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Review

Hemodynamic monitoring in cardiogenic shock

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ABSTRACT

Cardiogenic shock (CS) is a life-threatening condition characterized by acute end-organ hypoperfusion due to inadequate cardiac output that can result in multiorgan failure, which may lead to death. The diminished cardiac output in CS leads to systemic hypoperfusion and maladaptive cycles of ischemia, inflammation, vasoconstriction, and volume overload. Obviously, the optimal management of CS needs to be readjusted in view of the predominant dysfunction, which may be guided by hemodynamic monitoring. Hemodynamic monitoring enables (1) characterization of the type of cardiac dysfunction and the degree of its severity, (2) very early detection of associated vasoplegia, (3) detection and monitoring of organ dysfunction and tissue oxygenation, and (4) guidance of the introduction and optimization of inotropes and vasopressors as well as the timing of mechanical support. It is now well documented that early recognition, classification, and precise phenotyping via early hemodynamic monitoring (e.g., echocardiography, invasive arterial pressure, and the evaluation of organ dysfunction and parameters derived from central venous catheterization) improve patient outcomes. In more severe disease, advanced hemodynamic monitoring with pulmonary artery catheterization and the use of transpulmonary thermodilution devices is useful to facilitate the right timing of the indication, weaning from mechanical cardiac support, and guidance on inotropic treatments, thus helping to reduce mortality. In this review, we detail the different parameters relevant to each monitoring approach and the way they can be used to support optimal management of these patients.

Introduction

Two decades after the landmark Should We Emergently Revascularize Occluded Arteries in Cardiogenic Shock (SHOCK) trial demonstrated improvements in acute myocardial infarction–cardiogenic shock (CS) survival,[1] CS remains characterized by a short-term mortality rate of >40%.[2] Recent analyses of North American registries, however, suggest that outcomes may be improved through early shock recognition and the use of standardized treatment algorithms.[3–5]

Several definitions of CS have been proposed and are summarized in Table 1. Among them, a clinical definition proposed by Levy et al.[6] defines CS as a condition characterized by (1) a systolic blood pressure (SBP) of <90 mmHg, a mean arterial pressure (MAP) of <65 mmHg for 30 min, or the need for vasopressor therapy; (2) the presence of pulmonary congestion or elevated left ventricular (LV) filling pressures; and (3) signs of impaired organ perfusion (e.g., altered mental status, cold and clammy skin, oliguria, or an increased serum lactate level). However, hypoperfusion is not always associated with hypotension, as compensatory vasoconstriction may maintain blood pressure within the normal range.[7] By contrast, the presence of hypotension may not be required to define shock.[8]

Hospital mortality risk stratification can be performed using the Society for Cardiovascular Angiography and Intervention (SCAI) shock classification scheme, which can be broken down as follows: stage A, at risk; stage B, beginning (presence of hypotension/tachycardia without hypoperfusion); stage C, classic (hypoperfusion without deterioration); stage D, deteriorating (hypoperfusion with deterioration but no refractory shock); and stage E, extremis (hypoperfusion with deterioration and refractory shock, which is defined by SBP <80 mmHg or MAP <50 mmHg under vasoactive drugs; >2 vasoactive drugs or >1 vasoactive drug in association with an intra-aortic balloon

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Table 1
Cardiogenic shock definitions.

Study	SBP	Organ hypoperfusion	Lactate concentration	Pulmonary congestion	Cardiac index
SHOCK trial 1999[1]	≤90 mmHg for ≥30 min or vasopressors to maintain SBP > 90 mmHg	Urine output <30 mL/h or cool extremities	NA	PCWP >15 mmHg	≤2.2 L/min/m^2
IABP-SHOCK trial 2012[78]	<90 mmHg for ≥30 min or vasopressors to maintain SBP >90 mmHg	Altered mental status, cold extremities, or urine output <30 mL/h	>2 mmol/L	Clinical	NA
Levy et al. 2015[6]	<90 mmHg, MAP <65 mmHg for ≥30 min, or vasopressors to maintain SBP >90 mmHg	Altered mental status or cold extremities or low urine output	Elevated	Clinical or echographic	NA
IMPRESS trial 2017[79]	≤90 mmHg for ≥30 min or vasopressors to maintain SBP >90 mmHg	NA	NA	NA	NA
CULPRIT-SHOCK trial 2017[80]	≤90 mmHg for ≥30 min or vasopressors/inotropes to maintain SBP >90 mmHg	Altered mental status or cold extremities or urine output < 30 mL/h	>2 mmol/L	Clinical	NA
Chioncel et al. 2020[13]	SBP can be preserved	Tissue hypoperfusion	Elevated	NA	Inadequate cardiac output
ESC guidelines 2021[81]	SBP can be preserved	Altered mental status, cold extremities, low urine output, or dizziness	Elevated	NA	Inadequate cardiac output

ESC: European Society of Cardiology; MAP: Mean arterial pressure; NA: Not available; PCWP: Pulmonary capillary wedge pressure; SBP: Systolic blood pressure.

pump; or an admission lactate level of >10 mmol/L).[9] In this scoring system, SBP, MAP, heart rate, signs of hypoperfusion (e.g., urine output, increased creatinine level at admission, and maximum lactate level), and the number of vasoactive drugs are determinants of the condition's severity and underlie the importance of using monitoring tools to follow their evolution.

