Advanced Echocardiography for the Critical Care Physician

Part 1

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This is the first of a two-part series that reviews advanced critical care echocardiography (CCE) techniques designed for critical care physicians. In this section, we review training in basic and advanced CCE. This is followed by a review of Doppler principles, including pulsed wave, continuous wave, and color flow Doppler. Included are Doppler measurement techniques that are useful for assessing the patient with cardiopulmonary failure and the common pitfalls of Doppler. This section ends with a review of the quantitative and semiquantitative measurements of stroke volume, as well as problems with measurement of stroke volume in the ICU and its useful clinical applications. Video-based examples will help demonstrate the techniques that are described in the text.
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Abbreviations: CCE = critical care echocardiography; CFD = color flow Doppler; CWD = continuous wave Doppler; LV = left ventricular; LVOT = left ventricular outflow tract; NBE = National Board of Echocardiography; PWD = pulsed wave Doppler; SV = stroke volume; TTE = transthoracic echocardiography; VTI = velocity time integral

Echocardiography enables the intensivist to assess the patient with hemodynamic failure. The examination allows the clinician to categorize the shock state and to develop an effective management strategy. Early and repeated echocardiography is a valuable tool for the management of shock in the ICU, and the frontline intensivist should consider skill at bedside echocardiography to be a key element of their training.[1]

The American College of Chest Physicians/Société de Reanimation de Langue Française statement of competence in critical care ultrasonography divides critical care echocardiography (CCE) into two parts: basic and advanced.[2] Competence in basic CCE is a mandatory component of skill in general critical care

ultrasonography. Depending on their interest and the requirements of their ICU practice, some frontline intensivists will want to develop competence in the field of advanced CCE.

Basic vs Advanced CCE

Performance of the basic examination requires that the clinician have skill in image acquisition, image interpretation, and clinical application of a limited num-

ber of echocardiographic views. The examination can be performed in several minutes, is limited in scope, goal directed, and can be repeated as often as the clinical situation warrants. Competence in basic CCE is readily achieved with a short course of training.[3,4]

Similar to basic CCE, advanced CCE requires a high level of skill in all aspects of image acquisition and interpretation. Mastery of advanced CCE means that the intensivist has a skill level that is similar to a cardiology-trained echocardiographer, although with additional skill in image acquisition at the bedside and more knowledge of relevant critical care applications.

Advanced CCE avoids the time delays and clinical disassociation that are intrinsic to standard echocardiography, as the examination is performed by the intensivist who has full knowledge of the patient's clinical condition. The advanced CCE examination is flexible in scope, becoming as goal directed or comprehensive as the situation demands. It can be performed immediately and repeated as often as required, an approach that contrasts with the traditional practice of performing a comprehensive exam that is often delayed and rarely repeated.

Training in Advanced CCE

Achieving competence in advanced CCE is challenging and time consuming. It should be regarded as an optional part of critical care practice, unlike competence in basic CCE. The intensivist must develop a comprehensive knowledge of cognitive elements of the field that may be found in standard literature.[5,6] In addition, the intensivist must have definitive training in image interpretation. This requires considerable time spent interpreting a large number of full echocardiographic studies under the direct supervision of an expert level reader. Unlike the cardiologist who relies on highly skilled technicians for image acquisition, the intensivist must spend many hours personally performing full echocardiographic studies. High-level skill at image acquisition is a requirement for advanced CCE.

Part of competence in advanced CCE is that the intensivist understands the limitations and unique applications relevant to their skill set. For example, diagnosis of complex congenital heart disease, guidance of intraoperative valve repair, or detailed analysis of artificial valve function requires an echocardiographer with expertise in these areas. However, determination of preload sensitivity by real-time measurement of stroke volume (SV) variation or straight leg raising, identification and treatment of adverse heart-lung interactions related to ventilator settings, or integration of lung ultrasonography into echocardiographic results are areas where intensivists have expertise.

A recent statement described training standards for both basic and advanced CCE.[7] The working group held that advanced CCE required a formal certification process, given its complexity. In the United States, there is no formal method for certification in advanced CCE at the national level. The National Board of Echocardiography (NBE) offers certification in echocardiography only to physicians who have completed cardiology fellowship training. An alternative approach that intensivists may follow is to satisfy the American Heart Association/American College of Cardiology requirements for competence in echocardiography[8] and then to take the NBE Examination of Special Competence in Adult Echocardiography. Many cardiologists choose not to take the NBE echocardiography examination, and prefer to satisfy the American Heart Association/American College of Cardiology requirement for competence in the field (which does not require passing the NBE examination). Although they are optional, we recommend that the interested intensivist takes the echocardiography board examination, as it is a clear demonstration of a comprehensive knowledge base.

