One approach to circulation and blood flow in the critical care unit

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Abstract

Evaluating and managing circulatory failure is one of the most challenging tasks for medical practitioners involved in critical care medicine. Understanding the applicability of some of the basic but, at the same time, complex physiological processes occurring during a state of illness is sometimes neglected and/or presented to the practitioners as point-of-care protocols to follow. Furthermore, managing hemodynamic shock has shown us that the human body is designed to fight to sustain life and that the compensatory mechanisms within organ systems are extraordinary. In this review article, we have created a minimalistic guide to the clinical information relevant when assessing critically ill patients with failing circulation. Measures such as organ blood flow, circulating volume, and hemodynamic biomarkers of shock are described. In addition, we will describe historical scientific events that led to some of our current medical practices and its validation for clinical decision making, and we present clinical advice for patient care and medical training.

Key words: Shock; Volume status; Fluid; Vasopressors; Mean systemic pressure; Pulse pressure; Plethysmography variability index
INTRODUCTION

In the era of evidence-based medicine and quality measures, shock has become a synonym for critically ill patients. Shock has a significant effect on morbidity, mortality, and costs; septic shock has been associated with 40%-80% of all sepsis-related deaths in the hospital and has increased hospital costs to more than $3000 per day for these patients\(^1\). The management of patients with shock remains a challenge for clinicians and subspecialists involved in their care. Not only is circulatory failure common in the hospital and intensive care unit (ICU) setting (to the point that administrative efforts by the hospitals are now made to protocolize management), but it is also such a common problem that physicians sometimes focus more on symptomatic stepwise approaches than on understanding the disease process to determine the best treatment.

In this review we will discuss the pathophysiology of shock, the assessment of volume status, and approaches to management.

DEFINITIONS AND PATHOPHYSIOLOGY

**Shock**

For the medical practitioner in charge of the ICU, shock is the clinical manifestation of inadequate blood flow and circulatory failure\(^2\). Some define it as insufficient oxygen delivery; the problem with this definition is that there are overlapping diseases of the respiratory tract associated with hypoxemia, which cause inadequate tissue oxygenation but not necessarily a state of shock.

**Hypotension**

Blood pressure determines the blood flow distribution but does not define the state of shock or the adequacy of circulation. Manual blood pressure readings are an appropriate way to determine blood pressure, but an arterial line continues to be the best practice when more accurate readings are needed, even though arterial lines are invasive, painful, and difficult in patients with vascular disease and have a variety of complications.

To understand circulatory failure, it is paramount to recognize that blood pressure and flow are uncoupled physiological processes. From basic physiology, we know that in the range of acceptable blood pressures and normal circulation, all vital organs (including the brain and kidneys) have a wide array of blood flow patterns that are completely disengaged from blood pressure; thus, clinicians will be incapable of making any assumptions about organ flow and cardiac output based on blood pressure alone (Figures 1 and 2, Table 1)\(^3,4\).

**Regulation of blood flow**

In basic science classes, we learn about the physiology of cardiovascular circulation based on the idea that organ blood flow is similar to electric voltage and currents; consequently, we have adapted Ohm’s principle of conduction for a better understanding of the cardiovascular system: Voltage (V) = electric current (I) x resistance (R). Replacement with hemodynamic parameters results in mean arterial pressure (MAP) – right atrial pressure (PRA) = cardiac output (CO) x systemic vascular resistance (SVR): MAP – PRA = CO x SVR.

For explaining the theoretical bases of hemodynamics and flow, this equation is adequate. The clinical application of this equation fails since it neglects the fact that humans have baroreceptors and reflex responses to changes in pressure. Therefore, when CO decreases, there is an instantaneous vasoconstrictor response to maintain equilibrium within the system, thereby maintaining a normal blood pressure. Understanding this concept is imperative, since patients may become overtly hypertensive with low cardiac output or uncalibrated/dysfunctional baroreceptors\(^5,6\).

The sicker the patients become, the more difficult it is for the cardiovascular system to increase the SVR to maintain balance; when the ability to increase the SVR is...
exhausted, patients develop hypotension. Conversely, when patients present with a vasodilated state (e.g., septic shock), they will attempt to increase the CO to preserve an adequate MAP, and as the blood pressure continues to drop, they may reach a point at which the ability to increase the CO is surmounted, following which they become overtly hypotensive. These ideas indicate that low blood pressure is a late and insensitive indicator of inadequate circulation. Furthermore, this concept applies when you are describing cardiogenic shock, sepsis, cardiac tamponade, or traumatic shock. For example, an ICU patient with class 3 hypovolemic shock (Table 2) exemplifies the fact that 40% of the blood volume needs to be lost before the blood pressure decreases.