The central pathophysiologic derangement in CS is diminished cardiac output,[2] which leads to systemic hypoperfusion and maladaptive cycles of ischemia, inflammation, vasoconstriction, and volume overload, often culminating in multiorgan system failure and death.[2,10]

This large hemodynamic variability is due to the diversity of previously quoted pathogenic mechanisms, the type of ventricle damage (right, left, or both), systemic inflammation and associated vascular involvement, and the severity of the shock. As a consequence, the optimal management of CS needs to be readjusted in view of the characteristics, phase, and evolution of CS. Moreover, identifying different hemodynamic profiles according to the etiology could help to individualize treatments; for example, research suggests that patients with CS secondary to acute myocardial infarction exhibit lower systemic vascular resistance compared to those with acute decompensation of chronic heart failure and could be related to systemic inflammation.[11] This should be considered when making the choice of catecholamines.

Indeed, hemodynamic monitoring may be of significant help because it enables (1) characterization of the type of cardiac dysfunction and the degree of its severity, (2) very early detection of associated vasoplegia, (3) detection and monitoring of organ dysfunction and tissue oxygenation, and (4) guidance of the introduction and optimization of inotropes and vasopressors as well as the timing of mechanical support.

Recently, Tehrani et al.[3] examined whether a standardized team-based approach could improve outcomes in CS and whether a risk score can guide clinical decision-making. Their algorithm included invasive hemodynamic monitoring (IHM) in addition to a therapeutic protocol, and its use in their observational study led to a better outcome in patients with CS.[3] Similar results were reported in a study using data from a real-world contemporary database[12] including 394,635 patients subdivided into an IHM group (with measurement, monitoring, or insertion of a monitoring device to check cardiac output or pulmonary artery hemodynamic; n=62,565) or a non-IHM (n=332,070) group. After propensity score matching, two well-matched groups were compared (IHM group, n=62,220; non-IHM group, n=62,220), and it was determined that the IHM group had a lower in-hospital mortality rate (24.1% *vs.* 30.6%, P <0.01) and higher percentages of LV assist device use (4.4% *vs.* 1.3%, P <0.01) and heart transplantation (1.3% *vs.* 0.7%, P <0.01), while there was no difference between the two groups in terms of vascular complications, major bleeding, or the need for renal replacement therapy.[12]

Furthermore, expert recommendations concerning CS management and a conference consensus on monitoring during shock emphasize the initiation of basic monitoring in the first hours of shock, which should be completed by an advanced one in more complicated and refractory shock.[6,8,13,14] The intensity and degree of invasiveness of the monitoring thus depend on the severity and the degree of instability of the shock (e.g., stage A [at risk] *vs.* stage E [extremis]) as well as on comorbidities, the

etiology of the CS, and the patient's hemodynamic profile. The relative experience of the clinician with the different techniques is also a factor that should be taken into account when choosing the most appropriate monitoring. In all cases, for the diagnosis and management of shock, the use of a number of different variables rather than any one alone is recommended.[8]

In this review, we discuss methods of hemodynamic monitoring during CS, the different parameters displayed by each monitoring approach, and the way we can use them to support the optimal management of patients.

First-Line Monitoring

Initial evaluation and repeated clinical examinations are necessary for the evaluation of hypoperfusion signs (e.g., mottling, cold and sweaty extremities, dizziness, and mental confusion). In addition, continuous monitoring of vital signs at the bedside, including pulse oximetry, blood pressure, respiratory rate, and cardiac rhythm, needs to be very rapidly enacted in CS patients. Moreover, urine output monitoring and repeated electrocardiograms are also mandatory. However, clinical evaluations may be unable to estimate cardiac output, which is an essential parameter in the management of CS patients.[15] The first-line monitoring parameters and devices have been summarized in Figure 1 and Table 2.

Echocardiography

Current guidelines recommend performing routine transthoracic echocardiography (TTE) or transesophageal echocardiography (TEE) in the management of CS.[6,8] TTE is recommended first in nonventilated patients, but TEE should be used when TTE does not provide the required information. TEE has better echogenicity, sensitivity, and an improved view of deep anatomic structures (such as the aorta, patent foramen ovale, valves, canulae, and localized hematomas).[16]

First-line echography should be performed as soon as possible to confirm the etiology of the shock and rule out other causes (e.g., obstructions such as cardiac tamponade or pulmonary embolism or vasoplegic or hypovolemic causes), some of which require urgent treatment.[6]

Echocardiography can help to identify the etiology of the CS, such as left or right systolic dysfunction (secondary to acute myocardial infarction, myocarditis, acute or chronic heart failure, or rhythm or conduction disturbances), severe valvular disease (endocarditis, aortic dissection, or chordae or papillary muscle rupture), or LV outflow tract obstruction, which is crucial information to know in order to correct the cause.[17]

