CHEST Recent Advances in Chest Medicine

Advanced Echocardiography for the Critical Care Physician

Part 2

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This article is the second part of a series that describes practical techniques in advanced critical care echocardiography and their use in the management of hemodynamic instability. Measurement of left ventricular function and segmental wall motion abnormalities, evaluation of left ventricular filling pressures, assessment of right-sided heart function, and determination of preload sensitivity, including passive leg raising, are discussed. Video examples help to demonstrate techniques described in the text.
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Abbreviations: 2DE = two-dimensional echocardiography; AP4 = apical four chamber; ASE = American Society of Echocardiography; CCE = critical care echocardiography; CWD = continuous wave Doppler; IVC = inferior vena cava; LAP = left atrial pressure; LV = left ventricular; LVOT = left ventricular outflow tract; PAH = pulmonary arterial hypertension; PAOP = pulmonary artery occlusion pressure; PASP = pulmonary artery systolic pressure; PSL = parasternal long axis; PSS = parasternal short axis; RAP = right atrial pressure; RV = right ventricular; SC = subcostal; SV = stroke volume; TAPSE = tricuspid annular plane systolic excursion; TDI = tissue Doppler imaging; TR = tricuspid regurgitation; TV = tricuspid valve; VTI = velocity time integral

The evaluation of left ventricular (LV) function is an essential skill for both basic and advanced critical care echocardiography (CCE) examination. It allows the intensivist to categorize shock state and to determine the appropriateness of rapid volume resuscitation.

Measurement of LV Function and Segmental Wall Motion Abnormality

Measurement Technique

There is a qualitative and a quantitative approach to assessing overall LV function using two-dimensional echocardiography (2DE). With the qualitative approach, the clinician makes a visual estimate of overall LV function. He or she examines the contractile function of the left ventricle in the parasternal long-axis (PSL) and parasternal short-axis (PSS) views, the apical four-chamber (AP4) view, and the subcostal (SC) view. In the PSS view, the estimate of LV function should be made at the level of the papillary muscles. The descriptors commonly used are normal, mildly reduced, moderately reduced, severely reduced, and hyperdynamic LV function. Hyperdynamic LV function is defined as end-systolic effacement of the ventricular cavity. Visual estimates of overall LV function are reliable if the observer is experienced.[1] Quantitative assessment of LV function uses the Simpson method, where the end-systolic and end-diastolic areas of the left ventricle are measured in the AP4 and apical two-chamber views to calculate an ejection fraction. The Simpson method is time consuming, requiring clear endomyocardial definition and perfect long-axis orientation from the apical window. Because of time constraints and technical

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difficulties in obtaining the requisite high-quality images, it has limited utility in the ICU.

In addition to assessing overall LV function, the advanced CCE examination includes assessment of segmental wall function. Standard segmental wall anatomy includes 17 segments.[2] Wall motion and thickening for each myocardial segment is graded as normal, hypokinetic, akinetic, or dyskinetic (Video 1). Wall motion abnormalities at the segmental level may be identified qualitatively by visual examination of the 2DE image set in multiple standardized views. For quantitative purposes, wall thickening of $<50\%$ or wall excursion <5 mm defines abnormal segmental contractility. The coronary distribution of these segments is reviewed in Figure 1.

Limitations of LV Function Measurement

Assessment of overall LV and segmental wall function requires high-quality 2DE imaging. The standard views must be on the axis with clear endomyocardial definition, which may be difficult to achieve in the critically ill patient because of constraints of body habitus, wound dressings, and inability to achieve optimal body position. The intensivist must be proficient at assessing LV function with limited views. Limitations of the identification of segmental wall abnormalities are under the same constraints as assessment of overall LV function. This is compounded by the consideration that the abnormalities may be subtle and, therefore, require a high level of training on the part of the clinician.

