The identification of relative intravascular volume insufficiency in the hemodynamically unstable patient and the restoration of optimal intravascular volume remain among the core challenges in the ICU. By the Frank-Starling mechanism, the normal heart automatically adjusts stroke volume (SV) for changes in ventricular end-diastolic volume load via the relationship between initial sarcomere length (preload) and force of contraction. Hence, myocardial preload clinically may be considered the end-diastolic volume of the right or left ventricle and, in turn, is a reflection of the relative intravascular volume of the patient. Unlike skeletal muscle however, the heart normally functions not at the maximal, or plateau, portion of its force versus length (ie, preload) cardiac function curve but rather on a roughly linear or ascending portion of the curve. Volume resuscitation will increase SV in the hypovolemic patient only while on the ascending portion of the cardiac function curve; fluid administered once the plateau is reached will contribute to tissue and pulmonary edema, right ventricular dysfunction, and increased intra-abdominal pressure. In practice, the clinician is faced with the challenge of not only identifying intravascular volume deficiency but also restoring the volume of the intravascular space while avoiding overresuscitation.

Generally, techniques for the assessment of cardiac preload attempt to measure—either directly or, more commonly, indirectly—the end-diastolic volume of the right or left ventricle or both in combination. These may be static measurements, such as the central venous pressure (CVP) (right ventricle), the pulmonary artery occlusion pressure (Ppao) (left ventricle), assessments of right ventricular end-diastolic volume (RVEDV) or global end-diastolic volume (GEDV) via thermodilution, or echocardiographic measurement of left ventricle end-diastolic area (LVEDA). Alternatively, dynamic measurement indices have been developed in which respiratory variations in systolic pressure, pulse pressure, or SV are used to assess preload status and fluid
responsiveness. This article focuses on static methods for determining preload, specifically pressure and volumetric indices measured at the bedside. Dynamic measurement techniques are addressed in a separate article in this issue.

PRESSURE MEASUREMENTS: CVP AND Ppao

CVP is the simplest and most common invasive method of assessing ventricular preload. Given the nature of CVP, only right heart pressures (right atrial pressure as a surrogate for right ventricular end-diastolic pressure [RVEDP]) and, hence, right ventricular preload (RVEDV) are assessed. Whether right-sided measurements are superior or inferior to left-sided measurements for optimizing preload is still debated and is beyond the scope of this article. However, it is clear that given the steady-state requirement of cardiac output (CO) equaling venous return, and the fact that the right heart is the interaction point of the venous return system with the cardiac system, the right heart’s function is crucial to the optimization of the left. Furthermore, the high compliance of veins (compared with arteries) and the capacitance nature of the venous system are such that the left-sided arterial pressures are not the primary force returning blood to the right heart; the regulation of right atrial pressure (CVP) by the right heart determines venous return and hence right ventricular preload and subsequent cardiac output. This effective regulation of CO through the right heart’s determination of venous return, independent of the left heart’s function, gives rise to Magder’s maxim “no left-sided success without right-sided success.”

CVP is universally measured throughout ICUs for preload assessments in critically ill patients and is even incorporated into formal resuscitative algorithms and guidelines such as the Surviving Sepsis Campaign. Although convenient and accessible given the wide use of central venous catheters, the measurement of CVP for assessing preload is complicated by several factors.

