Invasive Hemodynamic Monitoring

Sheldon Magder, MD

KEYWORDS

• Cardiac output • Central venous pressure • Pulmonary artery catheter
• Pulmonary artery occlusion pressure • Pulmonary pressure

KEY POINTS

- Proper use of invasive monitoring must begin with careful attention to the details of making the measurements and making the measurements safely.
- A useful start in managing hypotension is to consider whether the problem is a cardiac output problem or a systemic vascular resistance problem.
- If the cardiac output is the primary problem, the next question is whether this is due to a cardiac function problem or return problem (venous return).
- Measurements of cardiac output and central venous pressure are central to separating these possibilities.
- Trends in cardiac output and central venous pressure are more useful than static measures.
- Pressure tracings can provide diagnostic information beyond the simple hemodynamic measures, including indications of pulmonary function.

INTRODUCTION

The use of invasive hemodynamic monitoring has decreased significantly over the past 2 decades. An important likely factor is failure to find an effect on outcome in an evidence-based medicine driven approach to patient management.[1] However, lack of evidence of benefit does not mean that there is no benefit. Studies on the use of pulmonary artery catheters (PACs) have been limited by lack of algorithms that can show their usefulness, lack of precision in making the measurements, and lack of physiologic rationale of what actually can be fixed based on the information obtained.[2–5] Invasive monitoring also requires a greater skill set on the part of the practitioner, yet studies have shown a striking lack of knowledge of the measurements obtained with the PAC.[6,7] Another issue is the risks associated with insertion of the

Disclosure: None.
Department of Critical Care, Royal Victoria Hospital, McGill University Health Centre, 687 Pine Avenue West, Montreal, Quebec H3A 1A1, Canada
E-mail address: sheldon.magder@muhc.mcgill.ca

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catheter. However, a major component of such risks is the insertion of a central venous line, which needs to be inserted anyway in most critically ill patients to allow infusion of vasoactive drugs. Furthermore, less invasive devices are not necessarily noninvasive and carry risks of their own, including cannulation of brachial or femoral arteries, which are more invasive than the simple insertion of radial artery catheters. In general, the less invasive the device the less accurate, precise, and reliable it is. Less invasive devices cost more than the simple PAC and the information they give also is more limited. Although the complexity of clinical problems makes it difficult to rigorously establish a role for PACs in randomized trials, the author's sense is that there will likely remain a place for their use in complex patients who are difficult to manage. However, use of PACs requires knowledge of how to use them properly. This article begins with a short review of the basic physiology that determines cardiac output and blood pressure, thus to understand how the measurements obtained can be used for both diagnosis and direct management. Data from a PAC only can be useful if properly measured, so the basics of making such measurements are reviewed. Use of the PAC in making a diagnosis and for management is addressed; these are not the same, and the emphasis is on the use of a responsive approach to management. Finally, the author explores uses of the PAC that are not indications by themselves for placing the catheter, but can provide useful information when a PAC is in place.

Purpose of the Circulation

The primary purpose of the circulation is to deliver the appropriate amount of oxygen and nutrients to the tissues to meet their needs and to remove wastes. The delivery of oxygen (D_{O_2}) is determined by the product of cardiac output (Q), hemoglobin concentration ([Hgb]), and the saturation of hemoglobin, which in turn is determined by the partial pressure of oxygen (P_{O_2}) and a constant (*K*) that gives the O_2-carrying capacity of hemoglobin:

$$D_{O_2} = Q \times [Hgb] \times O_2 \text{ saturation} \times K$$

Values for *K* used in the literature vary from 1.34 to 1.39. Isolated pure hemoglobin carries 1.39 mL O_2 per gram, but blood also has methemoglobin and carboxyhemoglobin so that lower empiric values for *K* are used for determining the oxygen content in blood. This simple equation indicates that only 3 variables can increase or decrease D_{O_2}. The range of manipulation of hemoglobin is usually not large, and that of saturation even less. For example, an increase in arterial O_2 saturation from 85% to 100% only increases D_{O_2} by 18% and increases [Hgb] from 90 to 100 g/L by 11%. It should thus be evident that cardiac output is the primary variable that can be manipulated for making major changes in D_{O_2}.

Regulation of Cardiac Output

Cardiac output is determined by the interaction of cardiac function and a function that defines the return of blood to the heart (venous return function) (**Fig. 1**).[8,9] A key implication of this statement is that the heart only can pump out what comes back to it. In turn, this is primarily determined by the properties of venous drainage back to the heart because almost 70% of blood volume is in small systemic veins and venules.[10] By stretching the small veins and venules, this volume creates an elastic recoil pressure that drives flow back to the heart through the small resistance that separates the venous reservoir from the right heart.[8,9] In this analysis arterial blood pressure does not have a significant impact on the return of blood to the heart, for it is the volume

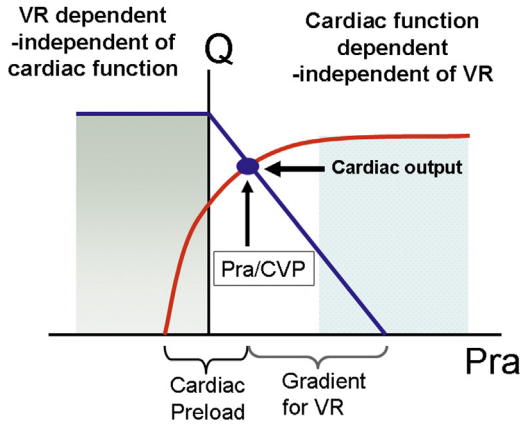

Fig. 1. Cardiac output and right atrial pressure (Pra) are determined by the interaction of cardiac function and return function (venous return [VR]). On the flat part of the cardiac function curve, cardiac output is independent of VR. On the flat part of the VR curve, cardiac output is independent of cardiac function. CVP, central venous pressure.

per minute filling the veins and venules rather than the arterial inflow pressure that determines venous emptying. Changes in cardiac function increase or decrease cardiac output by regulating right atrial pressure and allowing more or less blood to return per beat. When cardiac function increases, the same cardiac output can occur with a lower right atrial pressure. This "permissive" action increases the gradient for venous return, and allows more blood to come back to the heart and to be pumped out. Cardiac function is increased by an increase in heart rate, increase in contractility, or decrease in afterload, which is essentially the arterial pressure in the main pulmonary artery and aorta. The cardiac function curve is also limited by the maximum end-diastolic volume.[11] In the right heart this occurs in most people at a right atrial pressure of 10 to 12 mm Hg (when measured by a fluid-filled pressure transducer whose zero pressure reference is made 5 cm vertical distance below the sternal angle),[12] and once this limit is reached, further increases in preload do not increase cardiac output and an increase in cardiac function is required to increase cardiac output. The maximum potential for increases in cardiac function to increase cardiac output occurs when the right atrial pressure is at or below atmospheric pressure when breathing is spontaneous. However, during positive pressure ventilation, pleural pressure is greater than atmospheric pressure so that right atrial pressure rises with pleural pressure and decreases the pressure gradient for venous return. The range of right ventricular preloads that can alter cardiac output, estimated as right atrial pressure, is small, ranging from 0 to 10 mm Hg in most people. Thus, large increases in cardiac output also require adjustments in the venous return function that are discussed next.

