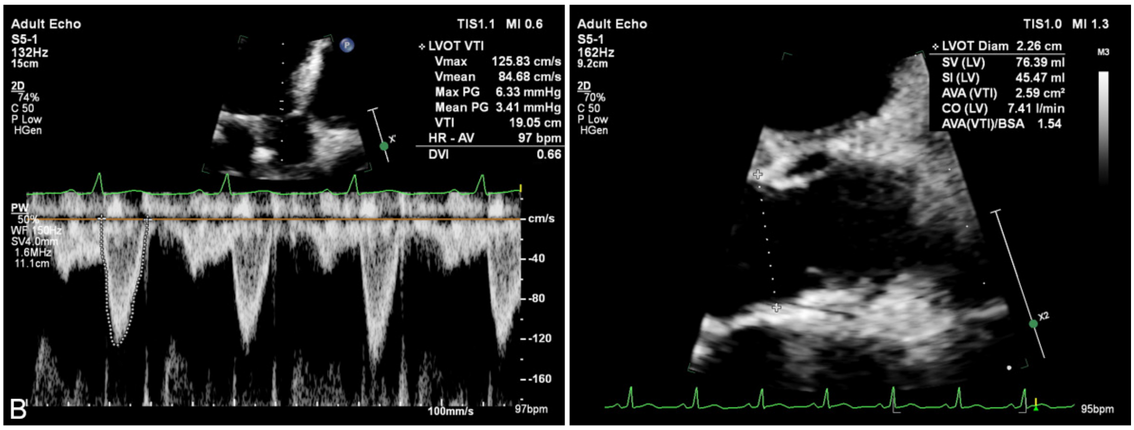


Figure 2. Echocardiographic assessment of LV systolic function. **2A**: LVEF measurement using Teichholz method in M-mode; **2B**: LV outflow tract velocity-time Integral; **2C**: LV outflow tract diameter measurement.

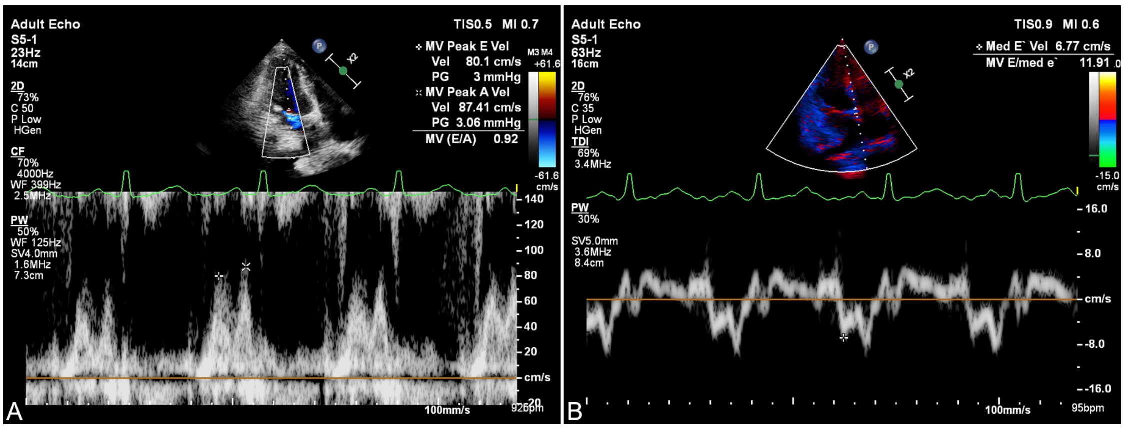


Figure 3. Assessment of LV Diastolic Function. **3A**: Mitral E/A ratio of 0.92; **3B**: Ea measured at the medial mitral annulus is 6.77 cm/s, with E/Ea = 11.91. This suggests that the patient is likely to have grade 2 diastolic dysfunction.

ing pressure [19]. Tongyoo et al. found that an E/Ea value above 10 at the medial annulus can predict LVEDP over 15 mmHg with a sensitivity and a specificity of 82% and 84%, respectively [20]. Additionally, in predicting weaning failure in the medical ICU, there was a significant association between an E/Ea ratio over 14 and weaning failure [21]. The association between LV diastolic dysfunction parameters and fluid responsiveness is currently being studied by the authors, and previous data are limited and equivocal [22].