Understanding this concept will afford a clinical advantage when assessing the patient as one will know that hypoperfusion may be the result of a low SVR, a low CO, or a high SVR in the setting of a critically depressed CO. As a result, planning medical care and prognosis based solely on blood pressure may not work. In 2013, Lehman et al. reported interesting data related to the clinical applications of these concepts and observed that only when the MAP dropped below 70 mmHg did the risk for acute kidney injury and/or mortality increase.

### Adequacy of circulation and venous oxygenation

For more than 20 years, critical care medicine has been trying to assess the adequacy of circulation. There are overwhelming data and information on mixed venous oxygen saturation (SvO$_2$), lactic acid, and clinical signs and symptoms, such as mental status and urine output.

We should start with an understanding of adequate oxygen (O$_2$) delivery and consumption to assess SvO$_2$. A healthy individual deliver approximately 1,000 ml/min of oxygen to peripheral tissues, and the tissues extract nearly 25% of the oxygen [extraction ratio (ER)]. In low-oxygen delivery states, such as low CO, anemia, or hypoxia, there is an increase in the extraction of oxygen that continues until the low O$_2$ state is either corrected or surpasses the capacities of the tissues to extract O$_2$ (approximately 60%–70% ER). At this point, any further decline in O$_2$ delivery will cause an abrupt decline in O$_2$ consumption, with deterioration of the clinical condition (Figure 3, Table 3). As a result, assessing SvO$_2$ provides a quantitative method of assuring that patients do not encounter the critical points of O$_2$ consumption and extraction. With a better understanding of oxygen physiology in ICU patients, the concepts of venous oxygen saturation in central venous catheters (ScvO$_2$) vs mixed venous oxygen saturation in pulmonary artery catheters (SvO$_2$) were developed. The conclusion from regression analysis and determination coefficients (R$^2$) was that there is no significant difference between the two assessment tools with R = 0.945, SvO$_2$ = 1.16 (ScvO$_2$)$^{[8]}$. In clinical practice, this translates to two different procedures with different risks, costs, and complications but with similar medical utility.

### Early goal-directed therapy

Because of the similar findings and the lesser risk associated with the insertion of a central venous catheter compared to a pulmonary artery catheter, ScvO$_2$ became an important measurement in the original “early goal-directed therapy (EGDT) in the treatment of sepsis and septic shock” (Figure 4). With the implementation of the EGDT across the board as a standard of care for sepsis and septic shock, it was found that the clinical validity for ScvO$_2$ vs SvO$_2$ performed well for sepsis and septic shock (R = 0.88 – R = 0.89, P < 0.001)$^{[14,19]}$, but not as well for cardiac surgery patients (R = 0.72, P < 0.001 – ScvO$_2$ most reliable > 70%)$^{[11]}$. Therefore, for patients with significant cardiac disease/cardiac surgery, ScvO$_2$ and SvO$_2$ are not interchangeable for medical decision making.

A series of clinical trials concerning EGDT and clinical outcomes have been performed through the years. The ProCESS trial published in 2014 compared the EGDT vs an alternative protocol vs usual care. There was no difference in 60-d ($P =$

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### Table 1 Types of shock and relationship with blood pressure and cardiac output

| Blood pressure | Cardiac output |
|---------------|----------------|
| Hypovolemic    | ↓              |
| Cardiogenic    | ↓              |
| Obstructive    | ↓              |
| Distributive   | ↓ (Most of the time) |
Figure 1  Renal autoregulation. Total renal blood flow over a range of perfusion pressure. Adapted from [61].

0.52) or 1-year mortality ($P = 0.92$) [17]. Similar findings were published in 2015 in a trial by Mouncey et al. [18], in which 1200 patients were randomized to EGDT vs usual care, with no difference in mortality outcomes ($P = 0.63$).