Echocardiography is also necessary for the evaluation of cardiac output.[17] For patients who do not respond to the initial therapy, routine measurement of cardiac output is recommended, and echography is the preferred modality for the measurement of cardiac output over more invasive technologies.[8]

Echocardiography can evaluate both the right and left filling pressures, fluid responsiveness, and pulmonary artery pressure. Most CS patients present with elevated LV pressures, but hypovolemia can also be present in some cases. The evaluation of right (inferior vena cava diameter and respiratory variations, sus hepatic vena) and left (mitral E/A and E/é) congestive signs is important for tailoring therapeutics and determining whether diuretics are needed.[18,19]

Moreover, repeated echocardiography can detect mechanical complications in cases of acute myocardial infarction, such as LV or right ventricular (RV) free wall rupture, interventricular communication, mitral chordae or papillary muscle rupture, or complications of mechanical cardiac assistance. In such cases, echocardiography can also assist with controlling the cannula insertion and monitoring the recovery of heart function and the timing of weaning.[17,20]

Echocardiography is a useful tool for monitoring therapeutic effects on hemodynamics regardless of the type of shock (i.e., not only in CS), with some studies demonstrating an interest in the resolution of hemodynamic instability but no impact on mortality.[21–23]

Recently, a retrospective analysis of patients in the cardiac intensive care unit with an admission diagnosis of CS and TTE imaging performed within 1 day of admission[23] suggested the LV outflow tract and velocity–time integral to be the best predic-

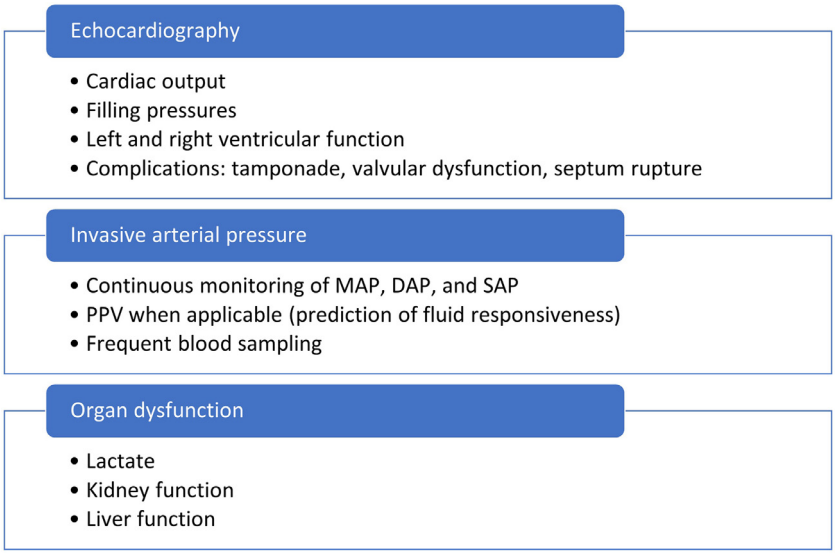

Figure 1. First-line monitoring. DAP: Diastolic arterial pressure; MAP: Mean arterial pressure; PPV: Pulse pressure variation; SAP: Systolic arterial pressure.

Table 2
Monitoring devices used during CS.

Devices	Advantages	Disadvantages
First-line devices		
Echocardiography	Noninvasive May be repeated with no supplementary risk Important information about the cause of CS	Not continuous monitoring Requires training period May be operator-dependent
Arterial catheter use	Continuous blood pressure monitoring Derived parameters for testing fluid responsiveness Allows repeated blood sampling	Insertion-related complications Hematoma Infections
Central venous catheter use	Safe catecholamines administration Measurement of important Hemodynamic parameters (CVP, $ScVO_2$, and PcO_2 gap)	Insertion-related complications Hematoma Infections
Advanced hemodynamic monitoring		
PAC use	Measurement of cardiac output (semi-intermittent) Continuous measurement of CVP, $ScVO_2$, and PAP Measurement of PcO_2 gap and PCWP Measurement of cardiac power output Early identification of patients with significant hemodynamic compromise requiring immediate MCS	Insertion-related complications Heart block Pulmonary artery rupture
Transpulmonary thermodilution devices	Continuous monitoring of cardiac output (in addition to the intermittent technique) Measurement of: EVLW, GEF, and CFI	Insertion-related complications
Non-IHM		
NICOM	Noninvasive	Unreliable in the case of CS

CFI: Cardiac function index; CS: Cardiogenic shock; CVP: Central venous pressure; EVLW: Extravascular lung water; GEF: Global ejection fraction; IHM: Invasive hemodynamic monitoring; MCS: Mechanical cardiac support; NICOM: Noninvasive cardiac output monitor; PAC: Pulmonary artery catheter; PAP: Pulmonary arterial pressure; PcO_2 gap: The veno-arterial difference in the partial pressure of carbon dioxide; PCWP: Pressure capillary wedge pressure; $ScVO_2$: Central venous oxygen saturation.