This article will review some important aspects of advanced CCE. These include measurement of SV, evaluation of left ventricular (LV) function, identification of segmental wall abnormalities, measurement of left-sided filling pressures, evaluation of right-sided heart function, and identification of preload sensitivity. This article will not review the evaluation of valvular function using advanced CCE techniques, as this requires a separate discussion. The primary focus is on measurements that are made with transthoracic echocardiography (TTE) and will not include a comprehensive discussion of transesophageal echocardiography. Illustrative video clips are found throughout the text and are a key element of the article. The reader is encouraged to be connected to the *CHEST* video supplements and to call up the video images in sequence with the text. This will greatly augment the utility of the article. This article is not a comprehensive review of the subject; the emphasis will be on measurements that have immediate practical application and that can be performed rapidly at the bedside of the critically ill patient.

Principles of Doppler

Advanced CCE requires comprehensive knowledge of Doppler measurements. It is beyond the scope of this article to review in detail the physical principles of Doppler measurements. For this information, the reader is referred to comprehensive discussions that are found in standard texts.[9] Instead, this section will summarize some key concepts and limitations of bedside Doppler measurements.

The Doppler phenomenon occurs when the sound source (the transducer) and the object reflecting the source (blood cells or myocardium) are moving relative to one another as opposed to the case where the transducer and the reflector are both immobile. In the case of moving reflectors, the frequency of the returning sound wave will be different than the transmitted wave. The Doppler equation uses the measured frequency difference between the transmitted and reflected sound waves to derive the velocity of the reflector. In this way, the velocity and direction of blood flow may be measured within the cardiovascular system. The angle of incidence between the direction

of blood flow and the ultrasound beam is of utmost importance in making Doppler measurements. If the angle of incidence is <20°, the velocity measurement is of acceptable accuracy. At values above this, the velocity will be increasingly underestimated, such that at an incident angle of 90°, the velocity measurement will be zero (Fig 1). The operator, therefore, must align the axis of Doppler interrogation as close as possible with direction of blood flow. Doppler measurement of blood flow velocity will never overestimate velocity. It can easily underestimate it, however, if the operator is not successful in optimal beam alignment. Under some circumstances, the absolute velocity of blood flow is not as important as changes in the velocity, as might occur during the respiratory cycle when making serial semiquantitative measurements of SV. When making serial measurements of velocity variation, the operator must focus on obtaining the same angle with each measurement. Otherwise, changes in velocity might be caused by changes of the incident angle rather than by changes in physiologic function.

The most commonly used Doppler modalities are pulsed wave Doppler (PWD), color flow Doppler (CFD), and continuous wave Doppler (CWD). Some practical suggestions for their use are as follows.

Pulsed Wave Doppler

PWD has utility for the measurement of blood flow velocity at a specific location within the cardiovascular system. PWD cannot be used to measure high velocities of blood flow. It has utility in measuring velocities in normal physiologic range, such as during SV measurement in the LV outflow tract (LVOT) or during mitral valve inflow. To control aliasing, the operator may use several strategies: (1) use a shallower sample volume, (2) decrease the ultrasound frequency, (3) optimize incident angle, (4) use CWD. The main pitfalls of PWD relate to suboptimal incident angle of interrogation, poor sample volume placement, translational artifact-related movement of the heart with the respiratory cycle, and placement of the sample volume too close to a stenotic point, so that flow acceleration gives an overestimation of velocity.

Color Flow Doppler

CFD is a form of PWD whereby multiple sample volumes are created within an area selected by the operator. The direction and velocity measured in each sample volume is displayed by a specific color and color intensity, respectively. This color-coded grid is superimposed over the two-dimensional image, allowing for assessment of flow directions and velocities over a designated area. To optimize functionality of CFD, the operator seeks the shallowest and smallest map area for CFD measurement.