**External Reference Landmark**

First, the CVP depends on the external reference landmark used for the zero point in its measurement. This zero point is the position in the circulatory system where the CVP varies little, if at all, with postural changes. This point theoretically lies within the right atrium. Accordingly, the transducer’s external reference point (in practice, the stopcock of the transducer, the point at which the transducer can be “zeroed” by opening the stopcock to atmospheric pressure, the reference point for all hemodynamic catheter measurements) should be placed co-level (“leveled”) with this point. The classic position used is that of the phlebotstatic axis, taken as the line where a coronal plane midway between the back and sternum (in practice, the midaxillary line) intersects a cross-sectional plane through the fourth intercostal space. An alternative zero point, advocated by Magder’s group, is a point 5 cm vertically below the sternal angle (at the junction of the sternum and the second rib costal cartilage). This point is within the right atrium and essentially remains within the right atrium regardless of the incline of the patient’s head and torso from the supine position. In reality, changes in the angle of the patient’s position do have a small effect on CVP measurements because of changes in the position of the heart in the chest (and hence the CVP zero point) relative to the anatomic landmark used to set the transducer’s external reference point. Given these variations, Magder recommends the midaxillary-fourth intercostal space be used only when the patient is supine. Whatever technique used, the importance of an agreed upon zero point and consistent, identical leveling of the transducer by all staff cannot be overstated. In a recent study, Figg and Nemer-gut tested 50 health care providers (registered nurses, anesthesiology residents,
and anesthesiology attendings) as they placed a CVP transducer at a specified level on the same mock patient in three patient positions (supine, 30 degrees head up, and 15 degrees head down). At a repeat session 6 months later, the same 50 health care providers repeated the exercise on the same mock patient in the same three patient positions but now were given a laser level to identify anatomic landmarks and place the transducer at the proper level. The results of the study were revealing. The initial session resulted in variations in zero-level positioning that corresponded to standard deviations in CVP measurements of 3.2, 4.8, and 3.2 mm Hg in the supine, 30 degrees head up, and 15 degrees head down positions, respectively. Even more revealing, the repeat test using laser levels showed no change in the variance of the positioning, with corresponding pressure measurement standard deviations of 2.9, 4.3, and 2.6 mm Hg, respectively. The investigators concluded that hospital-wide standardization of appropriate zero-point levels and staff education are required to minimize systematic errors in CVP measurement from interprovider variability.

The Effects of the Respiratory Cycle

The effects of the respiratory cycle must be considered when determining CVP (and Ppao). During spontaneous inspiration, the CVP falls as the pleural pressure declines relative to the external atmosphere and, during positive pressure ventilation, CVP rises as pleural pressure increases with inspiration. Hence, a respiratory variation is seen in CVP and Ppao measurements. However, the relevant pressure for determining intravascular volumes (such as preload) is the transmural pressure. Thus, it is the difference between the intravascular and the extravascular (ie, pleural) pressure that correlates with volume. Given the complexity and impracticality of determining pleural pressure (various approaches have involved measuring intraesophageal pressures or measuring variations in Ppao in patients with pulmonary artery catheters), hemodynamic pressures such as CVP and Ppao are measured at end-expiration when the pleural pressure is closest to zero relative to atmosphere (the reference point for all hemodynamic catheter measurements) and intravascular pressure most closely approximates transmural pressure. Even this technique is imperfect, however, because positive end-expiratory pressure (PEEP) (both intrinsic and extrinsic), active expiration, pericardial fluid or mediastinal edema, and increased intra-abdominal pressure (IAP) will alter pleural pressure in ways that are difficult to quantify. Theoretically, assuming chest wall (C_w) and lung compliance (C_L) are known, the proportion of airway pressure (P_{aw}) transmitted to pleural pressure (P_{pl}) is given by P_{pl} = P_{aw}(C_L / C_L + C_w). In practice, when considering PEEP (ie, P_{aw} at end expiration), some comfort may be taken from the fact that approximately half of the airway pressure in normal lungs is transmitted to the pleural space; in diseased lungs (stiffer, less compliant lungs) less than half is transmitted. Thus, in diseased lungs, especially when ventilated with low lung volumes and low levels of PEEP, the increase in end-expiratory CVP (and in the approximation of transmural pressure) is likely to be small: less than 4 to 5 cm water at a total PEEP of 10 cm H_2O. Higher PEEP levels will have a greater effect but, even then, the magnitude will depend on the percentage of pressure transmission: with low lung compliance the heart may or may not see much transmitted pleural pressure and even that amount may vary in the respiratory cycle as lung recruitment around the heart occurs. Even more concerning is the effect of active expiration. Active use of the muscles of the thorax and abdomen by a ventilated patient during expiration, particularly if the patient actively expires throughout the whole expiratory cycle (as opposed to active force only at the beginning of the cycle with passive flow for the remainder) will result in a pleural pressure that is elevated above atmospheric pressure throughout expiration. Hence, at no point in
the respiratory cycle (and definitely not at end-expiration) will the pleural pressure be close to zero. In such instances, which are common in ventilated patients, an accurate measurement of CVP cannot be made. A similar effect is seen with IAP, in which investigators have demonstrated the transmission of IAP to the chest and quantified its effects on end-expiratory measurements of CVP and even intracranial pressure. Indeed, taking this effect into account and applying it to the previously discussed problem of forced expiratory efforts confounding CVP determination, Qureshi and colleagues demonstrated that in spontaneously breathing patients with active expiratory effort, subtracting the respiratory change in IAP from the end-expiratory CVP corrects for the expiratory effort and gives an accurate estimation of transmural pressure. In short, just as both lung and chest wall compliance affect the pleural pressure, so does the abdominal compliance, and efforts to measure end-expiratory CVP as a guide to resuscitation must take into account elevated IAP. Finally, it should be noted that measuring hemodynamic pressures such as CVP and Ppao at end-expiration requires the interpretation of pressure tracings. Although arguably the most accurate measure of transmural pressures is through pressure tracings, such readings have been shown to have high interobserver variability and require expertise for proper assessment. Because of these challenges, many practitioners use the mean pressures obtained over the respiratory cycle, calculated by software in the transducer’s computer system and displayed on the monitor. This approach avoids the problems of interobserver variability and the difficulties of tracing interpretation. However, there is the risk of allowing artifacts from the respiratory and cardiac cycles to skew the measurements.