**Lactate**

Lactic acid measurement has become an important method for the assessment of critically ill patients while avoiding the cumbersome process of obtaining central venous oxygen saturation. Some of the initial algorithms for the use of lactate measurements in the ICU involved combining the measurements with ScvO$_2$, to provide a stepwise approach for guiding the resuscitation of patients with circulatory failure: If lactate > 3.0 meq/L, then the ScvO$_2$ should be checked, and if it is not more than 3.0 meq/L, then there is no need to check the ScvO$_2$. However, when serum lactic acid was compared to ScvO$_2$ as the goal for resuscitation of patients with sepsis and septic shock, there was no difference in outcome [20]. Considering these outcomes, there has been a shift in clinical practice from using central venous oxygen saturation to lactate in patients with sepsis and septic shock (i.e., for patients without major cardiovascular disease).

**Circulating volume/volume status**

What is the volume status in the ICU patient? We do not know. A more definite answer is “nobody knows”. However, to better understand, assess, and manage volume in critically ill patients, we need to first recognize what we do know about circulating volume and the fact that physical examination, regardless of many years of training and experience, is neither sensitive nor specific [21].

In the 1950s, Guyton et al.'s experiments with the Frank and Starling models of cardiac physiology gave rise to some interesting concepts regarding circulation and blood flow. One of his conclusions regarding venous return (VR) physiology is that when the PRA and the mean systemic filling pressure (PMS) are equal, there will be no return of blood to the heart: VR = (PMS – PRA)/resistance to the venous return (RVR).

Furthermore, Guyton et al.'s model established that PRA is not an indicator of circulating volume but a marker of pressure exerted by the venous system for the return of blood to the heart; thus, the lower the PRA, the higher the venous return (Figure 5). With his description, we understood the importance of the PMS as the driving force for the return of blood volume back to the heart and one of the most useful parameters for assessing the actual circulating volume status [24].

**Central venous pressure and capillary wedge pressure**

With the understanding of the mechanistic aspect of circulatory physiology described with the Starling curve (Figure 6) and the notion of venous return by Guyton’s model, it is possible to extrapolate the central venous pressure (CVP) as a product of the interaction between the venous system and cardiac function. Under those circumstances, the clinical inference from the CVP measured in patients is that, regardless of the number, it is lower than the mean systemic venous pressure (Figure 7).

Although the bedside utility of CVP alone for predicting volume responsiveness and medical decision making is not ideal, it is, however, a measurement available for the evaluation of critically ill patients with circulatory failure. The CVP alone in the ICU does not correlate with either the circulating volume status (R = 0.27) [25] or the clinical response to volume/fluid administration [26]. Similarly, the estimated left atrial pressure by pulmonary capillary wedge pressure (PCWP) via the more invasive
Figure 2 Cerebral autoregulation. Blood flow over a range of perfusion pressures. Reproduced from[4] with permission of the Society of Photo Optical Instrumentation Engineers (SPIE)

pulmonary artery catheterization (Swan-Ganz catheter) was once considered to be one of the most reliable methods to assess the ventricular preload and circulating volume. This method was one of the characteristic features of critical care medicine, but has been shown to underperform in the clinical setting in predicting responsiveness to intravascular volume administration[27].

Peripheral vs central venous pressure
As an available tool, the CVP continues to be widely used alone or in combination with other parameters to enable an educated guess about the venous system volume status. An alternative and less invasive method, which provides an equivalent physiological estimation of the volume status, is the peripheral venous pressure (PVP). The PVP is a tool that is inadequately and seldom used, is less invasive, requires the same transducer/equipment as the CVP, and has similar results. Any patent peripheral intravenous access (for flushing and drawing) may be used for measuring PVP. One does need to adjust the value of PVP by subtracting 2 mmHg. Thus, PVP = CVP + 2 or PVP − 2 = CVP[28]. The PVP not only is useful but also has been validated in many clinical scenarios in humans and animals (R = 0.97)[29,30]; its validity has been tested and proven in surgical patients (for surgical scenarios such as brain, abdominal, and cardiac surgery), in ICU patients, and in pediatric patients[28,31,32].

ASSESSMENT OF THE PATIENT WITH CIRCULATORY FAILURE

Once the basic concepts of blood flow and circulating volume are understood for a critically ill patient with circulatory failure, the next step is to determine if the patient responds to volume expansion. The most physiologically correct method to determine this is by measuring the mean systemic pressure (PMS). Currently, we do not have a validated clinical tool to measure the PMS in the hospital. However, there is research in the Netherlands with noninvasive devices to quantify the PMS and predict volume responsiveness, which may entirely change our methods of approaching and managing shock and volume administration[33].