RIGHT VENTRICULAR FUNCTION

Evaluation of RV function is crucial in conditions such as pulmonary embolism and acute cor pulmonale. This section focuses on signs of RV overload, tricuspid annular plane systolic excursion (TAPSE), and pulmonary hypertension. Understanding these RV echocardiographic parameters helps physicians detect RV failure non-invasively, which aids in deciding whether to perform treatment modalities to unload the RV or optimize RV function.

Signs of right ventricular overload

Due to its pressure-sensitive nature, the RV morphology is prone to change when subjected to acute increases in pressure. This includes evaluating RV size, shape, septal motion, and wall thickness [10, 23]:

RV/LV size: The size of the RV can be evaluated by comparing the linear dimension of the RV to the linear dimension of the LV, which is best seen at the level of the papillary muscles in the PSAX view but can also be assessed in the PLAX or A4C view using the internal diameters of both the RV and LV during end-diastole. A RV/LV ratio greater than 0.6 suggests RV dilatation, while a ratio exceeding 1 indicates severe dilatation (Figure 4A).

RV/LV shape: RV overload changes the RV shape from crescent to oval. Severe cases lead to ventricular interdependence (paradoxical septal motion) and the LV D-shaped appearance seen in the PSAX view (Figure 4B).

RV wall thickness: if the wall thickness at end-diastole is less than 0.5 cm, it may suggest an acute process. Conversely, a thickness greater than 1 cm may indicate the presence of an underlying chronic condition.

Additionally, a unique feature of pulmonary embolism is the McConnell sign, which is characterized by a hyperkinetic RV apex and hypokinetic mid-free wall seen in the A4C view. Although it has very high specificity for pulmonary embolism, it can also be seen in RV infarction and chronic pulmonary hypertension [24].

Tongyoo et al. studied the diagnostic efficacy of transthoracic echocardiographic parameters for detecting RV dysfunction in medical ICU patients compared to the gold standard pulmonary artery catheter. They found that an RV/LV size over 0.65 appears to have a sensitivity of 0.94, while the loss of the RV apical triangle and LV-D shape have specificities of 0.80 and 0.85, respectively [25].

Right ventricular systolic function

In addition to assessing RV overload, echocardiography can be used to evaluate RV systolic function using the tricuspid annular plane systolic excursion (TAPSE). TAPSE is a measurement of longitudinal RV contraction, which has a good correlation with RVEF and RV fractional area change by cardiac MRI. It is measured by placing the M-mode cursor at the lateral tricuspid annulus in the A4C view and determining the distance of annulus movement towards the apex during systole (Figure 4C). The cut-off value to determine RV dysfunction is lower than 16 mm [23, 24].

Pulmonary hypertension

Pulmonary hypertension (PH) is a hemodynamic disorder characterized by elevated mean pulmonary arterial pressure (mPAP), which can lead to right heart failure and eventually a life-threatening pulmonary hypertensive crisis. Echocardiography plays an important role in the detection and evaluation of PH. In addition to the echocardiographic findings of RV overload, specific measurements, including tricuspid regurgitant jet velocity (TRV) and right ventricular systolic pressure (RVSP), can provide valuable information on pulmonary arterial pressure [24, 26].

TRV is measured by placing a sampling line of continuous wave doppler at the tricuspid valve opening area in A4C view and measuring the peak velocity of the tricuspid regurgitation jet (Figure 4D). Using TRV in conjunction with other echocardiographic signs suggesting PH, such as dilatation of PA, RV, RA, or IVC, can aid in determining the likelihood of PH, as summarized in Table 2.