Beyond the problems of PWD related to incident angle, CFD has specific pitfalls. It is gain dependent, such that under- or overgaining the color map will predictably under- or overestimate the severity of valvular regurgitation ("dial a jet") (Video 1). A practical method to set proper CFD gain is to turn on a CFD map without the transducer on the patient and to turn the gain down until the map area is completely black. The gain is then turned up slowly until a few color dots are visible. Another problem with CFD occurs in the estimation of the severity of eccentric valvular regurgitation. CFD jets that are directed along the wall of the atrium will systematically underestimate the severity of the regurgitation (Video 2).
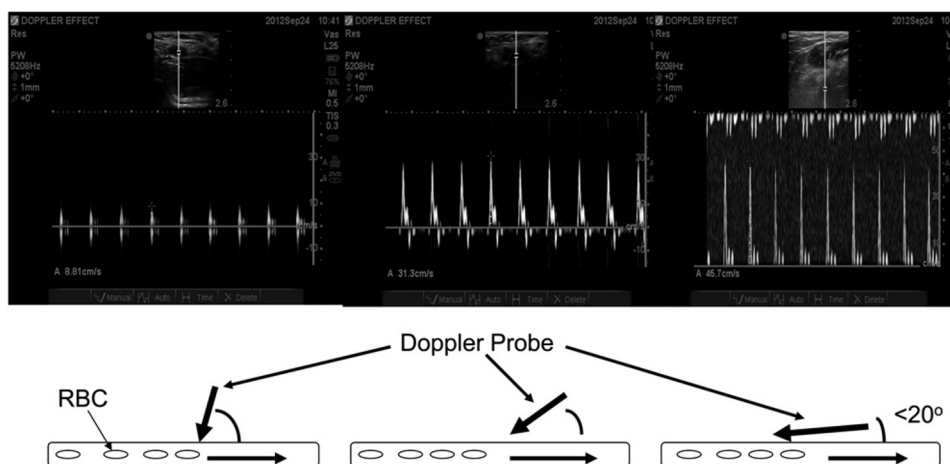
Angle Dependence of Doppler Velocity Measurement

FIGURE 1. Brachial artery pulse wave velocity Doppler measurements demonstrating the dependence of velocity on incident angle. The angle of the transducer has been changed such that the incident angle of Doppler interrogation is reduced with a resultant increase in the measured velocity.

In this case, other techniques must be used for accurate determination of the severity of regurgitation.[10] Finally, it is important to understand that the color map is measuring velocity; the operator may erroneously assume that the size of the color jet represents a flow map. Unlike contrast used in cardiac catheterization, the size of the color map may have variable relationship to the severity of regurgitation. The advantage of CFD is its ease of application; its disadvantages are these unrecognized pitfalls.

Continuous Wave Doppler

Unlike PWD, CWD is capable of detecting high-flow velocity but it is unable to pinpoint the location of the high velocity at a specific point along the ultrasound beam. The advantage of CWD lies with its ability to measure high velocities, but its disadvantage rests with this range ambiguity of the modality. It is used most commonly for detection of high-velocity blood flow that occurs with stenotic or regurgitant valvular dysfunction. Although free of aliasing limitation, it is susceptible to problems related to incident angle.

The Doppler techniques described in the previous section allow for the measurement of intracardiac blood flow velocities. Using these Doppler-derived values for velocity, the intensivist is able to calculate intracardiac pressures using the following simplified Bernoulli equation:

$$\text{Pressure gradient}\left(\Delta P\right) = 4 \times \left(V_{peak}\right)^2$$

Where ΔP is pressure gradient, and V is maximal flow velocity. The velocity across the orifice is related directly to the pressure difference or drop between the proximal and distal portions of the orifice. This formula forms the basis for measurements of cardiac pressures with echocardiography.

MEASUREMENT OF SV

The cardiac SV may be accurately measured with echocardiography.[11] Multiplication of SV by heart rate yields the cardiac output. Both values may be indexed to body surface area and used to calculate a variety of derived values such as systemic or pulmonary vascular resistance and oxygen delivery. Measurement of SV allows accurate, quantitative, noninvasive assessment of hemodynamic function without the need for a pulmonary artery thermodilution catheter. Bedside measurement of SV is a key skill for the intensivist with interest in advanced CCE.