The determinants of venous return are the stressed vascular volume, the resistance draining the venous compartment (venous resistance), the compliance of veins and venules, and the outflow pressure of the venous system, which is the right atrial pressure.[9] Stressed volume refers to the volume that actually stretches the elastic walls of blood vessels. Under resting conditions only about 30% of blood volume, or approximately 1.3 to 1.4 L, actually does this.[13] The rest of the volume just fills out the vessels and is "unstressed." Neural-humeral mechanisms can tighten vessels and convert unstressed volume into stressed volume. In someone who is volume replete, approximately 10 mL/kg to even as much as 18 mL/kg of unstressed volume can be

recruited into stressed volume by what is termed a decrease in capacitance.[10,14] A decrease in capacitance increases the upstream venous pressure and thereby increases venous return. To understand the magnitude of the effect of a decrease in capacitance on the circulation, 10 mL/kg in a 70-kg person would increase stressed volume by more than 50% and could increase cardiac output by almost 5 L/min if the heart was able to accommodate the increase in venous return. This recruitment of volume occurs through a reflex mechanism, and thus occurs in seconds. An increase in capacitance could equally reduce stressed volume very rapidly and decrease cardiac output. Unfortunately the important reserve of unstressed volume cannot be measured in an intact person, because it does not produce anything measurable. The use of a volume bolus in resuscitation acts in the same way as a decrease in capacitance. It increases the upstream venous pressure and thereby increases venous return. However, only volume that remains in the vasculature can serve this function. Increasing stressed volume increases capillary pressure, which increases capillary filtration. The net increase in intravascular volume is thus reduced, as is the potential of increasing stressed volume to maintain the transient increase in the venous return function.

A decrease in venous resistance also increases venous return, and does so without increasing upstream venous pressure. This mechanism is important for production of the high cardiac output that occurs during aerobic exercise,[15] but also likely contributes to the increase in cardiac output in septic shock.[16]

An increase in venous return function only can increase cardiac output if the heart is functioning on the ascending part of the cardiac function curve; this, too, greatly limits how much can be achieved by giving fluids. When the right heart becomes volume limited, only an increase in cardiac function can result in an increase in cardiac output (see **Fig. 1**).

Safety Issues

Attention to safety can reduce potential harm with the use of a PAC. This article deals with some important specific issues. Insertion of central venous lines and PACs needs to be done under sterile conditions[17,18] including the use of gown, gloves, face-mask, and sterile drapery that completely covers the patient. The balloon on the catheter should be inflated ex vivo before insertion to ensure that it is intact and that it does not expand asymmetrically. The displayed distal tip vascular pressure and the associated electrocardiogram (ECG) rhythm must be carefully watched on the bedside monitor for arrhythmias and changes in vascular pressure while the catheter is floated through the heart with the balloon inflated, along with immediate awareness of the amount of catheter inserted in centimeters. Because the wave patterns indicate where the end of the catheter is located, it is essential to know what these waveforms should look like as the tip passes from the vena cava through the right heart and into the pulmonary artery (**Figs. 2–4**). Before starting PAC insertion, it is important to ensure that the transducer sensing this pressure is leveled properly so that pressure is measured relative to a standard reference level. If an arrhythmia occurs during placement, and the catheter has to be rapidly pulled out, this may be the only measurement obtained. On a practical level, gently shaking the catheter and noting the paired sinusoidal pressure response on the monitor is useful for validating that the pressure is being seen on the monitor and that the gain on the monitor is appropriately set for the patient's expected hemodynamic values. PAC insertion is usually done through an internal jugular access point, using a specially modified catheter sheath that can continually infuse fluids through a side port while allowing PAC insertion through the central lumen. On insertion, the pressure waveform

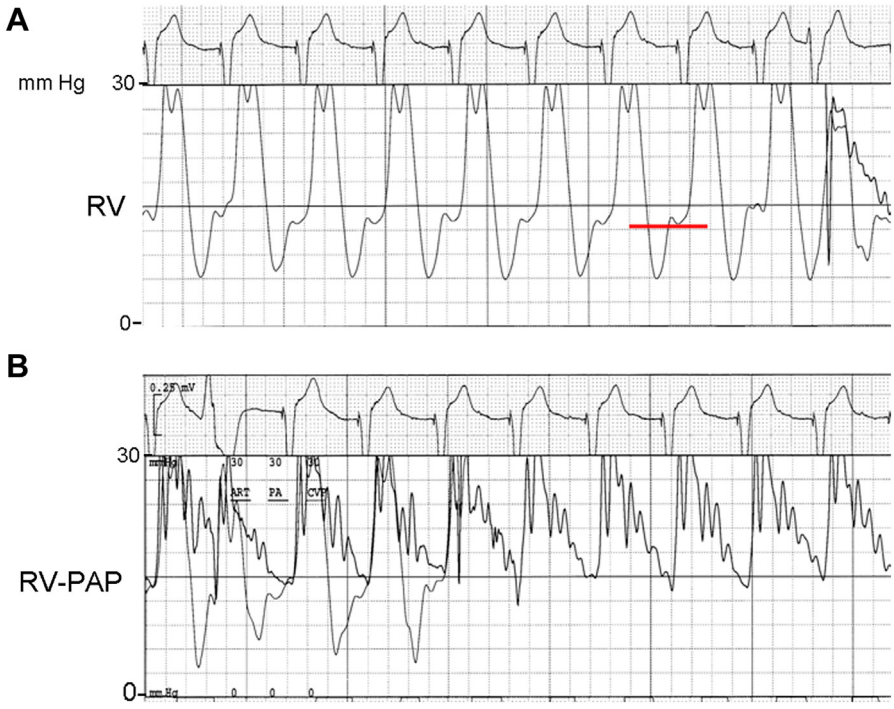

Fig. 2. Right ventricular (RV) (*A*) and pulmonary artery tracing (*B*) in a spontaneously breathing subject. The rhythm, top row of *A* and *B*, is sinus with atrial sensing ventricular pacing. The horizontal line in *A* indicates the preload of the right heart. The first 4 beats of *B* show both RV and pulmonary artery pressure (PAP) tracings and then only PAP. The second beat is a ventricular ectopic.

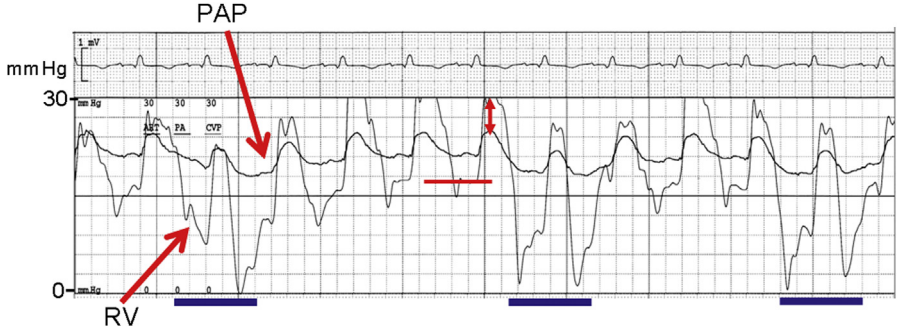

Fig. 3. Simultaneous RV and pulmonary artery tracings obtained by advancing the PAC so that the proximal port is in the right ventricle. The RV diastolic pressure is almost 18 mm Hg (*horizontal line*) and has a marked respiratory variation. There is a pressure gradient between the peak systolic RV pressure and PAP pressure (*shown by double arrow*), which is especially apparent during expiration. The subject had a heart transplant, and the gradient is likely because the pulmonary artery anastomosis was too tight.