tors of hospital mortality, even after multivariable adjustment in association with LV ejection fraction.[24]

The main limitation of both TTE and TEE is that neither is a continuous monitoring tool (i.e., they can be used only intermittently [or semi-continuously if using a miniaturized TEE probe]). Other limitations of TTE include poor echogenicity in some patients (e.g., ventilated patients, obese patients, patients with dressings or chest tubes, or patients in a prone position), while those of TEE are its time-consuming and invasive nature with risks for tracheal, hypopharyngeal, esophageal, or gastric injury. Absolute contraindications of TEE include esophageal strictures, tumors, perforation, diverticulum, and active upper gastrointestinal bleeding.[25]

Arterial Catheterization

Although the noninvasive application of cuff arm pressure can reliably assess MAP most of the time,[26] severe hypotension and hypothermia affect the agreement between noninvasive and invasive MAP values.[27] Indeed, a study by Burstein et al.[28] showed that a mean MAP of <65 mmHg (attained with a mix of invasive and noninvasive measurements) during the first 24 h in CS patients was associated with a higher mortality rate. For patients who do not respond to the initial therapy, the experts reached a strong agreement on the need to place an arterial catheter to monitor not only SBP and MAP but also diastolic arterial pressure, which reflects the coronary artery perfusion pressure during relaxation and dilatation of the ventricles.[7,8] Furthermore, a low pulse pressure (PP) (calculated by systolic arterial pressure – diastolic arterial pressure) can help to detect a low stroke volume. Invasive arterial pressure measurement allows for hemodynamic diagnosis, continuous monitoring, titration of vasopressors and inotropes, and the prediction of fluid responsiveness in mechanically ventilated patients (ΔPP measurement).[29]

Arterial catheterization also enables repeated samplings for blood analysis and arterial lactate monitoring (see below); however, it can increase the number of unnecessary blood sample collections and can be complicated by vascular lesions (occlusion, ischemia, dissection, pseudoaneurysm, and hematoma) and local or bloodstream infections.[30] An ongoing clinical trial is evaluating the effect of an indwelling arterial catheter on mortality in the monitoring of acute circulatory failure.[30]

Organ Dysfunction

Lactate

Lactate is a metabolite in two energy (adenosine triphosphate)-producing processes: glycolysis and oxidative phosphorylation. Lactate production is related not only to anaerobic metabolism in tissue hypoxia but also to aerobic glucose metabolism in the case of β2 stimulation,[31] alkalosis, diabetic ketoacidosis, mitochondrial dysfunction, thiamine deficiency, or medication use.[32] Lactate elevation can also be related to impaired clearance, mainly secondary to liver dysfunction.[33]

In patients suffering from CS, plasma hyperlactatemia mainly indicates the presence of increased endogenous production secondary to abnormal anaerobic metabolism,[34] with a usual cut-off value of 2 mmol/L.[12] This cut-off value is used for the definition of hypoperfusion in the SCAI CS classification scheme.[9] A maximal value higher than that recorded at admission is one of the items defining a deterioration in the classification, whereas a value of ≥10 mmol/L at admission is a criterion to diagnose refractory shock.[9] Initial lactate levels are commonly

used as a prognostic tool, as it has been shown that a correlation exists between the initial lactate level and mortality in CS secondary to acute myocardial infarction.[35]

Elevated lactate levels may also indicate tissue hypoperfusion despite adequate MAP. Close monitoring of plasma lactate concentrations may help clinicians to anticipate deterioration and adapt therapeutics.[36] Arterial lactate measurements at 8 h (with a cut-off value of >3.1 mmol/L) showed a better prognostic value compared to baseline or lactate clearance values.[37] Plasma lactate should thus be assayed repeatedly to assess the evolution of shock during treatment every 2 h in the first 8 h and then every 8–12 h thereafter as recommended by recent guidelines.[8]

Organ function

As emphasized by experts' recommendations, the biological values of kidney and liver function, neurological status, and splanchnic perfusion should be repeatedly assessed.[8] Laboratory testing should be performed at admission and 1–2 times/day thereafter depending on the severity and evolution of the patient's clinical state.[38,39]

Severe acute kidney injury (acute kidney injury stage 3), which is observed in about one-third of patients with CS, is associated with mortality[40,41] in one-third of patients with severe CS requiring short-term mechanical assistance and is a predictor of long-term mortality.[42]

Elevated liver enzymes are observed in >50% of patients in CS and are associated with mortality (e.g., aspartate aminotransferase is an independent predictor of 30-day mortality according to the study by Jung et al.[43]) It is noteworthy that multiorgan failure (defined by the failure of ≥2 organs) is associated with mortality in CS patients. Accordingly, in a recent study including data from 1959 patients with CS, the authors used machine learning to identify and validate three distinct CS phenotypes: noncongested, cardiorenal (characterized by a lower glomerular filtration rate with renal involvement from shock), and cardiometabolic (characterized by elevated lactate and alanine aminotransferase levels with multiorgan involvement). This latest phenotype was associated with the highest risk of developing stage D or E SCAI shock and the highest in-hospital mortality rate.[44]