Measurement Technique

The measurement of SV is usually made at the LVOT. When using the TTE approach, the operator measures the diameter of the LVOT from the parasternal long-axis view immediately below the hinge point of the aortic valve leaflets (Fig 2). The LVOT area (cm^2) is calculated from this diameter measurement using the formula:

$$\text{LVOT area}\left(cm^2\right) = \left(\text{LVOT diameter}/2\right)^2 \times 3.14$$

Next, the operator places the PWD sample volume in the LVOT to measure the systolic velocity envelope of blood flow in the LVOT, using the five-chamber apical view (Video 3). Integration of the resulting velocity-time envelope yields the velocity time integral (VTI), which represents the distance in centimeters that blood has moved over the course of systole through the LVOT. The SV is calculated as follows:

$$\text{SV}\left(cm^3 \text{ or mL}\right) = \text{LVOT area}\left(cm^2\right) \times \text{VTI}\left(cm\right)$$

Normal values of VTI are between 18 and 22 cm, while LVOT diameter varies according to body size. Typical values in clinical practice for LVOT diameter range between 1.8 and 2.2 cm.

Problems With Measurement of SV

Measurement of LVOT diameter must be very accurate, as any inaccuracy will be squared when calculating the area. For example, if the LVOT diameter measurement is 1.8 cm and the VTI is 18 cm, the resultant SV will be 46 mL; if the LVOT measurement is 2.1 cm and the VTI is 18 cm, the resultant SV will be 62 mL. A 3-mm error in LVOT diameter measurement yields a substantial error in SV. Measurement of LVOT diameter requires a good-quality,

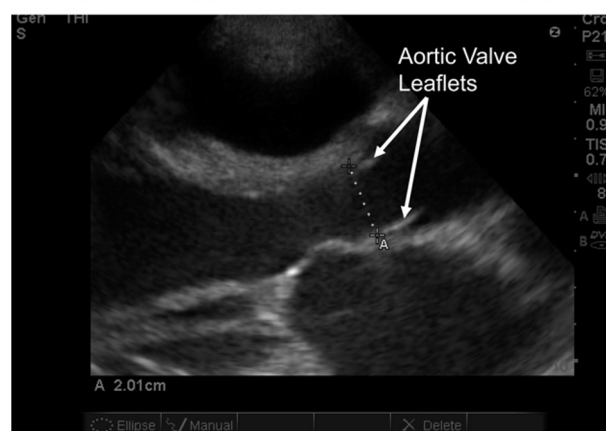**Measurement of Left Ventricular Outflow Tract Diameter**

FIGURE 2. Magnified, parasternal, long-axis view of left ventricular outflow tract. The calipers have been placed at the hinge point of the aortic valve leaflets with a diameter placement of 2.01 cm.

parasternal, long-axis view with clear endomyocardial borders and caliper orientation that is strictly perpendicular to the walls of the LVOT. If the measurement is critical for clinical operations, the LVOT diameter should be measured several times.

Determination of the VTI is subject to problems related to Doppler measurement. The site of the measurement is important.[12] The PWD sample volume is placed just proximal to the aortic valve at the location where the LVOT measurement was made. The VTI recording should show a smooth velocity curve, a well-defined peak, and a narrow band of velocities throughout systole. The sample volume may need to be moved slowly toward the apex to obtain a smooth velocity curve. Placement of the PWD interrogation box too close to the aortic valve will overestimate the VTI, particularly if there is any stenosis of the aortic valve. The VTI is angle dependent. Measurement of the systolic velocity envelope when the interrogation angle is not well aligned along the axis of blood flow will yield an underestimate of the VTI. At times, the best measurement axis is not achieved from the best two-dimensional image orientation. The operator may need to adjust the image position on the machine screen for best angle of Doppler measurement. This may require using the three-chamber view or a five-chamber view. Translational movement of the heart during the respiratory cycle may also be a challenge. The position of the Doppler sample volume may be constant on the screen, but the LVOT may move due to respiratory translational motion, thereby yielding an inconstant VTI measurement. Finally, in patients with an irregular heart rhythm such as atrial fibrillation, SV changes according to R-R interval. In this situation, an average SV needs to be calculated by averaging the VTI over a number of beats, typically at least 10.

Quantitative vs Semiquantitative SV Measurement

When compared with other techniques, the measurement of SV using ultrasonography is accurate, and there are circumstances when it is important to have an explicit measurement of the value. Alternatively, semiquantitative measurements may be sufficient to make important decisions at the bedside. The LVOT area does not change during the cardiac cycle or with change of loading conditions. Given that the LVOT area is constant, changes in VTI represent changes in SV, even if the exact VTI is not calculated with each cardiac cycle. Given this principle, the VTI or the peak velocity of the VTI, rather than the absolute value of the SV, may be used to assess hemodynamic function. In the patient in sinus rhythm who is completely passive on mechanical ventilation, changes in VTI that occur during ventilator cycle may be used to determine preload sensitivity, as these changes reflect changes in SV, as will be discussed.