In the absence of pulmonic stenosis, the RVSP is equal to the pulmonary artery systolic pressure. RVSP can be calculated using the formula [$RVSP = 4(TR\ Vmax)^2 + RAP$], where RAP comes from CVP or is estimated by using IVC. An RVSP of more than 50 mmHg generally correlates with an mPAP of more than 25 mmHg, while an RVSP of a less than 36 mmHg is suggestive of less likely PH.

Table 1. Diastolic dysfunction grading based on LV filling dynamics.

	Grade 0 (Normal)	Grade 1 (Impaired relaxation)	Grade 2 (Pseudo-normal)	Grade 3 (Restrictive pattern)
Mitral inflow pattern (E/A ratio)	0.8-2	<0.8	0.8-2	>2
Relaxation velocity of medical mitral annulus (Ea [cm/s])	>8	<8	<8	<<8
LV filling pressure (E/Ea ration)	<8	<8	8-15	>15

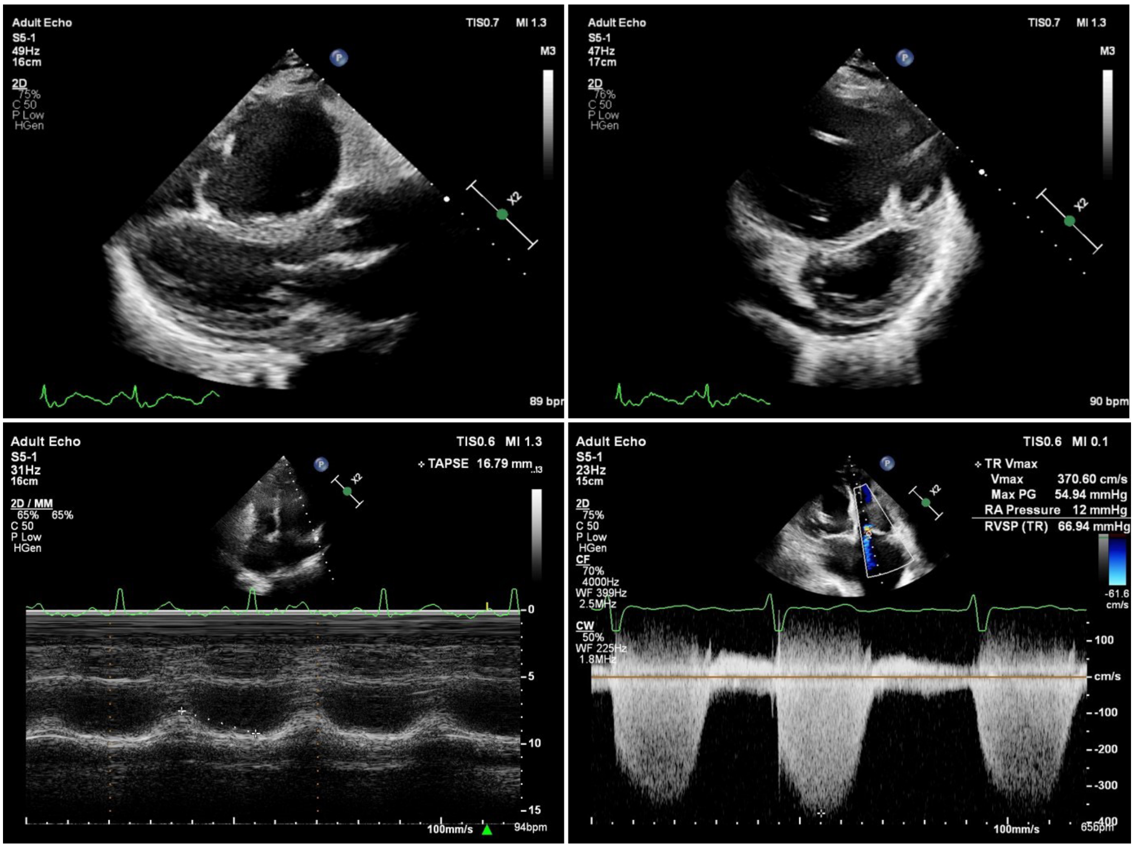


Figure 4. Assessment of RV function. **4A**: Marked RV dilatation with an RV/LV ratio over 1; **4B**: Severe RV dilatation with LV D-shaped observed in PSAX; **4C**: TAPSE measurement of 16.79 mm; **4D**: Peak velocity of TR jet and RVSP measurement with TRV max of 3.7 m/s and RVSP of 66.94 mmHg, suggesting a high probability of pulmonary hypertension.

Table 2. Summary of echocardiographic indicators for assessing the probability of pulmonary hypertension.

Tricuspid regurgitation velocity (m/s)	Presence of other echo 'PH signs'	Echocardiographic probability of PH
≤ 2.8 or not measurable	No	Low
≤ 2.8 or not measurable	Yes	Intermediate
2.9-3.4	No	Intermediate
2.9-3.4	Yes	Hight
>3.4	Not required	Hight

PERICARDIAL EFFUSION AND TAMPONADE

Pericardial effusion is the accumulation of fluid in the pericardial space, which can lead to cardiac tamponade when the fluid restricts cardiac filling and causes hemodynamic instability. Echocardiography is crucial for identifying pericardial effusion and detecting signs of tamponade physiology. Once tamponade has been diagnosed, the immediate or urgent release of pericardial effusion is necessary.

Quantification of pericardial effusion involves measuring its maximal thickness at end-diastole (Figure 5A). Effusion thickness less than 1 cm is mild and rarely causes tamponade. Thickness between 1 – 2 cm is moderate, and over 2 cm is severe. However, the rate of fluid accumulation also plays a role in the development of tamponade physiology. Some findings can mimic pericardial effusion, such as the epicardial fat pad, which is more echogenic and not gravity-dependent. Pleural effusion can also be mistaken for pericardial effusion, but in the PLAX view, pleural effusion is seen posterior to the descending aorta, while pericardial effusion is located anteriorly to the aorta [27].