Troponin monitoring is recommended at admission in all cases, especially in the case of acute myocardial infarction–CS,[45] but not systematically in patients with other causes.[38]

Parameters Derived from Central Venous Catheter Sampling

In patients with CS, one of the main goals of treatment is to increase the cardiac output. More specifically, the aim is to improve oxygen delivery to the tissues and correct the mismatch between the oxygen demand and supply, which is the hallmark of shock.[46] However, no absolute normal value of cardiac output or oxygen delivery has been defined, as their adequate values basically depend on unique tissue oxygen requirements. In other words, the correct value of cardiac output is that which ensures a flow of oxygen that meets the metabolic demand.[46,47] Thus, any treatment aimed at changing the cardiac output must be driven by the assessment of the ratio of oxygen demand and supply, which may be based on central venous oxygen saturation ($ScvO_2$) and/or the veno-arterial difference in CO_2 pressure ("ΔPCO_2" or "the PCO_2 gap"). In addition to these latter parameters, measurement and monitoring of central venous pressure may be very useful during CS (Figure 2).

Central venous pressure

The insertion of a femoral vena cava catheter allows for monitoring of the central venous pressure, which reflects the right atrial pressure and RV preload[48] and can support an estimation of the degree of congestion of extra-thoracic organs. Because of measurement constraints and its limits as a marker of preload and preload dependency as a static parameter, its routine use with single point measurements is not recommended,[6,8] but continuous monitoring can provide information on trends in

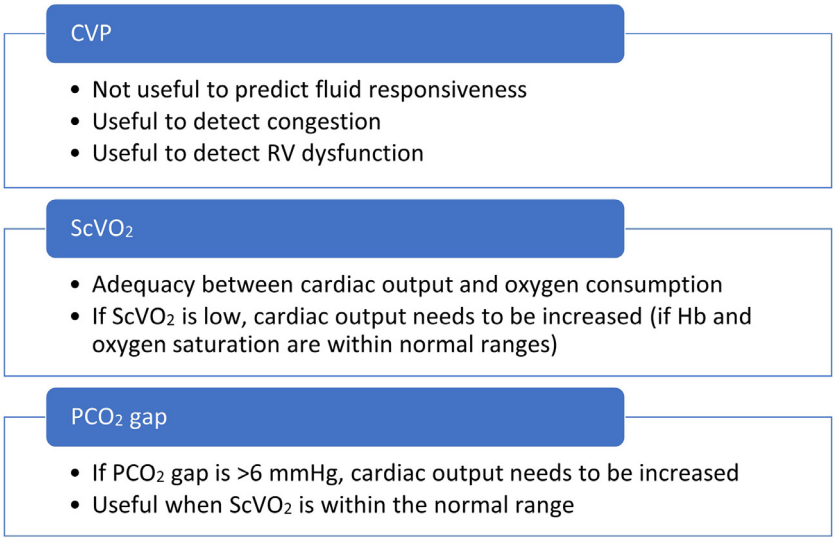

Figure 2. Parameters derived from central venous catheterization. CVP: Central venous pressure; Hb: Hemoglobin; PCO_2 gap: Veno-arterial difference of CO_2 pressure; RV: Right ventricular; $ScVO_2$: Saturation of central venous oxygen saturation.

fluid status[14] and can be useful to assess preload in a multimodal way. In addition, it can be helpful to distinguish organ failure related to congestion[45] rather than hypoperfusion, as the right timing of using loop diuretics to improve organ function following the correction of perfusion is indeed sometimes unclear in CS.

A high central venous pressure (>12 mmHg) can help to diagnose RV failure in CS under left-sided mechanical assistance and is associated with higher in-hospital mortality rates.[49]

Central venous oxygen saturation ($ScVO_2$)