Mean systemic pressure, systolic pressure variation, and pulse pressure variation
Since we do not currently have a way to measure PMS in our patients, what has been done through the years for assessing the circulating volume status and volume administration is to measure indices, such as the systolic pressure variation (SPV) and pulse pressure variation (PPV) in mechanically ventilated patients with circulatory failure[34] (Figure 8). The idea behind using these volumetric indicators (SPV and PPV) comes from the expected fluctuation of the Frank-Starling curve with mechanical ventilation and the minimal variability in the systolic and pulse pressures on the flat portion of the Starling curve. However, as volume depletion develops, the venous return decreases, and the system shifts towards the steep portion of the Starling curve, resulting in an increase in the variability in systolic pressure and pulse pressure. The implication is that the higher the PPV and SPV, the greater the expected response to volume administration, and this provides a guide for volume resuscitation[35].

The correlation between PPV/SPV and respiratory changes has been widely
Table 2  Hypovolemic shock categories

|                  | I          | II         | III        | IV         |
|------------------|------------|------------|------------|------------|
| Blood loss (mL)  | Up to 750  | 750-1500   | 1500-2000  | > 2000     |
| % of blood loss  | Up to 15   | 15-30      | 30-40      | > 40       |
| Blood pressure   | Normal     | Normal     | Decreased  | Decreased  |
| Mentation        | Preserved  | Anxious    | Confused   | Lethargic  |

Summary as described by the American College of Surgeons in The Advanced Trauma Life Support training program.

validated as a means to predict volume responsiveness in different scenarios, with sensitivities and specificities of 94% and 96%, respectively. For septic shock, the correlation ($R = 0.85$) is higher than the PCWP and PRA ($R = 0.5$ for both RAP and PCWP)$^{[39]}$. It also performs well after cardiac surgery compared with the CVP and PCWP (PPV/SPV: $R = 0.8$, CVP/PCWP: $R = 0.5$)$^{[35][36]}$. The two most important clinical scenarios in which PPV/SPV are known to fail are right ventricular failure (e.g., right ventricular infarction, cardiomyopathy, and pulmonary hypertension) and obstructive shock (e.g., tension pneumothorax, abdominal compartment syndrome, and cardiac tamponade)$^{[35][38]}$. However, what if the patient is not mechanically ventilated, is spontaneously breathing, does not have a regular heart rate or on adequate tidal volume—can PPV and SPV still be used? The answer is yes, they can. The requirement for specific ventilatory parameters has been challenged, and both PPV and SPV tests work well in patients breathing spontaneously, with an AUC (area under the curve) of more than 0.8 for both. However, it is important to be cautious when using PPV/SPV with spontaneously breathing patients due to the varying reliability and results with changes in breathing patterns$^{[39][40]}$. Similarly, the need for arterial catheter insertion to measure the changes in PPV/SPV has been questioned, and plethysmographic waveform changes by pulse oximetry make it possible to calculate the plethysmography variability index (PVI). Subsequently, validated with comparable results as the more invasive PPV/SPV, the PVI can detect circulatory volume changes as low as 4%. Measurements with blood pressure require > 30% reduction in circulatory volume for hypotension to be present. A PVI of more than 17% will correlate with volume responsiveness. Furthermore, the PPV will change in parallel to the PVI ($R = 0.85$, $P < 0.001$), making it an excellent tool for evaluating patients with circulatory failure$^{[41][42]}$.

Cardiac output

Interestingly, in the acute care setting when the patient has developed circulatory failure, knowing and calculating the current blood flow is not as essential as understanding and assessing the consequences of appropriate blood flow, such as mental status, urine output, lactic acid level, and even central venous oxygen saturation. Moreover, pulse pressure (PP) is one of the more reliable correlates of low cardiac output (Table 4) since the aorta functions as a left ventricular counterpulsation balloon pump, stretching during systole and contracting during diastole while maintaining the mean arterial pressure with changes in flow, but the PP will vary with the amount of volume per stroke. This translates to a scenario in which the more that the stroke volume decreases, the more that the PP will decrease, giving enough information for medical decision making in the ICU. However, if the need to know and quantify the cardiac output, then there are numerous devices available in hospitals to do so.