Signs of cardiac tamponade

If pericardial effusion raises pericardial pressure above right-side pressure, it can lead to cardiac tamponade. In critically ill patients with signs of low cardiac output and pericardial effusion, CCE is crucial for assessing whether the effusion contributes to shock. Signs of cardiac tamponade include IVC plethora, right-sided cardiac chamber collapse, and respiratory variation in transmitral flow velocities [27, 28].

IVC plethora, which refers to a dilated IVC with insignificant respiratory variation, is observed in the IVC longitudinal axis view. It indicates impaired venous return with a sensitivity of 0.97 and a specificity of 0.40.

Evidence of right-side collapse, specifically diastolic RV collapse, is assessed in the A4C view or using M-mode in the PLAX view. This is done by placing the cursor line at the tip of the mitral valve and observing the collapse of the RV during diastole (Figure 5B), with a sensitivity ranging from 0.48 to 0.60 and a high specificity of up to 0.90.

Echocardiographic pulsus paradoxus utilizes the same principle as classic pulsus paradoxus, which involves worsening of LV filling during spontaneous inspiration. In echocardiography, this is measured directly at the mitral inflow using a pulse wave doppler to capture the E wave and adjust the time frame to cover approximately four respiratory cycles. If there is respiratory variation in the mitral E wave velocity of more than 25%, the sensitivity of this method is 0.82. This respiratory variation in transmitral flow velocities is markedly attenuated in the setting of positive pressure ventilation.

PRELOAD ASSESSMENT

Preload assessment is a cornerstone in the management of circulatory shock, as both excessive and insufficient fluid resuscitation are associated with poorer outcomes. The fluid responsiveness test provides essential information regarding the benefits of fluid resuscitation for patients, aiding in fine-tuning decisions on when to administer fluids during the resuscitation process and optimizing phases of fluid management in shock.