Mixed venous oxygen saturation (SvO_2) is assumed to reflect the balance between arterial oxygen delivery (DO_2) and oxygen consumption (VO_2) provided that the arterial blood oxygen saturation (SaO_2) is normal. Indeed, the modified Fick equation states that SvO_2=SaO_2 − [VO_2/(cardiac output × Hb × 1.34)], with Hb being the hemoglobin concentration. Inadequate systemic oxygen delivery will result in an increase in tissue fractional oxygen extraction and a decrease in venous oxygen saturation.[50,51] Patients with low SvO_2 values can be either fluid-responsive in cases of hypovolemic shock or fluid-unresponsive in cases of CS. Indeed, the absence of fluid responsiveness should incite consideration of other therapies (e.g., inotropes) that enable a cardiac output increase with the ultimate goal of decreasing tissue hypoxia. The measurement of SvO_2 from the pulmonary artery has been advocated for as an indirect index of tissue oxygenation.[52] Over the last few decades, controversial data about the use of pulmonary artery catheters (PACs) have been published, leading to their unpopularity.[53–55] By contrast, the insertion of an intra-thoracic central venous catheter is considered standard care for the administration of inotropes and vasopressors in critically ill patients.[8,45] Just like with SvO_2, the measurement of $ScvO_2$ has been advocated for in order to detect global tissue hypoxia. Furthermore, reduced SvO_2 or $ScvO_2$ values in addition to low blood pressure, low cardiac output, and normal or increased pulmonary capillary wedge pressure (PCWP) values despite inotropic/vasopressor support may be helpful to identify patients who need left-sided mechanical cardiac support (MCS).[56] In addition, during the management of patients with MCS, SvO_2, or $ScvO_2$ represents an additional index of the adequacy of total flow by which to discern the physiological state of the patient. Indeed, while other tissue perfusion parameters, such as lactate, necessitate a delay when obtaining laboratory results or for their clearance, SvO_2 and $ScvO_2$ are more immediately available for guiding therapy. Accordingly, experts recommend (with strong agreement) that cardiac output as well as SvO_2 or $ScvO_2$ be continuously monitored in the case of shock refractory to empirical treatment.[8]

The PCO_2 gap

The difference between the mixed venous content and arterial content of CO_2 reflects the balance between its production by tissues and its elimination through the lungs. This veno-arterial difference in CO_2 content can be estimated at the bedside by calculating the veno-arterial difference in PCO_2 (venous partial pressure of CO_2 [$PvCO_2$] − arterial partial pressure of CO_2 [$PaCO_2$]), and this is known as the PCO_2 gap or ΔPCO_2.

According to the modified Fick equation, $\Delta PCO_2 = (k \times VCO_2)$/cardiac output, where VCO_2 is the CO_2 production and k is the factor in the relationship between PCO_2 and the CO_2 content that is influenced by the degree of blood pH, hematocrit, and the arterial oxygen saturation.[57–59] This relationship between ΔPCO_2 and cardiac output expresses the fact that, if cardiac output is low, the CO_2 clearance decreases, CO_2 stagnates at the venous side, and $PvCO_2$ increases relative to $PaCO_2$ at the venous level, leading to an increase in the PCO_2 gap. In other words, for a given VCO_2 value, a decrease in cardiac output results in an increased PCO_2 gap and vice versa. In clinical practice, a larger PCO_2 gap (>6 mmHg) suggests that the cardiac output is not high enough with respect to the patient's global metabolic condition. As a consequence, in the case of shock (e.g., increased blood lactate level), a large PCO_2 gap could prompt clinicians to increase the cardiac output with the aim of reducing tissue hypoperfusion.[60] Furthermore, in a patient with a high initial ΔPCO_2 value, following the time course of ΔPCO_2 can also be helpful in assessing the global metabolic effects of a therapy aimed at increasing the cardiac output.

An advantage of using the PCO_2 gap over $ScvO_2$ is that it remains a valid marker of the adequacy of cardiac output relative to the metabolic condition, even if the microcirculation is injured and the oxygen extraction is impaired (e.g., by an ischemic–reperfusion situation and high inflammation state during CS). This could be due to the fact that CO_2 is about 20 times more soluble than O_2.[60] The microcirculatory impairment, with large veno-arterial shunts, impedes the diffusion of O_2 between cells and red blood cells, while the diffusion of CO_2 remains unaltered.[60] A confirmation comes from the study by Ospina-Tascón et al.,[61] who suggested that, in the early phases of septic shock, ΔPCO_2 could indicate the adequacy of microvascular blood flow, as increased Pv-aCO_2 values were associated with microcirculatory dysfunction in septic shock, even when SvO_2 was within the normal range.[61]

In addition, it is noteworthy that previous studies found an increased PCO_2 gap in the first hours under veno-arterial extracorporeal membrane oxygenation to be significantly associated with an increased risk of mortality.[62,63] Interest in the PCO_2 gap focuses on its potential as a complementary tool to evaluate the adequacy of blood flow relative to the global metabolic demand when other parameters, including SvO_2 or $ScvO_2$ and lactate level, are discordant[64] and in patients receiving MCS.

Advanced Hemodynamic Monitoring

Advanced hemodynamic monitoring is recommended for patients nonresponsive to initial therapies or those with RV dysfunction[6] (Figure 3 and Table 2).

Pulmonary artery catheterization

PACs directly measure pulmonary and cardiac pressures and oxygen saturation (allowing for continuous monitoring of SvO_2) and are used to calculate an array of hemodynamic parameters, including cardiac output and vascular resistances. It is the reference method used to calculate cardiac output.[8] Such monitoring facilitates triage and the management of patients presenting with acute hemodynamic decompensation. Early recog-