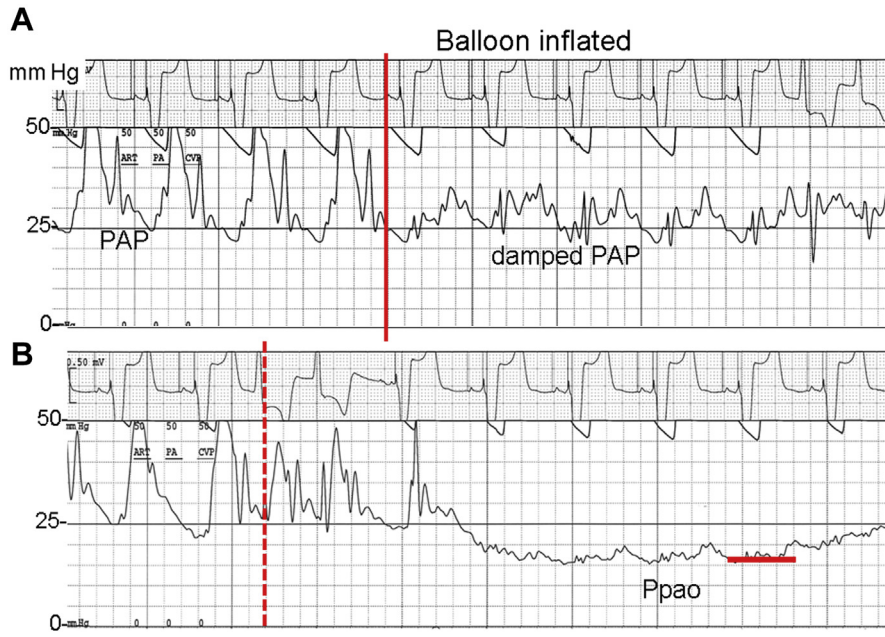

Fig. 4. Pulmonary artery and pulmonary artery occlusion pressure (Ppao). (*A*) The balloon of the PAC is inflated and the wave may appear to be a Ppao, but is actually a "damped" PAP. (*B*) The trace again starts with PAP, and the balloon is inflated at the vertical dotted line; the PAP dampens in the next 3 beats and then finally occludes the pulmonary artery and gives the true Ppao. The horizontal line shows where to measure Ppao (16 mm Hg).

changes into a low-pressure but spiked waveform signal on entering the right atrium. At around 30 cm in average-sized adults, the tricuspid valve is passed and a right ventricular pressure tracing is seen. If the right ventricular pressure recording does not occur following a right atrial pressure recording, the catheter may be coiled in the right atrium or may have passed down the inferior vena cava. Extreme care during insertion must be taken to prevent excess insertion for coiling of the catheter can occur, with the risk of creating a knot in the catheter that makes removal difficult. The pulmonary artery is usually reached by 40 to 45 cm and the pulmonary artery becomes occluded by the balloon (pulmonary artery occlusion pressure [Ppao]) from around 45 to 55 cm, although this can occasionally be farther if the right ventricle is very large. Insertion of the PAC much beyond these length limits again increases the risk of tangling the catheter. Once properly placed and noting that occlusion can be performed, a chest radiograph needs to be performed. A useful practice is to allow the tip of the catheter to remain within the mediastinal shadow because of the risk of pulmonary artery rupture if the PAC tip is farther out and continually striking the pulmonary arterial wall with each contraction. Occasionally this may mean that an occlusion pressure cannot be obtained in this new position. If so, selective readvancement of the PAC during times when Ppao measures are needed is a reasonable option, returning the PAC back to its withdrawn position afterward. Because the Ppao is more useful for diagnostic purposes than to titrate therapy, its measurement does not need to be made often. Furthermore, Ppao can be related to the pulmonary diastolic pressure, and trends in the pulmonary diastolic pressure can then be followed unless a more precise Ppao is needed. If the PAC is inserted beyond

55 cm, one should be especially careful to ensure that there is not a double loop in the right atrium by looking at the chest radiograph. Finally, the PAC balloon should never be left inflated if not being used for balloon inflation PAC insertion or for the measurements of Ppao.

PRESSURE MEASUREMENTS

Measurement of pressure requires care because there are many sources of error and artifacts.[19] Three things always must be considered when measuring pressure: zeroing, leveling, and calibration. Pressure-sensing catheters are all filled with fluid. PACs are fluid-filled catheters with multiple lumens, all attached to transducers. The pressure transducers contain a conductive material surrounded by a series of resistors that ensures constant voltage across the material. This electrical circuit is called a Wheatstone bridge. A change in pressure on the surface of the material changes its electrical resistance, producing a measurable change in current. Application of known forces to the device are used to "calibrate" the relation between the current change in external pressure, such that the force of the vascular pressure applied on the surface of the sensor causes a change in current, which is linearly related to the change in pressure. This measurement setup introduces 3 potential errors, the first related to the background pressure, another to gain, and the final one to the force of gravity and the weight of the fluid in the system. We are surrounded by atmospheric pressure, which is not zero but 760 mm Hg and, thus, almost 8 times the magnitude of arterial pressure and close to almost 1000 times the central venous pressure in the upright position. However, because the outside perimeter of the body senses this atmospheric pressure equally, atmospheric pressure can be used as a reference background pressure; this is dealt with by opening the membrane of the transducer to the surrounding air and calling this value zero. Positive or negative pressure measurements then are deviations from this reference value. Unless one is in the middle of a hurricane, atmospheric pressure changes slowly and by small amounts, so that once the device is zeroed changes in atmospheric pressure do not affect short-term values. The electronics of modern devices also do not have a "drift" in the zero measurement that was common in older devices, although such electromechanical zero-balance drift still can occur if there is an electronic malfunction. Drift is easily identified by opening the transducer to air and observing if the value is or is not still zero. Once the sensor is zeroed, a fixed known pressure signal is applied to the pressure transducer and the observed increase in sensed pressure noted. Usually an electronic validated mock signal of 100 mm Hg is applied to the transducer. However, one could just as easily apply a column of water or mercury to the tip of the transducer and note the gain. Some monitors allow the gain of the system to be changed either up or down, so that the external pressure signal causes the defined reported pressure to change. Many modern systems do not allow this calibration to be done because the pressure transducers are calibrated by the factory. Nevertheless, a good monitoring service, such as an intensive care unit or operating room, should periodically test the accuracy of the calibration of their pressure transducers using external pressure-generating devices (eg, blood pressure cuff).