**Effects of the Cardiac Cycle**

The cardiac cycle also affects the proper measurement of CVP and Ppao. Just as the optimal measurement of CVP and Ppao should be performed at end-expiration, the relationship of ventricular diastole and systole should be considered when interpreting CVP (and Ppao) pressure tracings. The normal CVP waveform contains three waves: a, corresponding to atrial contraction during ventricular diastole; c, corresponding to the bulging of the tricuspid valve into the right atrium during right ventricular systole (isovolumic contraction); and v, corresponding to venous filling of the right atrium during late ventricular systole while the tricuspid valve is closed. When the CVP is measured to estimate preload, the pressure just at the onset of the c-wave (the base of the c-wave) represents the final atrial pressure (and the ventricular end-diastolic pressure) before closure of the tricuspid valve and the beginning of ventricular systole. Thus, when measured at end-expiration, the base of the c-wave yields the CVP measurement that best represents the transmural end-diastolic pressure, or preload. As the c-wave is not always visible, the base of the a-wave may be used instead as an estimator; alternatively, the R-wave of the EKG on the monitor may be used to find the end of diastole or beginning of systole on the CVP tracing. Again, although more representative of transmural pressures, measurements from pressure tracings are subject to interobserver variability and are more difficult to obtain than the mean pressure.

**Physiologic and Anatomic Properties of the Heart**

Physiologic and anatomic properties of the heart affect the CVP. Changes in right-ventricular compliance (such as from heart failure or acute myocardial infarction) and venous tone (eg, hyperadrenergic states), or conditions such as pulmonary hypertension, may have profound effects on CVP independent of the patient’s intravascular volume status. Additionally, valvular disorders, such as tricuspid insufficiency, “ventricularize” the CVP waveform, resulting in an elevated mean CVP; careful pressure...
waveform reading before the ventricularized v-wave (ie, before the regurgitant systolic wave, best marked by the time of the EKG R-wave) is necessary to obtain an accurate CVP. Similarly, tricuspid stenosis elevates the mean CVP, resulting in a gradient between the RAP and the RVEDP. To illustrate just how fine the distinction between a pathologic CVP and a CVP indicative of normovolemia can be, Magder and colleagues demonstrated that a y-descent greater than 4 mm Hg correlated with a low likelihood of response to a fluid bolus, indicating a volume-loaded ventricle, while the loss of the y-descent (along with the loss of the x-descent) is a sign of tamponade.