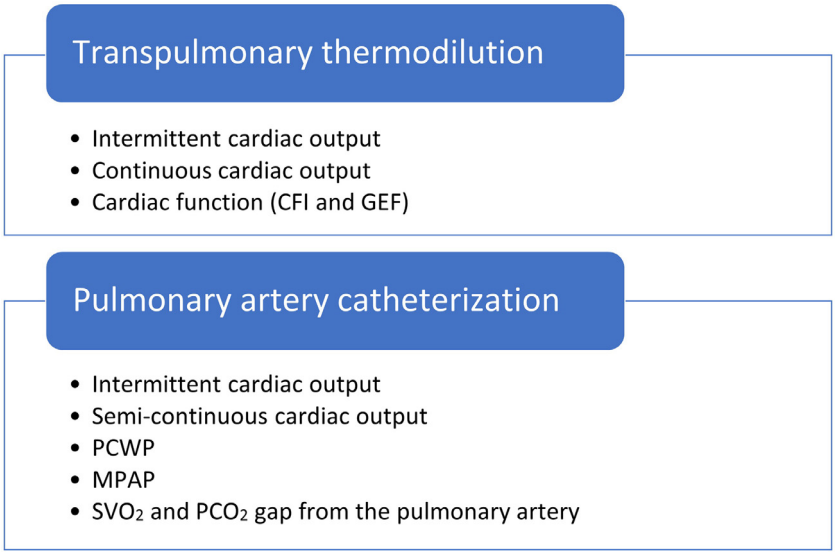

Figure 3. Advanced hemodynamic monitoring. CFI: Cardiac function index; GEF: Global ejection fraction; MPAP: Mean pulmonary arterial pressure; PCO_2 gap: Veno-arterial difference of CO_2 pressure; PCWP: Pulmonary capillary wedge pressure; SVO_2: Venous oxygen saturation.

nition and triage of patients with CS using specific therapeutic algorithms are increasing, including identification of the shock subtype and an understanding of the expected impact of a device on parameters such as cardiac output, PCWP, right atrial pressure, and mean pulmonary arterial pressure.[3] Knowledge of these parameters allows the clinician to choose the device or combination of devices that best match the patient's needs. PACs also enable measurement of the cardiac power output, which is the product of simultaneously measured cardiac output and MAP values and reflects the cardiac pumping ability. Notably, cardiac power output was associated with prognosis in an ancillary study of the SHOCK trial.[65] It also allows the assessment of RV dysfunction using the pulmonary artery pulsatility index (PAPI), which is calculated as the pulmonary artery PP (systolic pressure − diastolic pressure) divided by the right atrial pressure (PAPI = [PASP − PADP]/right atrial pressure) and reflects components of the right heart system (i.e., the systemic venous system, RV function, and pulmonary circulation).[66] Adopting a standardized team-based approach with a score based on cardiac power output and PAPI to guide clinical decision-making could improve patient outcomes, as we mentioned early in this review.[3]

Additional benefits from the acquisition of complete PAC data include early identification of patients with significant hemodynamic compromise requiring immediate MCS, which could avoid irreversible end-organ dysfunction resulting from treatment delays. Additionally, PAC data facilitate early recognition of a biventricular shock state, which is often underappreciated and may require consideration of biventricular support.[56] Finally, the continuous feedback obtained from PACs facilitates the optimization of volume status, adjustments of vasoactive medications in a more targeted fashion, and recognition of when patients can be weaned from such devices. In this regard, a recent study[67] including data from one of the largest multicenter registries reported that the use of complete hemodynamic data obtained by timely placement of PACs prior to MCS initiation was associated with lower mortality in patients with advanced stages of CS.[67] Several recent observational studies have evaluated the effect of PAC use on short-term mortality in CS, but they enrolled heterogeneous populations and were not randomized trials. A meta-analysis of these studies reported a lower incidence of short-term mortality with PAC insertion, which should be confirmed by further research. As underlined by the authors, no monitoring device can improve the outcome unless associated with a standardized therapeutic protocol in an integrated approach.[68]

Recent guidelines[69,70] recommend invasive hemodynamic assessment, with measurement of ventricular filling pressure, cardiac output, and systemic vascular resistance, for the diagnosis of CS. In addition, PACs are recommended for continuous hemodynamic monitoring in the acute management of patients receiving therapy with MCS to guide its withdrawal and supervise the pharmacologic support of patients with myocardial recovery from CS.[69,70] Furthermore, in patients without recovery of myocardial and end-organ function, hemodynamic monitoring is useful for assessing candidacy for and supporting the transition to advanced heart failure therapies, including durable mechanical circulatory support and heart transplantation.[42,43] Similar recommendations given by French experts[6] suggest undertaking pulmonary artery catheterization in patients with refractory CS and RV dysfunction.[6] It is noteworthy that PAC insertion may be associated with some complications, such as catheter insertion site–related complications (up to 3.6%), heart block (0.3–3.8%), and pulmonary artery rupture (<1/1000 people).[71]

Transpulmonary thermodilution (TPTD)