The third issue in measuring vascular pressure is leveling, and is also the most troublesome. When measuring pressure in fluid-filled systems, the fluid within the catheter lumen has a weight resulting from the force of gravity, and this force is proportional to the height of the fluid column and its density. The density of water is 1, and the density of blood is close to that value. The effect of the gravitational force can be large. In the upright posture, gravity adds a pressure to the veins in the feet

that is almost equal to mean arterial pressure.[20] The key point is that measurements in fluid systems are relative to where the properly zeroed transducer is placed. This decision is an arbitrary one, but in controlled physiologic studies the consensus is that this level should be at the mid-point of the right atrium, because at this location blood comes back to the heart before being ejected again.[21] This level can be approximated in an intact person by first identifying the sternal angle, which is where the second rib joins the sternum, then using a leveling device and dropping a line to 5 cm vertical distance from this point. This position is a good approximation in a person lying flat or sitting up to a 60° angle, because the right atrium is a relatively round structure and just below the sternum. There is some variation with body size and heart size, but at least always using a fixed point allows trends in values to be tracked whether the person is lying flat or is partially upright. More commonly the level is taken at the mid-axillary or mid-thoracic line in the fourth intercostal space. The advantage of this approach is that it does not require a leveling device. However, that may also be its disadvantage because the choice of this position is not done as carefully, resulting in greater variation among personnel. Measurement from the mid-axillary line also should be made with the patient supine, as the position of the mid-point of the right atrium moves relative to the mid-axillary line with changes in posture. In some situations, for example, in the operating room, one does not have a choice because the sternal angle and/or part of the surgical field is covered. On average, the mid-thoracic measurement is 3 mm Hg greater than the sternal angle–based approach, but the exact difference depends on chest size.[12] In this article the sternal angle–based reference is used for measurements.

The major energy producing the pressures that are important in hemodynamics is elastic energy. This force stretches the walls of the cardiac chambers and vessels, and determines filtration across capillary membranes. Moreover it creates a pressure difference between the inside and outside elastic structures, called transmural pressure. For structures that are not in the chest the pressure outside their walls is atmospheric pressure, which is zero (see earlier discussion). Thus the measured pressure with a transducer zeroed to atmosphere is the transmural pressure (inside pressure minus zero). However, if the surrounding pressure is greater than zero then actual pressure distending a vessel is less than intramural pressure alone. For example, under conditions of increased intracranial pressure following head trauma, cerebral perfusion pressure is mean arterial pressure minus intracranial pressure, not mean arterial pressure alone. Similarly, if intra-abdominal hypertension develops, intra-abdominal organ perfusion pressure will be mean arterial pressure minus intra-abdominal pressure. The same is true for structures inside the chest, as they are surrounded by pleural pressure, and pleural pressure can vary widely during breathing and with the application of positive end-expiratory pressure.[19,22] At resting end-expiration, referred to as functional residual capacity, the recoil of the lung inward and the chest wall outward produces a pleural pressure that is negative relative to atmospheric pressure. During spontaneous breaths pleural pressure falls further relative to atmospheric pressure owing to active chest wall expansion by the respiratory muscles, and during positive pressure breaths and the application of positive end-expiratory pressure (PEEP), pleural pressure increases relative to atmospheric pressure as a function of both lung and chest wall compliance. Thus, vascular pressures measured with standard pressure transducers no longer represent intrathoracic vascular transmural pressure. There is no simple way to eliminate this problem, but it can be minimized by always making intrathoracic vascular pressure measurements at the end of expiration (which is the same as pre-inspiration), because at this point pleural pressure is closest to atmospheric pressure. However, if a patient is receiving

high levels of PEEP, end-expiratory pleural pressure may be elevated and the vascular pressure value seen on the monitor will overestimate the transmural pressure. In normal subjects, with normal lung and chest wall compliance, a little less than half of the airway pressure is transmitted to the pleural space, meaning that with a PEEP of 5 cm H_2O less than 2 mm Hg is transmitted to the pleural space. The stiffer the lung, the less the transmission of airway pressure to the pleural space, so that even patients with high values of PEEP may not have large increases in pleural pressure if they also have acute lung injury. Unfortunately, there is no simple formula that is valid for all patients. It also is not valid to remove the PEEP to measure these intrathoracic vascular pressures because removing PEEP also changes the hemodynamics. It is possible to examine the effect of PEEP on the Ppao by rapidly removing the PEEP and observing the nadir of the decrease in the Ppao after 2 to 3 seconds,[23] but this cannot be used for the central venous pressure (CVP)/right atrial pressure because of the rapid changes in right heart filling along with changes in intrathoracic pressure. One method to estimate transmural Ppao is to compare the change in end-expiratory airway plateau pressure with PEEP as the delta airway pressure to the change in pulmonary artery diastolic pressure from end-expiration to end-inspiration. Because pulmonary arterial pressure senses pleural pressure as its surrounding pressure, the change in diastolic pulmonary artery pressure will equal the change in pleural pressure. The ratio of the change in pleural pressure to change in airway pressure reflecting lung compliance can be considered an index of the transmission of the airway pressure to the pleural space. To calculate transmural Ppao, one merely subtracts the product of the index of transmission for PEEP (measured in mm Hg) from Ppao.[24] Because lung compliance varies little over the course of the day, one need only calculate the index of transmission once, so these estimates of transmural Ppao can be calculated each time Ppao is measured.

Although the general rule is that measurements should be made at end-expiration, this is not always the case. Normally expiration is passive so that pleural pressure does not deviate much from the baseline during expiration. However, dyspneic patients often expire actively, which raises pleural pressure, and this occurs with 2 patterns (**Fig. 5**). In one the patient pushes out from the start of expiration and, depending on the length of expiration, all the inspired air may or may not be expired during the period of expiration, which elevates pleural pressure and, consequently, intrathoracic vascular pressure relative to atmosphere. Furthermore, measured pressures will then vary with the length of expiration. The other pattern is more problematic. In this situation the patient pushes down progressively more during expiration so that there is a marked increase in pleural pressure at end-expiration. When this pattern is present, pressures should be measured at the beginning of expiration and before the patient starts pushing down. Major errors will occur in this situation if measurements are made at end-expiration. One also can try to identify a breath that occurs without active expiration. Asking a patient to talk (even if intubated) can be tried to temporarily stop active expiration, as active abdominal muscles usually do not contract when talking.

Another consideration is at which point in the cardiac cycle the pressure measurement should be taken on a right atrial tracing (**Figs. 6** and **7**). This issue becomes important when there are large “a” and “v” waves or prominent “x” or “y” descents. Because a primary use of atrial pressure is assessment of cardiac preload, the pressure measurement should be taken at the base of the “c” wave, called the “z” point, or if the “c” is not evident just after the QRS wave on the ECG. The rationale is that this is the final pressure at the end of diastole and before the onset of contraction, and thus is the best estimate of preload.