Like CVP, which measures RAP as a surrogate for RVEDP and RVEDV, Ppao measures left atrial pressure as a surrogate for left ventricular end-diastolic pressure and volume (LVEDP and LVEDV). The pulmonary artery catheters (PA catheters) used for such measurements entail additional risks in their use above those of standard central venous catheters. However, they enable the measurement not only of Ppao but also CVP and CO; more modern catheters even allow determination of RVEDV and right ventricle ejection fraction (RVEF). Nevertheless, measurements of Ppao through PA catheters are subject to the same complicating factors already discussed for CVP measurements: much as the CVP is a reflection of RAP, the Ppao is a “delayed, damped reflection of left atrial pressure.” Hence, Ppao will be affected by the respiratory and cardiac cycles and by anatomic or physiologic factors (eg, mitral regurgitation and mitral stenosis; compliance changes from hypertrophy or ischemia; elevated pleural pressure from PEEP or forced expirations) in the same manner as the CVP (eg, the complexities of PEEP and the difficulty in determining its transmission to pleural and pericardial pressures). Attempts to more accurately measure Ppao in the face of hyperinflation secondary to PEEP led to measuring Ppao at end-expiration while the airway was briefly (<3 seconds) disconnected. Assuming no airway obstruction, the lung rapidly returns to its resting functional residual capacity, and the subsequently measured “nadir Ppao” provides an accurate measurement of the on-PEEP LVEDP when total PEEP is less than 15 cm H₂O. In addition to the obvious inconvenience of transient airway disconnection, the subsequent alveolar collapse after disconnection argues against this technique (Teboul and colleagues subsequently developed a corrective index of transmission I₇ that allowed an estimation of transmural Ppao without airway disconnection). Also, accurate measurement of Ppao usually requires that the tip of the PA catheter lie within West zone 3 of the lung where CVP exceeds alveolar pressure, otherwise Ppao will reflect alveolar pressure rather than LAP. Even a properly positioned PA catheter, however, only reflects LAP and not capillary pressure; that is, Ppao does not equal pulmonary capillary pressure. True pulmonary capillary pressure can be determined from the inflection point of the Ppao curve after balloon inflation as the measured occlusion pressure drops through the pulmonary arterial and pulmonary venous resistances in series. Its clinical significance serves as another warning of the complexities of Ppao: in conditions such as acute respiratory distress syndrome, increased pulmonary venous resistance can result in elevated pulmonary capillary pressures with low Ppao pressures, resulting in pulmonary edema in the face of a low Ppao.

Putting aside the difficulties inherent in the accurate measurement of CVP and Ppao, the larger problem of their usefulness as measures of preload and as predictors of fluid responsiveness is a separate question. In a prospective observational study of 83 patients admitted to a medical-surgical ICU, most of whom were nonseptic patients after cardiac surgery and all of whom had a PA catheter inserted, Magder and Bafaqeeh investigated fluid responsiveness over a range of CVP values in an attempt to identify a threshold CVP above which volume expansion was unlikely to increase cardiac output. Using fluid challenges that increased CVP by at least 2 mm
Hg (measured exclusively by pressure tracings from carefully zeroed and leveled transducers), a response was defined as an increase in CO of 300 mL/min/m² or more. Of the 66 patients in whom the CVP increased by at least 2 mm Hg with fluid challenges, there were 40 responders and 26 nonresponders. No patient responded when the CVP was greater than 13 mm Hg. Only 3 of the 12 patients with an initial CVP greater than 10 mm Hg responded to fluids on their first trial. Nonresponders, however, were identified at all initial CVP levels. They concluded that a CVP of greater than 10 mm Hg (measured with a transducer leveled 5 cm below the sternal angle) indicates a low likelihood of improving CO in response to fluid challenge, with the caveat that nonresponders will still be found at CVPs less than 10 mm Hg. Hence, CVP is best viewed as a negative predictor of fluid responsiveness. Similarly, Jellinek and colleagues showed that, in response to increasing PEEP challenges, a CVP less than 10 mm Hg predicted a decrease in cardiac output. However, the response in patients with a CVP greater than 10 mm Hg was unpredictable: increases, decreases, and no changes in CO were observed. Thus, CVP as a predictor of CO change in response to PEEP challenge functioned as a "one-way" test.