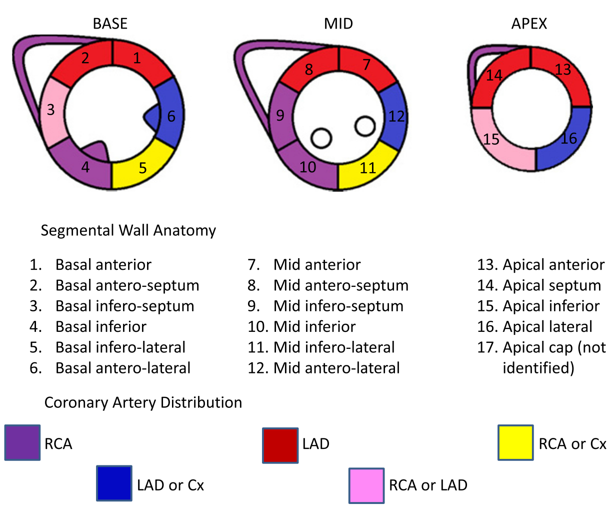

FIGURE 1. Segmental wall anatomy and typical distributions of the RCA, LAD, and Cx in the parasternal short-axis view at the basal, mid, and apical levels. The apical cap is not included in this analysis. Some segments have variable coronary artery perfusion so that arterial distribution varies between patients. Cx = circumflex coronary artery; LAD = left anterior descending coronary artery; RCA = right coronary artery. (Reprinted with permission from Lang et al.[3])

Clinical Applications

Information on LV function is useful to the intensivist for categorizing shock state. Severely reduced LV function with shock suggests a cardiogenic component. A hyperdynamic left ventricle with end-systolic effacement with shock may support a diagnosis of hypovolemia; alternatively, it may be associated with an afterload reduced left ventricle as a result of distributive/vasoplegic shock. The LV function may be hyperdynamic in obstructive shock due to a pulmonary embolism in association with right ventricular (RV) enlargement. The finding of normal LV function in a patient with shock suggests the possibility of distributive/vasoplegic shock. It may also suggest some reduction in intrinsic myocardial contractility because the LV function with distributive shock is commonly hyperdynamic. Assessment of LV function is helpful in guiding the rate of volume resuscitation. The patient with severely reduced LV function may not tolerate rapid volume infusion. Volume resuscitation, if appropriate, may be guided by repeated lung ultrasonography. The continued presence of A lines suggests that volume infusion may be continued from the point of view of lung function.[4] Chronic or acute myocardial segmental wall motion abnormalities may occur with a variety of cardiac diseases, such as stress cardiomyopathy or myocardial ischemia.

Measurement of LV Filling Pressures

Skill with advanced CCE allows the intensivist to estimate LV filling pressures without the use of a pulmonary artery catheter. Although measurement of the pulmonary artery occlusion pressure (PAOP) is not helpful in assessing preload sensitivity, knowledge of the PAOP is important in determining whether the patient has respiratory failure related to hydrostatic pulmonary edema.[5,6] The distinction between heart failure and primary lung injury as the cause for respiratory dysfunction is a key differential point that has major implications for management strategy.

Measurement Technique

The American Society of Echocardiography (ASE) published recommendations for the evaluation of LV diastolic function by echocardiography that include a definitive summary of the various methods of measurement of left atrial pressure (LAP) with echocardiography.[7] Included in the recommendations are two algorithms useful to the intensivist that allow a qualitative estimate of LAP. The reader is encouraged to review and use these algorithms, which are summarized next.

First, Determine LV Function by 2DE

For patients with depressed LV function (defined as an ejection fraction < 40%), the mitral inflow is measured from the AP4 view by placing the pulsed Doppler echocardiography sample volume between the tips of the mitral valve leaflets. This allows measurement of the E-wave velocity, the E-wave deceleration time, and the E/A ratio (Fig 2). If the E-wave velocity is < 50 cm/s and the E/A ratio is < 1, the LAP is normal. If the E/A ratio is > 2 and the deceleration time is < 150 milliseconds, the LAP is elevated. If neither result is found, the E/e′ ratio is measured, where e′ is the lateral annular velocity measured by placing the sample volume over the lateral mitral annulus and recording the tissue Doppler imaging (TDI) velocity of this structure. If E/e′ is < 8, the LAP is normal, and if it is > 15, the LAP is elevated. If E/e′ is between these values, a series of further measurements may be made. Except for measurement of the pulmonary artery systolic pressure (PASP), they are impractical for routine bedside use.

For patients with normal LV function, the E/e′ ratio is measured. If the ratio is < 9, the LAP is normal, and if > 14, it is elevated. Between these values, a series of further measurements may be made. Except for measurement of the PASP, they are impractical for routine bedside use.