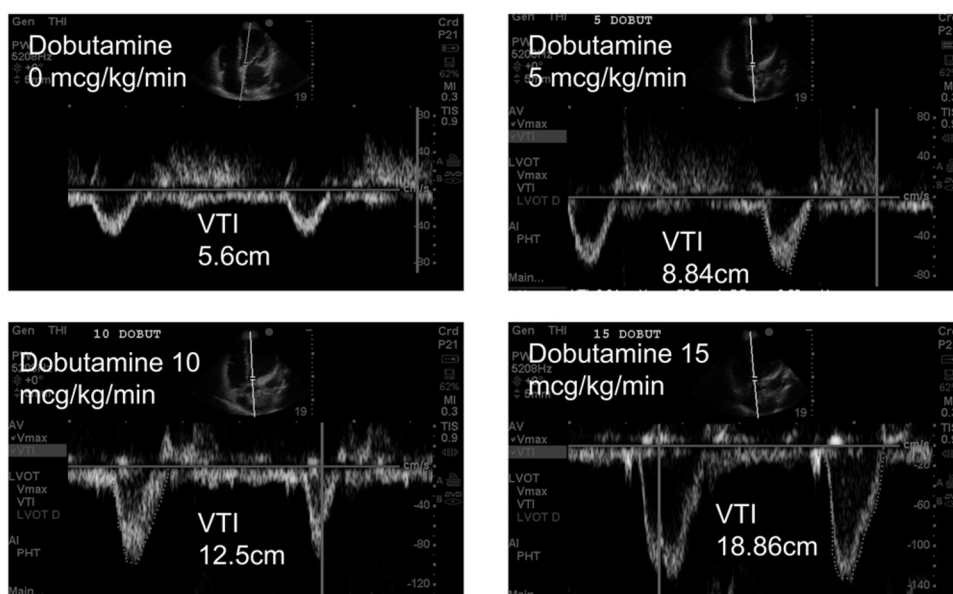## Results of Augmentation of Stroke Volume During Dobutamine Trial

FIGURE 3. Measurement of serial left ventricular outflow tract VTI with augmenting doses of dobutamine. This patient had severe left ventricular failure. At 4-min intervals, dobutamine dose was raised in increments of 5 μg/kg/min, with a resulting major increase in stroke volume. VTI = velocity time integral.

Clinical Utility of SV Measurement

The intensivist with skill in basic CCE identifies qualitatively whether the LV is compromised. While this has use in identifying a cause for hemodynamic failure and allows for design of management strategy, measurement of the SV adds information to the visual analysis of LV function. For rapid evaluation of LV function, the finding of a very low VTI in a patient in shock may be sufficient to identify low cardiac output without the need to measure an accurate SV. Measurement of SV is helpful if there is a discrepancy between the contractile function of the LV and the resultant cardiac output. For example, the patient with under-resuscitated septic shock with hyperdynamic LV function and a high ejection fraction may have, paradoxically, a low SV and cardiac output. Likewise, the patient with a dilated cardiomyopathy and low ejection fraction may have an adequate SV and cardiac output. Measurement of SV is required to identify these situations.

Measurement of SV may be useful in observing response to pharmacologic intervention. For example, in the patient in shock with severe LV dysfunction, management strategy may include an inotropic agent such as dobutamine. In our practice, we routinely measure SV serially at 4-min intervals during stepwise augmentation of dobutamine dose (Fig 3). Instead of relying on clinical parameters of response, the operator directly measures whether the agent is having its intended effect on SV while monitoring the patient for unwanted side effects. In this way, the dobutamine dose may be rapidly optimized. In measuring serial SV during rapid changes in vasoactive medication, it is important to maintain a constant angle and position of the Doppler sample volume. This requires that the transducer position be held constant with each measurement of VTI.

Measurements of VTI and SV at other sites in the heart have important clinical applications. For example, variation of the VTI measured in the pulmonary artery may identify adverse ventilator settings in the patient with right ventricular dysfunction. It is also a key element in quantitative evaluation of valve function.

Conclusions

Training in advanced CCE provides the intensivist with valuable tools for assessment of cardiopulmonary failure. This is the first part of a two-part series. This first section reviews some important aspects of advanced CCE, specifically Doppler theory and the practical use and pitfalls of Doppler in the critically ill patient. The measurement of SV is discussed in detail along with common problems with this measurement and its clinical application.

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