Further evidence against the utility of CVP measurements comes from a recent meta-analysis of 24 studies incorporating 830 medical and surgical patients that examined both CVP and changes in CVP as predictors of intravascular blood volume and fluid responsiveness. None of the studies calculated transmural pressures, factored in PEEP, or used end-expiratory pressure tracings in their determinations of CVP; mean pressures were used as is common practice in most clinical settings. In none of the studies was CVP able to predict either blood volume or fluid responsiveness. The pooled correlation coefficient between the CVP and intravascular blood volume (5 studies) was 0.16 (95% CI, 0.03–0.28); between CVP and stroke index (10 studies) was 0.18 (95% CI, 0.08–0.28); between change in CVP and stroke index (7 studies) was 0.11 (95% CI, 0.01–0.21); and the pooled area under the ROC curve (AUC) of CVP and fluid responsiveness (10 studies) was 0.56 (95% CI, 0.51–0.61). The AUC of CVP for predicting fluid responsiveness effectively suggests that CVP is barely better than a coin toss.

Multiple studies have examined Ppao as a predictor of fluid responsiveness and preload over the prior 3 decades. In 2002, Michard and Teboul reviewed 12 studies examining both static and dynamic measures of preload as predictors of fluid responsiveness in ICU patients, 9 of which included pulmonary artery occlusion pressures (all measured at end-expiration without adjustment for PEEP). Although the studies used different criteria and protocols for volume expansion, in 7 studies the preinfusion, baseline Ppao was not significantly lower in responders versus nonresponders. Of the 3 studies finding a difference in Ppao before and after volume infusion, 1 study found a higher preinfusion Ppao in responders compared with nonresponders and a poor correlation \( r = 0.42 \) between Ppao and cardiac index (CI). In the other 2 studies, preinfusion baseline Ppao was found to be lower in responders than nonresponders, with Tousignant and colleagues finding no correlation between Ppao and SV \( (r = 0.15) \) after fluid challenge, while Wagner and Leatherman identified a moderate \( (r = 0.58) \) negative correlation between change in SV and Ppao. None of the studies were able to identify a clear Ppao threshold value that predicted fluid responsiveness. More recently (2007), Osman and colleagues retrospectively analyzed prospective data on 150 fluid challenges in 96 patients with severe sepsis. Defining a response as a 15% or greater increase in CI, responders and nonresponders showed increases in Ppao and CVP after fluid challenge, with a baseline (preinfusion) Ppao difference that was slightly but statistically significantly lower in the responder group. The optimum threshold value of a preinfusion Ppao of less than 11 mm Hg
predicted fluid responsiveness with a sensitivity of 77% (95% CI, 65%–87%), a specificity of 51% (95% CI, 40%–62%), a positive predictive value of 54%, and a negative predictive value of 74%. The AUC was only 0.63 (95% CI, 0.55–0.70).

Further difficulties with Ppao and CVP as predictors of fluid responsiveness were demonstrated by Kumar and colleagues in a prospective study of 45 healthy normal volunteers. Using PA catheterization, radionuclide cineangiography, and volumetric echocardiography, they assessed ventricular filling volumes, cardiac performance, and fluid responsiveness during 3 L of normal saline infusion over 3 hours. They demonstrated no predictable relationship between Ppao or CVP and volumetric preload indexes (RVEDVI and LVEDVI) or cardiac performance measures (CI and SV index [SVI]). In addition, increases in neither Ppao nor CVP predicted the response of either SVI or end-diastolic volume-to-volume expansion.