Limitations of LV Filling Pressure Measurement

With the ASE approach, the LAP measurement does not give a quantitative result; rather, it is designated as normal or elevated. The implication of an elevated value is that the patient is at risk for hydrostatic pulmonary edema. The lack of a specific value for LAP is not of particular importance because the exact value of LAP (or its surrogate PAOP) has limited value in determining preload sensitivity. An elevated value of LAP has particular importance in identifying whether the patient may have cardiogenic pulmonary edema.

When the mitral valve inflow measurements and E/e′ ratio are indeterminate, the algorithm calls for more-complex measurements that are impractical for bedside use. This relates not only to time constraints intrinsic to ICU work but also to the difficulty in obtaining good-quality Doppler echocardiographic measurements of the type recommended in patients receiving mechanical ventilatory support, especially with transthoracic echocardiography. For patients with indeterminate results based on the ASE algorithm, lung ultrasonography may be helpful in estimating left-sided filling pressures. The ASE algorithm has not been validated in patients with mitral valve stenosis (or heavy mitral annular calcification), mitral valve repair or replacement, mitral regurgitation, sinus tachycardia, restrictive cardiomyopathy, hypertrophic cardiomyopathy, or atrial fibrillation.

Alternative Methods

Lung ultrasonography allows the intensivist to distinguish between cardiogenic pulmonary edema and primary lung injury. The finding of anterior A lines with sliding lung indicates that the PAOP is < 18 mm Hg

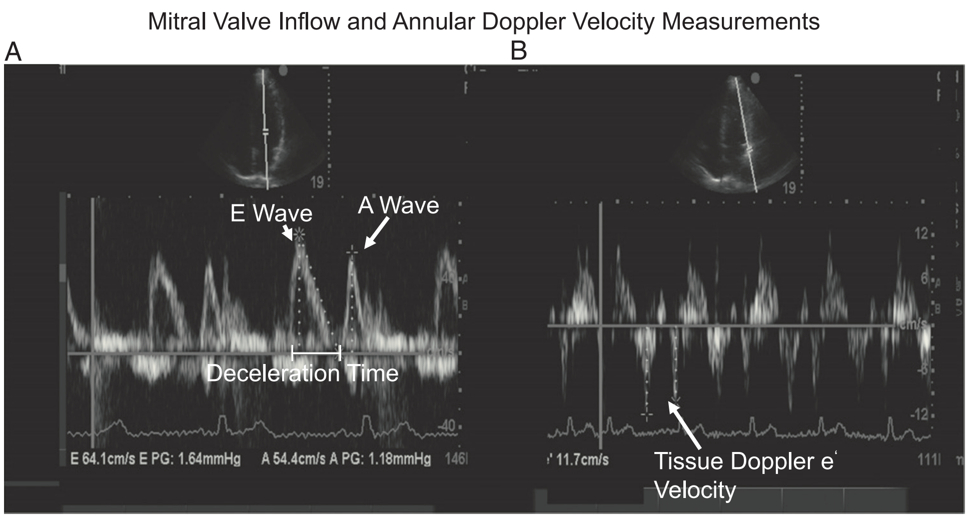

Figure 2. Apical four-chamber view showing both mitral inflow pulsed wave (PW) Doppler echocardiography velocities and mitral valve lateral annular tissue Doppler imaging (TDI) velocities. Measurement of these values allows for qualitative estimates of left atrial pressure. A, Mitral inflow using PW Doppler echocardiography. B, TDI of the lateral annulus of the mitral valve. In this example, the E-wave velocity is 64.1 cm/s, and the e′ is 11.7 cm/s. An E/e′ of 5.5 suggests normal left ventricular filling pressures, which applies to patients with ejection fractions > 40%. A wave = late mitral inflow peak velocity; e′ = lateral mitral annular peak velocity; E wave = early mitral inflow peak velocity.

and probably < 12 mm Hg.[8] A profuse B-line pattern is defined as the presence of multiple B lines in the ultrasound window without any spared areas at the pleural interface. A focal B-line pattern is the presence of B lines in the ultrasound window with spared areas at the pleural interface. The finding of profuse bilateral anterior B lines with smooth pleural line morphology is highly suggestive of cardiogenic pulmonary edema, whereas focal anterior B lines, whether unilateral or bilateral, with irregular pleural line morphology strongly suggest a primary pulmonary process (Video 2).[9] Lung ultrasonography should be routinely paired with echocardiography when assessing for the possibility of cardiogenic pulmonary edema.