Fluid responsiveness is generally defined as an increase in CO of more than 10-15% in response to a respective amount of fluid loading. Dynamic parameters are preferred over static parameters, making echocardiography a valuable tool for providing these dynamic indicators. It allows for the evaluation of changes in the IVC with respiratory variation or the direct measurement of alterations in CO, SV, or LVOTVTI after performing preload modification maneuvers, such as the passive leg raising test or fluid loading [29, 30]. It is essential to note that fluid responsiveness is not the same as fluid tolerance. A positive fluid responsiveness test does not necessarily mean that fluid loading is required [31].

Inferior vena cava with respiratory variation

The IVC is a vessel that exhibits collapsibility during negative pressure inspiration but can distend when subjected to positive pressure ventilation. While measuring the IVC diameter is a quick, simple, and repeatable method, interpreting the results can be challenging due to specific conditions. These include ensuring either completely passive ventilation or active ventilation, appropriate tidal volumes, and the absence of confounding factors such as cardiac arrhythmias, right-side cardiac dysfunction, increased intra-abdominal pressure, and very low lung compliance. Hence, it is essential to consider false positive and false negative results before interpreting the findings [32].

In most studies, the IVC is measured in the long-axis view, either at the hepatic vein junction or 1-3 cm from the right atrium junction. Utilizing M-mode allows for the convenient determination of the minimum IVC (IVCmin) and maximum IVC (IVCmax) diameters during the respiratory cycle (Figure 6). Subsequently, the IVC index can be calculated using the following formulas:

IVC collapsibility index = [(IVCmax - IVCmin) / IVCmax] x 100
IVC distensibility index = [(IVCmax - IVCmin) / IVCmin] x 100
IVC variability index = [(IVCmax - IVCmin) / IVCmean] x 100