The interplay of anatomic and physiologic characteristics of the heart, coupled with the effects of the respiratory cycle and the cardiac cycle on the measurement of Ppao (and CVP) complicates the use of static pressure measurements to predict fluid responsiveness. Pinsky highlights some of the underlying problems with Ppao: (1) the nonlinear relationship between Ppao and preload (LVEDV) and its variation among subjects implies that no set Ppao, or change in Ppao, can reliably predict a specific preload or change in preload; (2) the effect of juxtapericardial and pleural pressures such as forced expiration, tamponade, and PEEP; and (3) changes in compliance of the left ventricle from ischemia and arrhythmias or, in the right ventricle, from pulmonary embolus or acute onset pulmonary hypertension, all of which can have a rapid onset. Hence, the complex physiology of the cardiothoracic system conspires against predicting its function from isolated, static pressure measurements.

VOLUMETRIC MEASUREMENTS: CONTINUOUS RVEDV AND GEDV

The practical measurement of preload via volumetric techniques began in the 1980s. Bing and colleagues first proposed the idea of quantifying right ventricular volume by indicator dilution in 1951. The mounting of fast-response thermistors on PA catheters allowed the measurement of beat-to-beat pulmonary artery temperature changes from a cold injectate or, in the current generation of devices, a heated filament that emits a pulse of thermal boluses. Regardless of the technique, the resultant thermodilution allows the measurement of SV, CO, and RVEF. RVEDV is then calculated from RVEF and SV. That RVEDV is calculated from SV and, hence, CO gives rise to the possibility of “mathematical coupling,” in which a significant portion of any correlation between RVEDV and CO may arise from a computational, as opposed to a truly physiologic, relationship.

Multiple investigators have assessed RVEDV and its index RVEDVI as measures of preload and predictors of fluid responsiveness. Diebel and colleagues in a study of 29 patients with trauma or sepsis found that RVEDI correlated with CI significantly better than Ppao and was a far better predictor of fluid responsiveness and failure to respond than Ppao. In a second study of 32 critically ill trauma patients with a more stringent definition of fluid responsiveness (an increase in CI of at least 20% as opposed to 10% in their earlier study), Diebel and colleagues again found RVEDVI to be superior to Ppao in predicting fluid responsiveness, with RVEDVI cutoff values of less than 90, 90 to 140, and greater than 140 mL/m² predicting fluid responsiveness in 64%, 27%, and 0%, respectively, of test subjects.

Durham and colleagues similarly compared RVEDVI and Ppao and found a better correlation between RVEDVI and CI than Ppao and CI, even after correcting for mathematical coupling. They also constructed ventricular function curves for each patient...
and established that RVEDVI was a better clinical indicator of preload than Ppao. Cheatham and colleagues studied the effects of PEEP on RVEDVI, Ppao, and CI in mechanically ventilated patients. They concluded that there was a higher correlation between RVEDVI and CI than between Ppao and CI at all PEEP levels. Wiesenack and colleagues recently evaluated RVEDVI, Ppao, and LVEDA index (LVEDAI; measured with transesophageal echocardiography [TEE]) in patients undergoing elective cardiac surgery and found RVEDVI to more reliably reflect preload than Ppao or LVEDAI; however, RVEDVI did not predict fluid responsiveness. LVEDAI did correlate with fluid responsiveness (change in SV index), but only weakly ($r^2 = 0.38, P<.01$). In another recent multicenter study involving liver transplantation, Della Rocca and colleagues showed that RVEDVI better reflected preload than CVP and Ppao, and they were able to demonstrate an increase in SVI of 0.25 mL/m$^2$ for an increase in RVEDVI of 1 mL/m$^2$. No strong correlation between SVI and CVP or Ppao was noted. Della Rocca and colleagues again investigated RVEDVI in liver transplant patients, this time including LVEDAI via TEE in addition to CVP and Ppao. Both RVEDVI and LVEDAI demonstrated a superior correlation with SVI then either CVP or Ppao, although only RVEDVI reached statistical significance, with an increase in SVI of 0.21 mL/m$^2$ for each increase of 1 mL/m$^2$ in RVEDVI.