Clinical Applications

A common question for the intensivist is whether the patient with bilateral infiltrates has cardiogenic pulmonary edema or acute lung injury. Skill at advanced echocardiography and lung ultrasonography allows the intensivist to answer this question.

Evaluation of the Right Side of the Heart

The evaluation of RV function has clinical application when evaluating critically ill patients with cardiopulmonary failure. Skill at basic CCE allows identification of RV enlargement, whereas advanced CCE techniques permit more comprehensive evaluation of RV function. The ASE summarized the large number of measurements that may be used to evaluate RV function.[10] The intensivist, limited by time constraint, must select a few key measurements that are relevant and easy to perform at the bedside of the critically ill patient. The measurements may be divided into three general categories: assessment of RV function, assessment of the pulmonary circulation, and assessment of the tricuspid valve (TV).

Assessment of RV Function

RV Size: RV size is best estimated from the AP4 or SC views, with direct comparison with the LV size. Normal RV size is 60% of the LV size at end diastole. An end-diastolic RV cavity size between 60% and 100% and $> 100\%$ of end-diastolic cavity size of the left ventricle denotes moderate or severe RV enlargement, respectively (Video 3). As the right ventricle enlarges, it rather than the left ventricle forms the apex of the heart in the AP4 view. The thickness of the RV free wall either in the PSL or SC long-axis views identifies the patient with chronic elevation of RV afterload. The normal RV free wall thickness is < 4 mm, and the right ventricle is abnormal if it exceeds 5 mm.

Septal Kinetics: Two-dimensional imaging alone allows for a qualitative assessment of septal kinetics. With normal conduction and RV function, the septum moves toward the left ventricle during ventricular systole. Pressure or volume overload of the right ventricle results in characteristic patterns of septal position. Pressure overload of the right ventricle causes a straightening of the interventricular septum during systole, whereas straightening of the septum during diastole results from volume overload of the right ventricle. Either will yield a characteristic D shape of the left ventricle during systole or diastole, respectively (Video 4). Volume or pressure overload of the right ventricle also results in paradoxical motion of the septum. This is visualized as a bounce of the septum or movement of the septum toward the left ventricle during ventricular contraction. This paradoxical septal motion results from different rates of rise of intracavitary pressure during ventricular filling. The use of M mode permits a detailed analysis of septal kinetics and is useful in identifying patterns consistent with RV dysfunction.[11] It is important to have a concomitant ECG tracing for orientation of the cardiac cycle (Fig 3). The M-mode interrogation line is placed through the septum in the PSL or PSS views.

RV Systolic Function: Severe RV systolic dysfunction may be observed qualitatively as reduced contractility and movement of the RV free wall in the AP4 and SC views. Quantitative measurement of RV ejection fraction is limited by the complex geometry of the right ventricle. Therefore, indirect measures of RV systolic function are used. The right ventricle has more longitudinal than transverse motion, so the degree of longitudinal systolic movement of the tricuspid annulus correlates with overall RV systolic function. To measure the tricuspid annular plane systolic excursion (TAPSE), an M-mode interrogation line is placed through the tricuspid lateral annulus in the AP4 view (Fig 4). At times, the examiner will need to use a modified AP4 view to align the tricuspid annulus as parallel as possible with the M-mode interrogation beam. Normal TAPSE is > 17 mm; measurements below this value indicate reduced RV systolic function.[12] TDI of the TV annulus is another means of measuring overall RV function. The TDI sample volume is positioned at the lateral RV annulus (Fig 5), and the S-wave velocity is identified as an upward deflection during ventricular contraction. A TDI S-wave velocity of < 10 cm/s indicates reduced RV systolic function.[13]

Assessment of Pulmonary Circulation

Pulmonary Artery Systolic Pressure: The PASP may be measured by Doppler echocardiography. The measurement of PASP requires that there be some degree