In summary, before adding more accessories to measure cardiac output, we recommend going back to your previous answers when assessing the patient. If your biological markers (e.g., urine output, mental status) and your surrogates of blood flow (e.g., lactate, central venous saturation) are within normal limits, then the cardiac output should not be the major concern. On the other hand, if the available bedside tools fail to support your clinical assessment about the cardiac output, we recommend more physiological substitutes for blood flow and stroke volume, such as the PP to make inferences and medical decisions.

VOLUME MANAGEMENT IN A NUTSHELL

The “silver lining” of restoring adequate circulation is the balance between
Table 3  Conditions that affect the venous oxygen saturation measurement

| Condition                                      | SvO₂ change |
|-----------------------------------------------|-------------|
| Anemia (Hemoglobin < 8)                       | ↓           |
| Low cardiac output                            | ↓           |
| Agitation                                      | ↓           |
| Sepsis                                        | ↑           |
| States of hypoxia                              | ↓           |
| Anesthesia ([ O₂ utilization)]                 | ↑           |

Normal SvO₂: 60%-80%.

reestablishing tissue perfusion with the appropriate/physiological distribution of blood flow by improving circulatory volume and avoiding iatrogenic volume excess. In the event of hypovolemic failure (regardless of the state of shock), the treatment is to replace the volume. Needless to say, hemorrhagic shock necessitates blood transfusion.

The classic example of the most common type of shock seen in the ICU is a septic shock patient who has not felt well before admission, not eating or drinking, and who developed a low volume state from lack of water (dehydration) and solutes (nutrition). This is in addition to the associated loss of fluid from increased capillary permeability, which is part of the septic process, and this loss of extra volume from the intravascular space into the interstitium leads to a state of relative hypovolemia superimposed on actual hypovolemia. Additionally, septic shock also induces maladaptive venous vasodilation, which decreases the circulatory blood flow return to the heart even after adequate fluid replacement[43]. It may also cause cardiac dysfunction and vasomotor paralysis to the point that patients need inotropes and sometimes corticosteroids[2].

Protocols for optimal preload optimization and volume administration have been used in the clinical setting to improve outcomes (as previously discussed in the section: “Definitions and Pathophysiology”), but no benefit in survival or prevention of developing new organ failure has been achieved using protocolized fluid therapies. If anything, when comparing the fluid administration for patients receiving a lower total amount of fluid per usual care against the protocols, there may, in fact, be an association with renal dysfunction and the need for dialysis (P = 0.04) with the protocolized fluid therapies[17,44].

Type of fluid
The type and composition of fluid given do seem to matter. Recently published, the Isotonic Solutions and Major Adverse Renal Events Trial concluded that the use of balanced crystalloid solutions is overall better than the use of saline solutions, with less adverse kidney events (P = 0.04) and lower 30-d mortality (P = 0.02)[45]. Normal saline (0.9% NaCl) is the most commonly administered solution in our hospital and around the world[46]. Some of the problems associated with chloride-rich solutions include the development of hyperchloremic acidosis with an increase in morbidity and mortality outcomes[47-50]. On the other hand, the Saline vs Plasma-Lyte for ICU fluid Therapy trial did not show any difference in outcomes between the two solutions studied (P = 0.85), although it is important to mention that these patients received, on average, a total of less than 2 liters of either solution throughout the whole study. Additionally, this amount of fluid may not be enough compared with the fluid quantities used for resuscitation and maintenance for ICU patients with circulatory failure[51]. One clinical scenario in which normal saline should be the principal solution to use is in patients with intravascular volume depletion, metabolic alkalosis, and hypochloremic hyponatremia (e.g., over diuresis).

Hydroxyethyl starch is known to be nephrotoxic and is not used currently in the United States for fluid resuscitation (it was never used that much before either)[52]. Other colloids, such as albumin and gelatins, remain valuable tools when used appropriately (Table 5). However, no significant clinical benefit from using colloids instead of crystalloids for volume resuscitation has been demonstrated[53,54].

Vaspressors and corticosteroids
Several different classes of vaspressors, including inotropic agents, are widely available and used in the treatment of shock for primarily inducing vasoconstriction, increasing mean arterial pressures, and optimizing blood flow and tissue perfusion.
Figure 3 Relationship between oxygen delivery and venous oxygenation/oxygen consumption. VO₂: Oxygen consumption; QO₂: Oxygen flow delivery; ER: Extraction ratio; ERc: Critical point of extraction; QO₂c: Critical point of delivery.