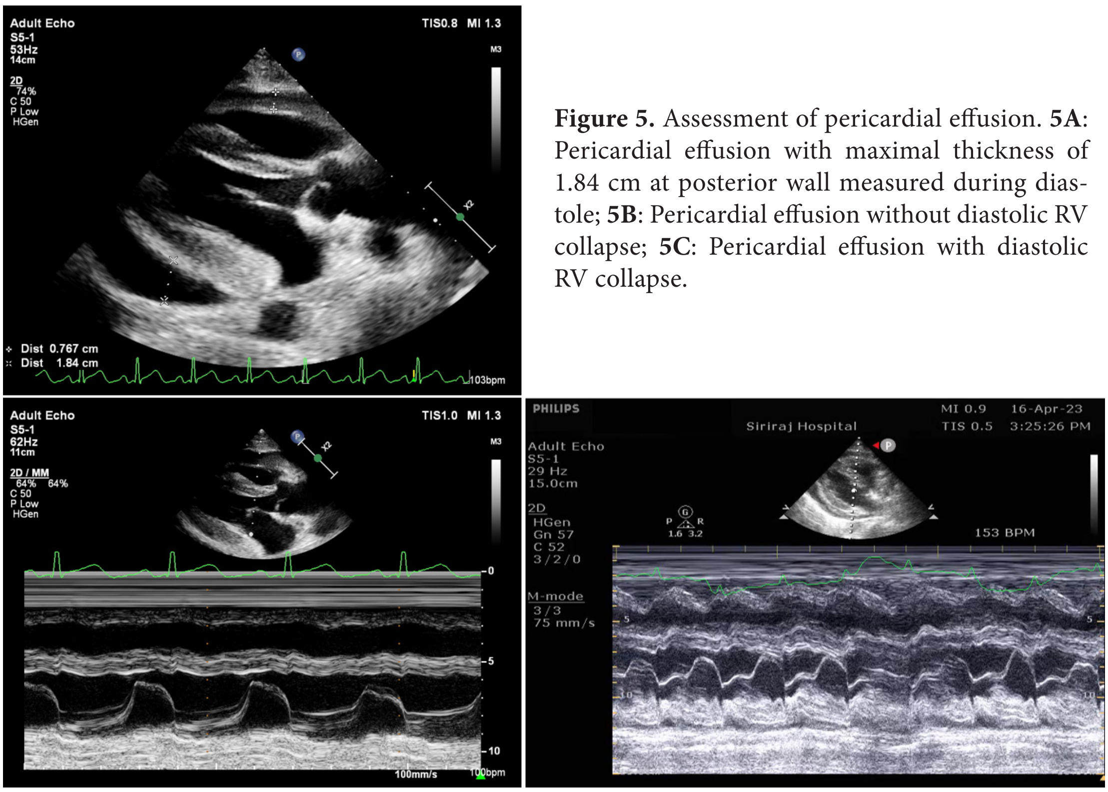


Figure 5. Assessment of pericardial effusion. **5A**: Pericardial effusion with maximal thickness of 1.84 cm at posterior wall measured during diastole; **5B**: Pericardial effusion without diastolic RV collapse; **5C**: Pericardial effusion with diastolic RV collapse.

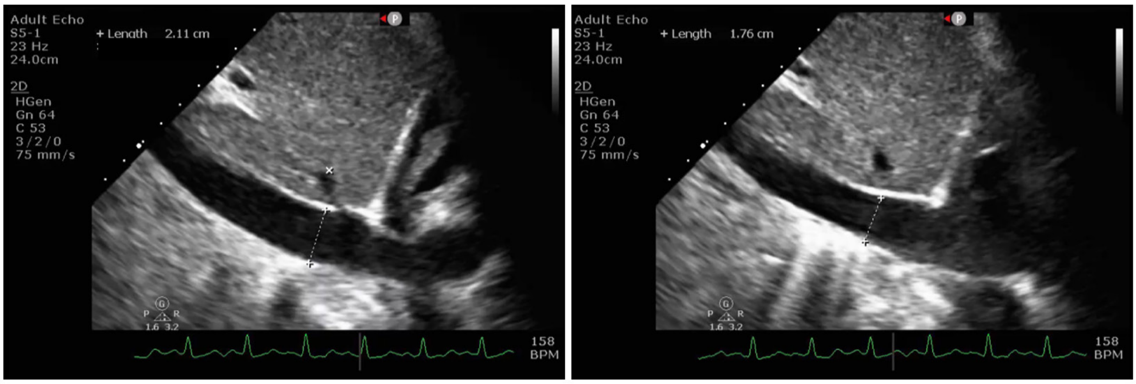


Figure 6. IVC with respiratory variation in a patient who received positive pressure ventilation. The maximal IVC diameter measured was 2.11 cm, and the minimal IVC diameter was 1.76 cm, resulting in an IVC variability index of 18% and an IVC distensibility index of 19.8%.

The IVC collapsibility index can be used only in spontaneous ventilation, while the IVC distensibility index can be used in positive pressure ventilation, and the IVC variability index can be used in both conditions. The cutoffs for predicting fluid responsiveness are set at more than 40%, 20%, and 12%, respectively, for the IVC collapsibility index, IVC distensibility index, and IVC variability index [33].

CONCLUSION

Critical care Echocardiography is a valuable tool in managing critically ill patients, providing real-time information to aid in clinical decisions and ultimately improve patient outcomes. Four fundamental examinations of basic echocardiography are essential, encompassing the assessment of left ventricular function, right ventricular function, the presence of pericardial effusion, and preload responsiveness. These assessments can be efficiently conducted at the patient's bedside, offering immediate insights to guide clinical decisions and enhance patient outcomes. To ensure accurate interpretation, acquiring high-quality images is important. Regular practice and supervised training are essential for skill development in this regard. It is crucial to recognize its limitations. If abnormalities beyond the scope of the examination are detected, patients should be referred for a comprehensive standard echocardiographic evaluation.

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