M-Mode Evaluation Showing Paradoxical Movement of the Interventricular Septum

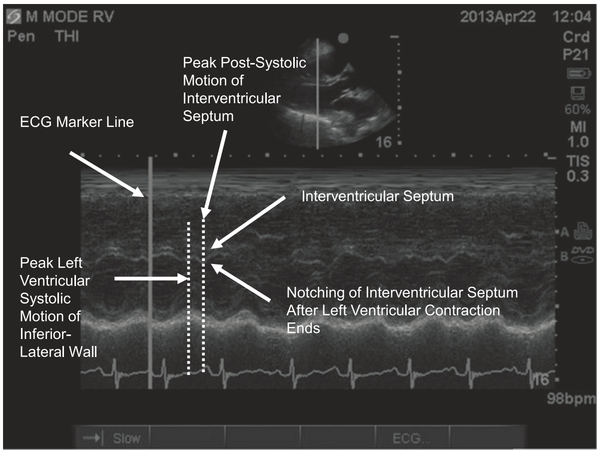

FIGURE 3. M-mode interrogation of the interventricular septum in a patient with right ventricular dysfunction and paradoxical septal motion. The M-mode interrogation line is placed through the middle of the interventricular septum in the parasternal long-axis view. As left ventricular contraction ends, there is posterior movement of the interventricular septum toward the left ventricular cavity. This appears as a bounce during two-dimensional echocardiography and represents paradoxical septal motion. RV = right ventricle.

Lateral Tricuspid Valve Annular S Wave Velocity Determination by Tissue Doppler

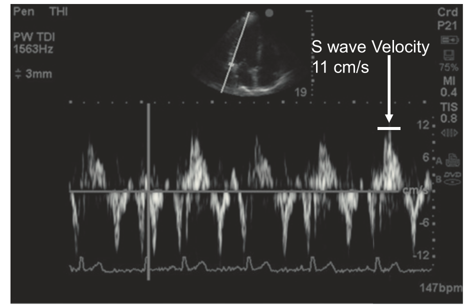

FIGURE 5. Apical four-chamber view showing TDI measurement of the lateral tricuspid valve velocity. Normal values are > 10 cm/s. Reduced velocity suggests right ventricular systolic dysfunction. See Figure 2 legend for expansion of abbreviations.

of tricuspid regurgitation (TR). The examiner identifies a TR jet by color flow Doppler echocardiography. The TR jet must be interrogated from multiple angles, such as the RV inflow, PSS, AP4, and SC views, to avoid underestimating the velocity. The continuous wave Doppler (CWD) echocardiography interrogation line is placed along the main axis of the TR jet to measure the blood flow velocity of the regurgitant jet (Video 5). With use of the modified Bernoulli equation, the pressure gradient across the valve is calculated. Once the pressure gradient is known, adding the right atrial pressure (RAP) to this gradient yields an estimate of the PASP. The RAP may be measured directly if a central venous catheter is in place or estimated from the size and respiratory variation of the inferior vena cava (IVC).[14]

Analysis of Pulmonary Outflow Pulsed Doppler Echocardiography Velocity Time Integral: The presence of pulmonary arterial hypertension (PAH) may be inferred indirectly from the systolic velocity time integral (VTI) of the main pulmonary artery. The pulsed Doppler echocardiography sample volume is placed in the main pulmonary artery from the PSS view at the aortic valve level. The acceleration time is measured as the time required to reach maximal systolic outflow velocity (Fig 6). Acceleration time of pulmonary arterial systolic flow is a measurement of a very short time interval that benefits from high time resolution. Reduction in acceleration time correlates with severity of PAH.[15] A biphasic VTI envelope is also characteristic of severe PAH.[16]

Assessment of the TV

Severity of TR: RV dysfunction often is accompanied by TR. The severity of TR generally is graded qualitatively from the size of the color flow Doppler echocardiographic map as trace, mild, moderate, or severe. Certain features of the CWD tracing of TR indicate severe TR. If the CWD TR jet density is greater than the CWD inflow density, or if there is a rapid fall-off of the TR velocity signal in late systole, the TR is likely to be severe.[17]

Limitations in the Assessment of RV Function

RV Size: Assessment of RV size requires an on-axis AP4 view with clear visualization of the RV free wall. Off-axis views may cause inaccurate assessment of RV size. Acquiring an adequate image may be difficult in the supine critically ill patient receiving ventilator