GEDV and GEDV index (GEDVI), and the closely related intrathoracic blood volume and index (ITBV and ITBVI), are another set of volumetric estimates of cardiac preload. Using a thermistor-tipped arterial catheter (usually placed in the femoral artery) and a central venous catheter (subclavian or internal jugular) devices such as the PiCCO system (Pulsion Medical Systems, Germany) allow the measurement of GEDVI and ITBVI via single-indicator transpulmonary thermodilution from a cold injectate of saline through the central venous catheter (earlier versions of the technique used a plasma-bound indicator dye in addition to the temperature injectate and were thus known as double-indicator dilution techniques). The GEDV measures the largest volume of blood in the four chambers of the heart. The ITBV is the GEDV plus the volume of blood within the pulmonary vessels. In addition to such measures of preload, the PiCCO also provides a continuous pulse contour-derived CO and an estimation of extravascular lung water.

Numerous investigators have studied GEDVI and ITBVI as measures of preload and predictors of fluid responsiveness. In an article by Della Rocca and colleagues, 18 studies comparing GEDVI or ITBVI with CI or SVI in diverse patient populations (eg, neurosurgery, cardiac surgery, abdominal and laparoscopic surgery, and intensive care patients) were examined. In all of these studies, ITBVI was a better measure of cardiac preload than CVP or Ppao. The question of mathematical coupling arises again, given that GEDV and CO are derived from the same thermodilution curve. Evidence to the contrary however was provided by Michard and colleagues in a study of 36 patients with septic shock. GEDVI and CVP were compared with SVI and CI in separate series of fluid challenges and dobutamine infusions. GEDVI, CVP, SVI, and CI significantly increased after volume loading, and the changes in GEDVI were correlated with changes in SVI whereas changes in CVP were not. Moreover, after dobutamine infusion SV increased as expected but no increase was seen in GEDVI, thus arguing against mathematical coupling as the cause of the correlation between GEDVI and SVI. The good correlation between changes in GEDVI and changes in SVI was also confirmed by Hofer and colleagues in a study of 20 elective cardiac surgery patients in whom RVEDI (via modified PA catheter) and LVEDAI (via TEE) were also monitored. Changes in GEDVI correlated with changes in SVI better ($r^2 = 0.576$) than changes in RVEDI correlated with changes in SVI ($r^2 = 0.267$).
Overall, the use of transpulmonary thermodilution-derived indices such as GEDVI and ITBVI appear to correlate better with preload and changes in CO or SVI than traditional pressure measurements. Even so, the correlations are generally moderate. Whether this imperfect correlation is due to rapid changes in cardiovascular physiology during illness or is due to flaws in the assumptions underlying thermodilution-derived volumetric measurements requires further study. Furthermore, the use of the PiCCO may be precluded by patient factors known to interfere with transpulmonary thermodilution, such as valvular disease or a thoracic aneurysm (which increases transit time) or by contraindications to the placement of a femoral arterial catheter, in which case the axillary artery is an alternative site.

SUMMARY

The use of static preload measurements should be approached with a careful appreciation of the weaknesses inherent in their measurement and their ability to reflect both preload and volume responsiveness. Given that volume responsiveness is the usual clinical question at hand, it is not simply the preload but also the underlying ventricular function that will determine where the patient’s position on their Frank-Starling ventricular function curve and, hence, the patient’s response to a fluid challenge. Later articles in this issue will address more advanced, dynamic methods of preload assessment and volume responsiveness. However, at the bedside, the most readily available methods still remain pressure-derived preload assessments, particularly the CVP. The proper interpretation and use of such measures, coupled with an understanding of their limitations and knowledge of alternative methods, is necessary to guide properly volume resuscitation in the critically ill.

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