The three main categories that divide vasopressors are catecholamines (e.g., epinephrine, norepinephrine, dopamine), non-adrenergic drugs (e.g., vasopressin, angiotensin II), and other adrenergic agonists (e.g., phenylephrine, midodrine, dobutamine).

Despite the fact that there is no difference in survival between norepinephrine and dopamine as the first-line agent for the treatment of shock ($P = 0.07$), there are significantly more adverse events related to arrhythmias (atrial fibrillation, ventricular tachycardia, ventricular fibrillation) with dopamine, and for this reason, its use has declined significantly over the years[55]. Although phenylephrine has not been tested against norepinephrine and continues to be widely available, there have been observational data reported after the 2011 shortage of norepinephrine in the United States which showed increased in-hospital mortality when phenylephrine is used as first line agent[56].

Vasopressin performs as well as norepinephrine and is a useful medication for second-line therapy if needed[57]. The new vasopressor being used more frequently in the ICU is angiotensin II. The Angiotensin II for the Treatment of Vasodilatory Shock (ATHOS-3) trial demonstrated that it works well for vasodilatory/high output shock, has a great safety profile, and has minimal side effects. It is an excellent second-line therapy currently and will be so the near future, with appropriate concerns about price and availability[58]. Corticosteroid use in septic shock has been debated throughout the years and is recommended for refractory shock per Surviving Sepsis guidelines. These drugs do not have any other proven benefit in this clinical setting[59,60].

In summary, we recommend avoiding dopamine as a first line drug due to the severity of side effects and possibility of harm. We continue to use norepinephrine as the first line agent, but vasopressin is also an option for either first or second drug choice. If available, angiotensin II will work well as second line vasopressor; it is possible that phenylephrine may lead to worse outcomes if used as first line therapy.

**CONCLUSION**

Accuracy in diagnosis with selection of the right tool for assessment and not simply symptomatic treatment must be a strategic element in the care provided to patients with circulatory failure. Understanding physiological concepts is vital. More importantly, learning and practicing medicine based only on protocols and flowcharts will always exclude an important portion of the science. The careful understanding and management of circulation must be part of daily clinical practice. Changing dogmas in medicine generates apprehension as the illusion of knowledge and expertise becomes vulnerable, but we as health care providers should continue evolving for the benefit of our patients.

Intravenous fluid solutions are more similar to drugs than is acknowledged and therefore need to be used with care and precision. The composition of the fluid does matter, but only if the patient is alive. When administering intravascular fluids, targets such as the restoration of intravascular volume should have more impact on medical decisions than urine output or blood pressure. Extravasation of water and solutes can occur, and for this reason, we need to be mindful that not every patient in a hospital bed needs a fluid bolus.
Table 4 Correlates of low cardiac output

|                  | Low CO | High CO |
|------------------|--------|--------|
| Blood pressure   | ↓      | ↓      |
| Heart rate       | ↑      | ↑      |
| Systemic vascular resistance | ↑      | ↓      |
| CO               | ↓      | ↑      |
| Pulse pressure   | ↓      | ↑      |

CO: Cardiac output.

Table 5 Crystalloid vs colloid solutions

| Crystalloid                      | Colloid                      |
|----------------------------------|------------------------------|
| Lower price                      | Expensive                    |
| Believed to be safer             | Some toxic (hydroxyethyl starch) |
| Higher amount needed for resuscitation | Less required               |
| Slower action                    | Faster action                |
| Moves out the intravascular space faster | Remains in circulation longer |

Figure 4 Protocol for early goal-directed therapy. Adapted from[9].
Figure 5  Guyton's model of venous return and cardiac output in relation to the right atrial pressure. Adapted from[62].

Figure 6  Frank-Starling curves representing normal contractility, diastolic dysfunction, and contractile dysfunction. PcwP: Pulmonary capillary wedge pressure. Adapted from[63].

Figure 7  Modified cardiac function curve representing the central venous pressure measured in the clinical setting by superimposing Guyton's model of venous return and Frank-Starling contractility curve. CO: Cardiac output; CVP: Central venous pressure; PRA: Right atrial pressure; VR: Venous return; PMS: Mean systemic filling pressure. Adapted from[62].
Figure 8  Description of the systolic pressure variation and pulse pressure variation during mechanical ventilation. SPV: Systolic pressure variation; PPV: Pulse pressure variation; artP: Arterial pressure; awP: Airway pressure; SBP: Systolic pressure. PP = 100 x (PPmax – PPmin) / [(PPmax + PPmin)/2].

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