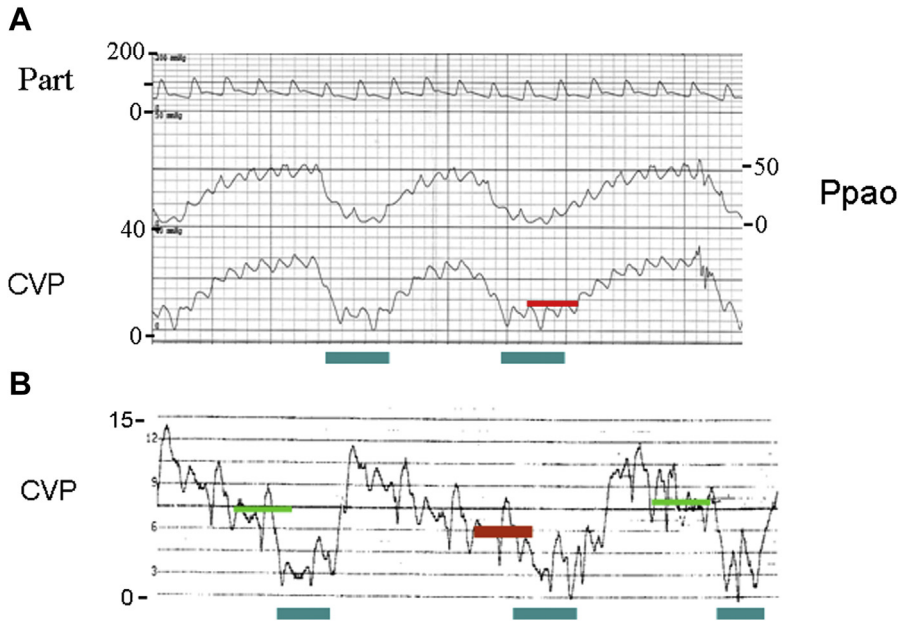

Fig. 5. (*A*) Example of a spontaneous effort with a marked active expiration with progressive increases in the pressures throughout expiration. The lines at the bottom indicate inspiration. The line on the CVP tracing suggests an appropriate place for the measurement; although it is early in expiration, it occurs before the major push. (*B*) Example of active expiration with a decrease in effort throughout the expiratory phase. The value at end-expiration in the middle breath is lower than the other 2 because the breath is longer and there is more time for expiration. (*Reproduced from* Magder S. Hemodynamic monitoring in the mechanically ventilated patient. Curr Opin Crit Care 2011;17(1):36–42.)

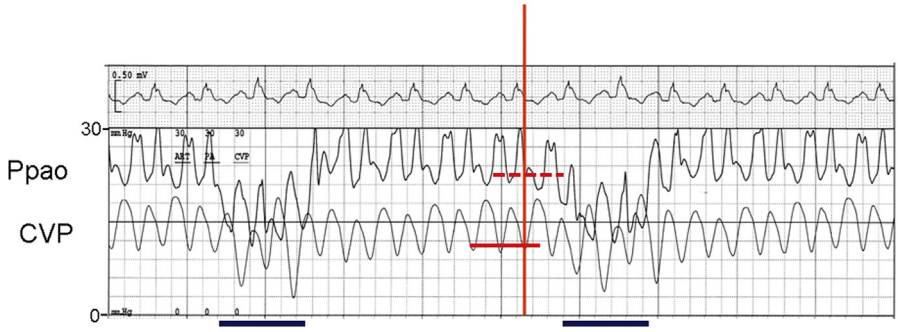

Fig. 6. Ppao and CVP in a spontaneously breathing subject. The vertical line shows where to make the measurement based on the QRS. The horizontal lines mark inspiration. The inspiratory decrease in Ppao is prominent, indicating a strong inspiratory effort, but there is only an increase in the "y" descent on the CVP with no change of the base of the "a" and "c" waves during inspiration (although there is a slight increase during expiration indicating some active expiration). Based on this pattern, it is unlikely that this patient would respond to fluid.

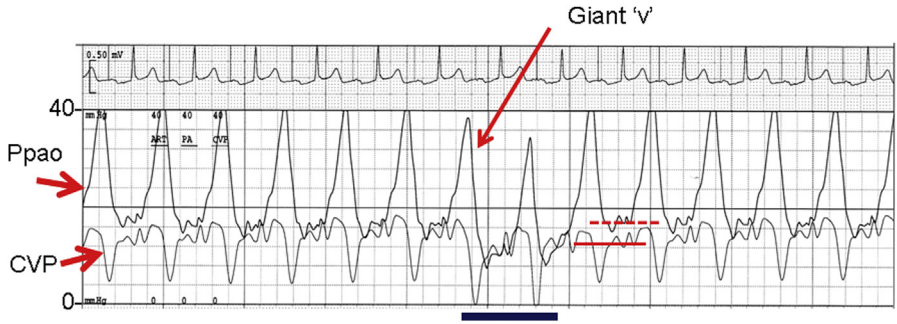

Fig. 7. Ppao and CVP in a spontaneously breathing subject. Giant "v" waves are evident on the Ppao tracing and there is a marked "y" descent. There is a slow rising "v" wave, suggesting limited left atrial compliance and prominent "y," indicating restriction on the right side. It is unlikely that this patient would respond to fluids. The thick bar marks inspiration, as is evident by the increase in the "y" descent on the CVP. There is slight forced expiration so that the Ppao (*dashed line*, 16 mm Hg) and CVP (*solid line*, 12 mm Hg) are not made at end-expiration.

Cardiac Output

Modern PAC injection setups have greatly reduced errors in the measurement of cardiac output by thermodilution. Helpful features include a syringe that only allows a fixed amount of volume, which is usually 10 mL of saline, valves that allow drawing the fluid from a bag and injecting without having to manually turn a valve, and a temperature probe that obtains the temperature of the injectate as it is goes into the patient. Precautions include ensuring that the exact amount of fluid is drawn up in the syringe, that the bolus is given quickly, and that the patient's baseline temperature in the blood is constant.[25] In this regard it is important to ensure that a large amount of another fluid is not being infused at the same time through another line, as this changes the baseline temperature and is the equivalent of adding extra indicator. After each injection the curves should be inspected on the monitor to ensure that there are no irregularities and that the downward curve is smooth (**Fig. 8**). It is not necessary to time injections to a phase of ventilation, because stroke volume does change during the ventilatory cycle and it is not possible to reach exactly the same point in the cycle. Repeated injections thus give an average value, which is also what the tissues see.

With the basic PAC, cardiac output is obtained by performing usually 3 or more injections of saline at room temperature, and taking the average of the 3 if the curves on the monitor look appropriate in that they have a clean rise and fall and are smooth. Devices are also available for continuous measurements of mixed venous oxygen saturation and continuous thermodilution cardiac output measures. The latter work by using transfer of heat from a filament mounted on the PAC close to the injection port at the level of the right ventricle, and the increase in temperature is sensed distally.[26] Repeated pseudorandom pulses of heat with different filament powers are used to reconstruct a thermodilution curve. The advantage of these devices is that trends are readily observed and provide earlier indications of significant changes. However, these continuous cardiac output devices are considerably more expensive than routine PAC, and their cost-effectiveness has not been demonstrated.[27] There are also some potential disadvantages. Variations in cardiac output and mixed venous oxygen saturation occur regularly because of biological variations such as changes in wakefulness, fever, or drug infusions, without there actually being a pathologic problem. There thus can be a tendency to overreact with these continuous cardiac output