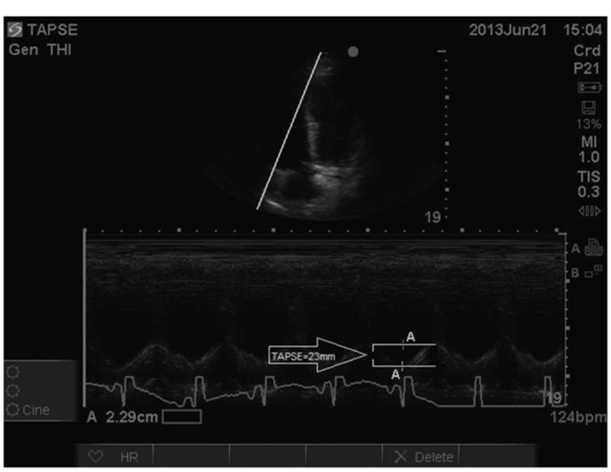

FIGURE 4. Apical four-chamber view with M-mode cursor placed through the lateral annulus of the tricuspid valve. Normal TAPSE is > 17 mm. In this example, the TAPSE is normal at 22.9 mm. HR = heart rate; TAPSE = tricuspid annular plane systolic excursion.

Main Pulmonary Artery Pulsed Wave Doppler Contour and Acceleration Time

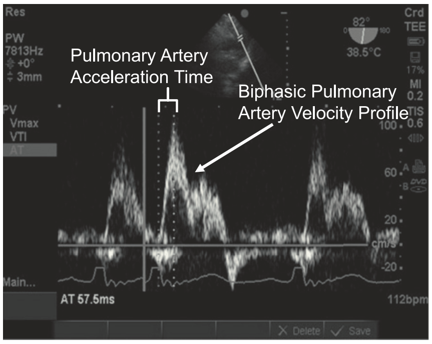

FIGURE 6. Transesophageal echocardiographic view of the main pulmonary artery with the PW Doppler echocardiography sample volume placed in the main pulmonary artery. The acceleration time is 57.5 ms, and there is a biphasic contour to the velocity profile, suggesting the presence of pulmonary arterial hypertension. AT = acceleration time; VTI = velocity time integral. See Figure 2 legend for expansion of other abbreviation.

support. The SC view is an alternative but may suffer from the same limitations.

Septal Kinetics: Paradoxical motion of the septum may occur with left bundle branch block and is commonly observed following any operation that requires pericardiotomy. An off-axis view of the left ventricle in the PSS view may mimic a D-shaped heart.

RV Systolic Function: Qualitative assessment of RV function requires adequate visualization of the RV free wall, which may be difficult in critically ill patients. TDI of the lateral RV annulus is subject to problems with incident angle typical of Doppler measurements.

Limitations in Assessment of the Pulmonary Circulation

Pulmonary Artery Systolic Pressure: Inaccurate measurement of the peak TR jet velocity may result in underestimation of the PASP, so measurement of TR jet velocity requires a complete contour of the CWD jet. In addition, the TR jet must be interrogated from multiple angles, such as the RV inflow, PSS, AP4, and SC views, to avoid underestimating the velocity. This is a result of problems with incident angle and the irregular three-dimensional configuration of the TR jet. The RAP is frequently estimated from the IVC. This method gives a range of RAPs rather than a specific value. The IVC method has also not been validated in patients receiving ventilatory support. Another potential source of error relates to use of the simplified Bernoulli equation as opposed to the full Bernoulli equation. For example, polycythemia may result in inaccurate estimates of the TR pressure gradient when using the simplified equation.

Limitations in the Analysis of Pulmonary Outflow Pulsed Doppler Echocardiography VTI: It may be difficult to adequately visualize the main pulmonary artery in all patients. An alternative approach is to use an SC short-axis view of the base that focuses on the pulmonary arterial trunk.

Limitations of Assessment of the TV

Severity of TR: The severity of TR by color flow Doppler echocardiography may be confounded by problems typical to the technique, including gain, angle, and wall jets.

Clinical Applications

Assessment of the right side of the heart is a key component of the basic CCE examination for the patient presenting with cardiopulmonary failure. Advanced CCE allows the intensivist to further characterize elements of right-sided heart function that may have implications for management. For example, an elevation of PASP in association with RV dilation and hypokinesis requires a specific diagnosis followed by a management decision, such as limiting ventilator-delivered inspiratory pressures, limiting positive end-expiratory pressure or automatic positive end-expiratory pressure, pulmonary embolism, hypoxemia, or correction of acidosis. A dilated right ventricle without elevation of PASP suggests the possibility of primary RV failure (eg, RV infarction). The effect of therapy designed to reduce PASP may be followed serially with TR jet velocity, TAPSE, and TDI S-wave velocity. Ventilator-induced RV failure due to an inappropriate increase in RV afterload from high cycling pressures may be identified by measuring an abnormal variation of the main pulmonary artery systolic VTI tracing in association with morphologic evidence of septal flattening and dyskinesia. The effect of changing ventilator settings can then be determined with serial echocardiography.