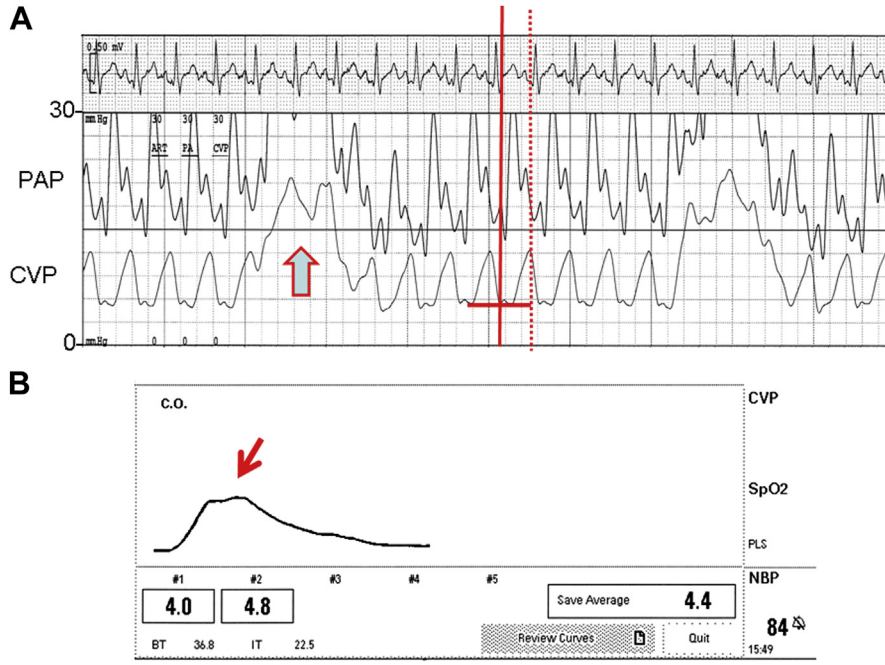

Fig. 8. (*A*) PAP and CVP tracings in a mechanically ventilated subject. The solid line shows how the electrocardiogram (ECG) can be used to time and identify the CVP waves. The prominent CVP wave (*arrow*) occurs after the QRS and is thus a prominent "v." The solid vertical line is drawn after the QRS and indicates a likely "c" wave, which is where CVP should be measured (*horizontal line*, 5 mm Hg). The vertical dotted line is drawn from the peak of "v" wave and appears late in the electrical cycle, indicating that in this case there is a significant delay between the electrical ECG signal and the fluid-based CVP and PAP signals. (*B*) Thermodilution cardiac output curve with a "notch" at the peak of the temperature curve (*arrow*) and variation in the measured cardiac outputs. There is a marked inspiratory increase in PAP and CVP in *A*, indicating that thoracic compliance is likely low. The consequent large increase in pleural pressure (>15 mm Hg) during inspiration interfered with the thermodilution curve. In support of this, the notch in the thermodilution curve was not present when the ventilator was paused (not shown).

devices. The averaging of values involved in the algorithm can sometimes fail to detect an increase in cardiac output following a fluid bolus because of the time needed for a change to be observed.[28]

Mixed Venous Oxygen Saturation

Mixed venous oxygen saturation is obtained by drawing blood from the distal end of the PAC and measuring the oxygen saturation with a co-oximeter, or in vivo by using a fiberoptic sensor at the tip of the PAC. When sampling mixed venous blood, it is important to ensure that the catheter is not wedged in the pulmonary artery or that blood is not withdrawn too quickly, as this will result in withdrawal of pulmonary capillary blood after gas exchange and thus render a falsely elevated O_2 saturation and decreased venous carbon dioxide pressure (PCO_2) value. Arterization of the mixed venous sample can be suspected when the mixed venous O_2 saturation is very high (ie, >80%). The PAC may be purposely wedged to obtain a "capillary" or left atrial equivalent sample if one wishes to calculate intrapulmonary shunt.

Approach to the Patient

Invasive hemodynamic monitoring comprises both arterial and central venous/PAC monitoring. Arterial catheterization is useful because it allows continuous monitoring of arterial pressure and its various components: systolic, diastolic, and pulse pressure, and pulse pressure variation during mechanical ventilation. The article by Pinsky on functional hemodynamic monitoring elsewhere in this issue focuses on arterial waveform analysis, so here the focus is on right-sided pressure and flow monitoring. One can approach the hemodynamic monitoring needs of the patient using data derived from the PAC, or with a less invasive measurement of cardiac output and CVP[8] using a central venous catheter.

The PAC is often used either as a diagnostic tool or for titration of therapy. A common diagnostic problem that can be assessed by data derived from the PAC is determination of the cause of hypotension. Blood pressure is approximately equal to the product of cardiac output and systemic arterial resistance. Resistance is a calculated variable based on the measurement of blood pressure and cardiac output. In the hypotensive patient, the initiating problem is the low blood pressure. Thus, measurement of cardiac output is key in the decision-making process. If cardiac output is normal or elevated then the primary reason for the low blood pressure is a decrease in systemic vascular resistance. The differential diagnosis is then clear, and the possibilities easily evaluated (**Box 1**). Of these, sepsis is by far the most likely commonly occurring cause seen in hospitalized patients. The most specific therapy for hypotension caused by low systemic vascular resistance is the use of a vasoconstrictor drug, such as norepinephrine, to increase vasomotor tone. However, using fluid boluses also can improve blood pressure if the heart is volume responsive by further increasing cardiac output, although this assumes that the volume-responsive heart is not functioning on the flat part of the cardiac function curve. Volume resuscitation increases cardiac output by

Box 1
Causes of decreases systemic vascular resistance

- Sepsis (systemic inflammatory response syndrome)
- Drugs (specifically drugs that actively dilate resistance vessels)
  - α-Antagonists
  - β-Agonists
  - Nitroprusside
  - Phosphodiesterase inhibitors (milrinone)
  - Hydralazine
- Spinal/epidural injections
- Spinal injury
- Cirrhosis
- Arterial-venous fistula
- Adrenal insufficiency
- Thyroid disease
- Anaphylaxis
- Anemia (severe, long-standing)
- Beriberi

increasing venous pressure, meaning that capillary pressures must also be increased, which will increase capillary leak, which is already increased in many of the causes of distributive shock.

When a hypotensive patient has a decreased cardiac output, low blood flow is the primary cause of hypotension. Because cardiac output is determined by the interaction of cardiac function and venous return, either of these can explain a decrease in cardiac output. Which of these two is the primary reason can be determined by examining CVP as a measure of right atrial pressure. In the presence of a low cardiac output, a low CVP argues for a primary venous return problem, whereas a high CVP argues for a primary cardiac problem. Trends in CVP and cardiac output are even more helpful. If the cardiac output decreased with a drop in CVP, the primary problem is a decrease in venous return, and cardiac output will most likely increase with a volume infusion. If the cardiac output decreased with an increase in CVP, the most likely problem is a decrease in pump function. Fluid is less likely to be of help, and attention should be turned to diagnosing the reason for the decrease in pump function and to increasing pump function. When it is not clear as to which is the culprit, a volume challenge can help distinguish between these two possibilities. A cardiac function problem may or may not respond to a volume infusion, but a venous return problem should always respond to a volume infusion. Thus, a failure of a volume bolus to increase cardiac output despite an increase in CVP indicates a cardiac limitation, and therapy should be directed at improving cardiac function.

There are two parts to monitoring patients. One is identifying the need to intervene because hemodynamic values are outside a desired range. These values can be set as goals for all patients in what is called goal-directed therapy, and implies a preventive approach, or according to set of triggers for specific interventions based on the patient's overall status, which implies a more responsive approach. Responsive approaches reflect traditional management principles, whereas goal-directed therapies represent which resuscitation targets that are empirically defined. Another article by Cannesson and colleagues elsewhere in this issue addresses goal-directed therapies and their logic. One form of goal-directed algorithms recommends giving fluids until the patient is no longer volume responsive. A recent clinical study supports the argument that this is not a good practice.[29] First, volume responsiveness does not indicate a volume need. Normal persons usually function on the ascending volume-responsive part of the cardiac function curve, thus allowing changes in both cardiac and return functions to regulate cardiac output. When the heart is functioning on the flat part of the cardiac function curve, only an increase in cardiac function can increase cardiac output, which is especially important when managing patients after heart transplantation. Because the transplanted heart is not innervated, changes in cardiac function require either secretion of adrenal catecholamines, which must arrive at the heart through the circulation, or intrinsic increases in contractility by the Anrep mechanism, both of which take minutes to realize. If the response is not sufficiently rapid to increase the cardiac output, the patient's condition can rapidly deteriorate.

The most common initial intervention in a hypotensive patient who is not bleeding or hypoxemic is the use of a fluid bolus. In an analysis of the use of fluid boluses in a recent study, the primary triggers were cardiac output or blood pressure below target.[30,31] The target value of CVP as a trigger for a volume bolus was set low and only rarely was a trigger, as was the case for urine output. In a responsive approach it is important to follow what happens after a fluid bolus is given. If the cardiac output or blood pressure triggers are corrected, nothing further needs to be done until they fall outside the desired range again. However, if they were not corrected, the next step is to determine whether the fluid challenge was adequate by

determining if the CVP rose sufficiently to increase cardiac output by the Starling mechanism. An increase in CVP of 2 mm Hg or more is considered significant because this pressure change can be recognized on the monitor. If the CVP rises by at least 2 mm Hg and cardiac output increases but the blood pressure still is below the target, more fluid can be given. If the CVP rises by 2 mm Hg or more and cardiac output does not increase, this indicates that the heart is functioning on the flat part of the cardiac function curve and that further volume loading will not be helpful. It should be appreciated that if the plateau of the cardiac function curve occurs at a cardiac output of 5 L/min and a CVP of 10 mm Hg, the slope from a CVP of zero to 10 mm Hg is 0.5 L/min, which underestimates the steep part of the cardiac function curve. Thus an increase in CVP of 2 mm Hg should produce an observable increase in cardiac output if the heart is volume responsive. If the heart is not responsive to a volume infusion, correction of hypotension requires a vasopressor if the cardiac output is adequate or an inotrope if the cardiac output needs to be increased. Although norepinephrine is thought of as a vasopressor, it still produces some increase in cardiac contractility[32] and can serve both purposes if only smaller increases in cardiac output are needed.

Pulmonary Artery Occlusion Pressure

In the discussion so far on fluid management, Ppao has not been included because Ppao is useful for diagnostic purposes and the potential of pulmonary edema, but not for the determination of the need of fluid to increase cardiac output. CVP indicates the interaction of cardiac function and return function, and thus always is the appropriate value to use for separating these 2 functions. This point is especially important when there is right heart limitation, a common occurrence in both postoperative cardiac surgery and septic patients. When there is right heart limitation, changes in Ppao have little effect on cardiac output, as the left heart only can put out what the right heart gives it. However, the value of Ppao allows distinction of a primary left heart versus right heart cause of a decrease in cardiac function. This rationale was the original one of Swan and Ganz when they developed the PAC.[33,34] Swan worked in a coronary care unit where left ventricular dysfunction without right ventricular dysfunction is common and not easily recognized with just CVP and cardiac output measurements. The failing left ventricle tends to produce more pulmonary edema with moderate decreases in cardiac output and little change in CVP. If Ppao is much more elevated than the CVP, the differential diagnosis favors left heart failure as the primary disease process. The problem must be due to a marked increase in left ventricular load (hypertension), aortic or mitral valve disease, or ischemic heart disease. And if Ppao rises high enough, there should also be pulmonary edema. By contrast, a generalized cardiomyopathy should affect both ventricles, and the failing right ventricle protects the left ventricle. The pertinent phrase is: no left ventricular failure without right ventricular success.

Ppao also gives an indication of the potential for pulmonary edema, especially when there is a capillary leak syndrome, although it has been shown not to be as good as an actual measurement of lung water.[35,36] An important potential artifact that can occur in measuring Ppao is failure to actually obtain an occlusion of the vessel but instead only dampening the pulmonary artery pressure (see **Fig. 4**). This artifact should be considered when the Ppao is the same as the pulmonary artery diastolic pressure, especially when there is an elevated pulmonary artery pressure. The wave pattern of the Ppao also can be helpful. Large “v” waves are suggestive of mitral regurgitation (see **Fig. 7**; **Fig. 9**). In severe, acute mitral regurgitation this even can look like a pulmonary artery tracing. However, large “v” waves also can be produced by overfilling of the left

Fig. 9. Arterial (Part), distal pulmonary artery catheter pressure (PAP), and CVP in spontaneously breathing subject. The PAP tracing is actually a large "v" wave from a Ppao occlusion. Note the slow upstroke of the wave compared with the PAP examples in Figs. 3 and 4. There was + to ++ mitral regurgitation on echocardiography. The "v" wave increased overnight after volume loading. The "y" descent is prominent, indicating likely RV limitation. The horizontal lines indicate inspiration. There is a mild active expiration (increase in CVP during expiration). The rhythm (*upper band*) is atrial paced.

heart because of excess volume. This pattern often is seen in patients who have a ventricular septal defect or rupture in association with an acute myocardial infection.

Pulmonary Artery Pressure

Pulmonary artery pressure gives an indication of the load on the right heart. Based on the approach of Wood,[37] mechanisms of pulmonary hypertension can be classified as the following: (1) passive pulmonary hypertension whereby the rise in pressure is due to increased left-sided diastolic pressure; (2) reactive pulmonary hypertension, which is due to changes in pulmonary vascular resistance because of persistent high pulmonary blood flow, as occurs with left to right cardiac shunts or chronic hypoxia; (3) obliterative pulmonary hypertension attributable to loss of the pulmonary vascular cross-sectional area that can be due to pulmonary embolic disease or vascular destruction from inflammatory or fibrotic processes; (4) primary pulmonary vascular disease caused by disease processes that directly target the pulmonary vasculature, including primary pulmonary hypertension. An elevated pulmonary artery pressure itself does not indicate the stress on the right heart, as the pressure is related to the cardiac output and the resistance. How well the right heart is coping with the elevated pressure can be evaluated by observing the cardiac output and CVP. If the CVP is low and cardiac output is normal, the right heart is tolerating the increased load. An increase in CVP and a decrease in cardiac output is a bad prognostic sign.

Mixed Venous Oxygen and Consumption of Oxygen

Presence of a PAC also allows sampling of mixed venous O_2 saturation from the pulmonary artery. Although directly targeting therapy based on mixed venous blood values has not been shown to be helpful and possibly harmful,[38] the addition of this measurement can be used to support other measurements. For example, a decrease in cardiac output would be expected to be associated with a decrease in mixed venous O_2 and an increase in lactate in patients who are in circulatory shock, and these then can be used to support the validity of an observed decrease.[38] Alternatively, if the patient has a low cardiac output but the mixed venous O_2 saturation is

70% and the lactate concentration is normal, the cardiac output likely is sufficient for the patient's needs, and observation rather than intervention might be the best approach. Although one should not treat an isolated low mixed venous O_2 saturation value, it should also not be dismissed. Interpretation needs to be based on the whole picture, including the actual cardiac output value, organ function, and metabolic status as indicated by lactate.