Measurement of Preload Sensitivity

In treating the patient with hemodynamic failure, a key question is whether the patient will benefit from volume resuscitation or, more specifically, whether the stroke volume (SV) and cardiac output improve with volume infusion. A major application of SV measurement, and its surrogate left ventricular outflow tract (LVOT) VTI, is identifying preload sensitivity. Competence in basic CCE limits the intensivist to measurement of IVC size and variation to identify volume responsiveness.[18,19] Advanced CCE measurements expand the ability of the clinician to accurately predict preload sensitivity.

Measurement Technique

The Doppler echocardiography sample volume is placed in the LVOT using the five-chamber view. The LVOT VTI is measured serially while the ventilator is cycling. Instead of the VTI, the peak velocity of the systolic velocity envelope may be used because it is easier to measure. It is not necessary to know the absolute value of the SV, as discussed in part 1 of this series.[20] Measurement of the change in the VTI or peak velocity of the VTI envelope is sufficient as a surrogate for change of SV. An increase of VTI or velocity of > 12% during passive inflation with the ventilator is indicative of preload sensitivity.[21] Similarly, detection of preload sensitivity is accomplished with transesophageal echocardiography with the use of the transgastric long-axis view at 120° or the deep gastric view of the LVOT to measure variation in the LVOT VTI.[22,23]

The major limitation of using variation in the VTI to identify preload sensitivity is that it requires the patient to be on a mechanical ventilator and making no respiratory effort. In addition, the degree of variation of SV depends on the tidal volume. When making the measurement, the patient should be receiving 8 mL/kg tidal volume (temporarily), and serial measurements should be made at the same tidal volume.[24] An irregular heart rate invalidates the measurement. In addition, this method for assessment of preload sensitivity has not been validated in patients with impaired RV systolic function.

Passive Leg Raising

The change in SV after passive leg raising has been validated as a means of identifying preload sensitivity.[25,26] This method also works in patients in atrial fibrillation provided that sufficient SV measurements yield a reliable average value, and it has utility in patients who are making a spontaneous respiratory effort.

The patient is placed in a supine, semirecumbent position with the torso at 45°. The LVOT VTI is measured from the five-chamber view. The patient position is then changed so that the torso is at 0° with the legs elevated to 45°. This position provides a rapid (and completely reversible) redistribution of several hundred milliliters of blood into the thoracic compartment. One minute after leg raising the LVOT VTI is measured again. A > 12% increase of LVOT VTI or peak velocity is predictive of preload sensitivity. This technique works with atrial fibrillation provided that at least 10 cardiac cycles are averaged. It also predicts preload sensitivity in patients with spontaneous respiratory effort. Passive leg raising is an attractive technique because it makes physiologic sense. The operator directly examines the effect of a reversible volume challenge. If SV rises, the patient is preload sensitive. The major limitation to the technique is that it takes time to perform properly, and it may not be practical for regular use in a busy ICU.

Alternative Methods

Several groups have reported on the use of a peripheral arterial Doppler signal to identify preload sensitivity (Video 6).[27-29] This parallels the use of the arterial waveform to identify preload sensitivity with pulse pressure variation coincident with ventilator cycling, which is a well-validated technique.[30] Instead of measuring the VTI at the LVOT, the peripheral arterial Doppler peak velocity is measured. A variation of > 12% between inspiration and expiration indicates preload sensitivity. The advantage of this method is the simplicity of obtaining the measurement. The same limitations apply as those of the SV variation methods.

Clinical Utility of Measurement of Preload Sensitivity

Skill at advanced CCE allows the clinician to determine whether volume infusion will improve hemodynamic function in the patient with shock before giving the volume challenge, avoiding the hazard of inappropriate volume use and allowing the clinician to avoid complications of excessive volume resuscitation.[31] These techniques have not been validated in patients with RV dysfunction.

Conclusions

Training in advanced CCE provides the intensivist with valuable tools for the assessment of cardiopulmonary failure. This second half of the two-part series reviews some important aspects of advanced CCE that have practical bedside application: evaluation of LV function, measurement of left-sided filling pressures, assessment of right-sided heart function, and determination of preload sensitivity.

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Additional information: The Videos can be found in the "Supplemental Materials" area of the online article.

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