A useful way of confirming that the measured values make sense is to calculate the oxygen consumption by using the indirect Fick method from the cardiac output, Hgb, and the arterial and venous saturations (use fractions instead of percentages to make the units work).

$$V_{O_2} = \text{Cardiac output (L/min)} \times \text{Hgb (g/L)} \times 1.36 \times (\text{arterial-venous } O_2 \text{ saturation})$$

The value is in mL/min and 1.36 is the amount of O_2 per gram of hemoglobin. Typical values are in the 200 to 300 mL/min range depending on body size and resting metabolic activity. If the calculated value is too high or too low for the patient, the components should be examined to determine which values likely are incorrect.

Nonhemodynamic Uses of Invasive Pressure Measurements

Because the heart is surrounded by pleural pressure, intracardiac pressures change with changes in pleural pressure. Both right and left atrial pressures increase and decrease with pleural pressure, but the relationship of change in left atrial pressure (referenced relative to atmosphere) to change in pleural pressure is much closer than in the right atrium, because when the venous return curve intersects the ascending part of the cardiac function curve, a decrease in pleural pressure lowers right atrial pressure relative to atmosphere and increases right heart filling. However, when the right heart is on the flat part of the cardiac function curve, the right atrial pressure does not decrease with a spontaneous inspiration because cardiac filling cannot be increased by the drop in pleural pressure (see **Figs. 6** and **9**; **Fig. 10**). Even a trivial increase in right ventricular volume immediately brings the CVP back to baseline. This process can be used to indicate whether the heart will or will not respond to volume.[39] The drop in pleural pressure can be recognized by an increase in the magnitude of the "y" descent, which then can be used to "mark" the inspiratory effort (see **Figs. 6**, **7**, **9**, and **10**).

In contrast to what happens with the right heart, the reservoir filling the left heart, the pulmonary venous compartment, also is in the chest, so that its pressure and that of the left atrium decrease together and the pressure gradient filling the left heart does not change with the drop in pleural pressure. Respiratory changes in Ppao thus track

Fig. 10. CVP in subject with a restrictive cardiomyopathy (myocardial fibroelastosis) breathing spontaneously. The "v" wave (*downward arrow*) is broad, indicating tricuspid regurgitation, and so is the deep "y" descent (*upward arrow*), owing to the restrictive cardiomyopathy. The horizontal lines mark inspiration. The rhythm is atrial fibrillation.

changes in pleural pressure very well[40] and can be used to assess inspiratory changes in pleural pressure. The decrease in Ppao with inspiration is slightly less than the decrease in pleural pressure as measured by an esophageal balloon, because lung inflation usually slightly increases left heart filling by squeezing blood out of the alveolar vessels. This process slightly increases left atrial transmural pressure during inspiration.[41]

Inspiratory swings in CVP and Ppao during positive pressure ventilation also can give an indication that thoracic compliance is decreased, which includes the chest and abdomen. When thoracic compliance is decreased, the increase in pleural pressure for the same tidal volume is larger; this is evidenced by larger than normal increases in CVP and Ppao during inspirations with normal tidal volumes (see **Fig. 8**).

The magnitude of the "y" descent on the CVP, an indication of early ventricular filling, also can be helpful. A large "y" descent (ie, >4 mm Hg) is suggestive of restrictive conditions (see **Figs. 7**, **9**, and **10**), meaning that the heart is functioning on the flat part of the cardiac function curve and that it is unlikely that a volume infusion will increase cardiac output.[12] Loss of "y" descents is seen when there is cardiac tamponade and, in the face of a decrease in cardiac output and blood pressure, indicates the need for an intervention to decompress the heart.

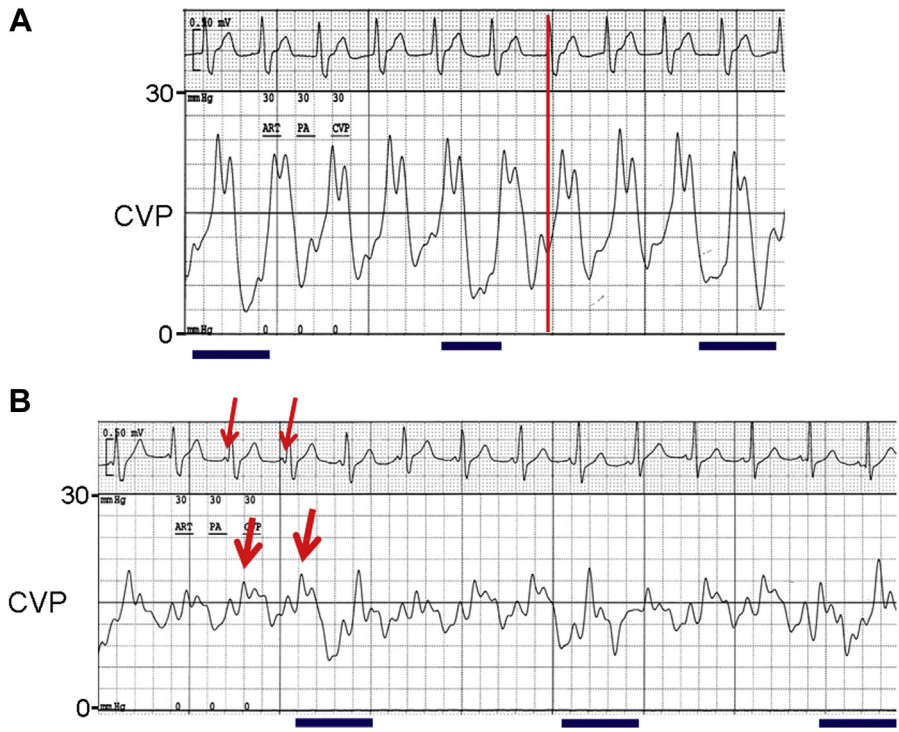

Fig. 11. CVP tracing from subject with junctional rhythm. The rhythm is regular and there are no "p" waves. (*A*) The prominent waves in the CVP tracing are cannon "a" waves caused by retrograde "p" waves and atrial contractions during systole. In (*B*) atrial activity is evident (*arrows*) but the PR interval is short, indicating a low atrial or junctional focus. The "a" waves are much smaller and increase at the end of inspiration. The subject had emergency mitral valve replacement after inferior wall myocardial infarction and ruptured papillary muscle.

Another potential use of pressure waveforms is to interpret rhythms on the ECG. An example of retrograde "p" waves producing cannon "a" wave on the CVP tracing is shown in **Fig. 11**.

SUMMARY

Almost 20 years ago an observational study by Connors and colleagues[42] started a debate on the use of the PAC, which many thought would lead to its extinction. However, the PAC is still in use and in selected situations can give much useful information at a lower cost than other devices. Proper use of a PAC requires an understanding of principles of measurements, attention to safety concerns, and, above all, a good understanding of the regulation of cardiac output. If one exerts the effort to master its use, it can be a valuable tool for the management of complex hemodynamic problems.

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