During the last decade, TPTD technique–based devices have emerged as an interesting monitoring approach that differs from the use of PACs. Indeed, this system allows for the assessment of cardiac output[72] in two different ways. First is a thermodilution technique that measures cardiac output by using the Stewart–Hamilton principle. Here, a cold saline bolus is injected in the right central vein, and the blood temperature is measured in the femoral artery. Second is the pulse

contour analysis of the arterial curve sampled through the arterial catheter, which allows real-time monitoring of cardiac output and is calibrated by TPTD each time thermodilution is performed, which makes this technique very precise. TPTD devices also allow the assessment of other parameters, particularly two indices of cardiac systolic function, which are the cardiac function index (CFI) and the global ejection fraction. Both appear to be correlated with the LV systolic ejection fraction measured with echocardiography in patients with circulatory failure.[73–75] The use of TPTD systems is a simple and easily reproducible technique that provides a consistent estimation of LV ejection fraction; however, they do not replace echocardiography. The physician should take a low CFI to be an alert of a possible impairment of LV systolic function, and echocardiography must be performed to exclude RV impairment. Once LV dysfunction is confirmed, CFI allows for consistent monitoring of LV function under inotropic treatment. Accordingly, the study by Perny et al.[75] demonstrated that CFI is significantly correlated with LV ejection fraction in CS, provided that the patient does not present with severe isolated RV dysfunction.[75] Indeed, the use of such techniques is suggested by experts[8] when CS is refractory to initial treatment in the absence of mechanical assistance and predominant RV dysfunction.

TPTD also provides continuous measurement of $ScvO_2$. The combination of TPTD and pulse contour analysis makes it an alternative to using PACs, especially in complex situations like hemodynamic instability or acute respiratory distress syndrome. Conversely, devices using pulse contour analysis without calibration should not be used in this setting because of low performance in the case of low cardiac output.[45]

Drawbacks to TPTD include that cardiac output is not a continuous measure and requires an association with a measure by pulse contour analysis, which necessitates regular recalibration; global end-diastolic volume does not distinguish between the LV and RV; and global ejection fraction overestimates LV systolic function in the case of ventricular dilation.[76]

Noninvasive Hemodynamic Monitoring

As we have mentioned, the use of IHM is indicated in selected patients in whom a clinical evaluation does not provide sufficient data to determine optimal medical theray.[69,70] For these reasons, the measurement of cardiac output using noninvasive or minimally invasive devices has gained popularity. The bioreactance technique is one example of such an option, but in a study[77] that enrolled 50 patients suffering from CS, the correlation coefficient for cardiac output measured by the bioreactance technique using a noninvasive cardiac output monitor was poor compared to those obtained with the indirect Fick and thermodilution methods.[77] The authors concluded that noninvasive cardiac output monitoring technology is not a reliable method of measuring cardiac output in patients with decompensated heart failure and CS.[77] There are some potential reasons that explain the unreliability of such a technique in CS patients. First, bioreactance technology is reliant on the diffusion of oscillating electrical currents through the thoracic cavity and, hence, is likely to be affected by the pulmonary and interstitial edema frequently present in patients with CS. Second, elevated right- and left-sided preloads in patients with CS are also likely to affect the intrathoracic impedance and, hence, alter the current phase shifts used to estimate stroke volume and, subsequently, cardiac output. Third, the low flow state in CS may also contribute to the erroneous assessment of cardiac output with the bioreactance technique. Finally, it should be noted that such technology continues to offer an unreliable measurement of cardiac output in patients with advanced heart failure (Table 2).

Conclusions

CS is a life-threatening condition characterized by acute end-organ hypoperfusion due to inadequate cardiac output that results in multiorgan failure and even death in a nonnegligible proportion of cases. Hemodynamic monitoring allows for early recognition, classification, and precise phenotyping of CS cases, leading to a targeted management scheme that contributes to better patient outcomes. In addition, IHM using an algorithmic approach for managing CS with the rapid deployment of MCS is nowadays the preferred approach, as it is associated with a reduction in mortality.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Hochman JS, Sleeper LA, Webb JG, Sanborn TA, White HD, Talley JD, et al. Early revascularization in acute myocardial infarction complicated by cardiogenic shock. SHOCK investigators. Should we emergently revascularize occluded coronaries for cardiogenic shock. N Engl J Med 1999;341(9):625–34. doi:10.1056/NEJM199908263410901.

[2] van Diepen S, Katz JN, Albert NM, Henry TD, Jacobs AK, Kapur NK, et al. Contemporary management of cardiogenic shock: a scientific statement from the American Heart Association. Circulation 2017;136(16):e232–68. doi:10.1161/CIR.0000000000000525.

[3] Tehrani BN, Truesdell AG, Sherwood MW, Desai S, Tran HA, Epps KC, et al. Standardized team-based care for cardiogenic shock. J Am Coll Cardiol 2019;73(13):1659–69. doi:10.1016/j.jacc.2018.12.084.

[4] Basir MB, Kapur NK, Patel K, Salam MA, Schreiber T, Kaki A, et al. Improved outcomes associated with the use of shock protocols: updates from the national cardiogenic shock initiative. Catheter Cardiovasc Interv 2019;93(7):1173–83. doi:10.1002/ccd.28307.

[5] Taleb I, Koliopoulou AG, Tandar A, McKellar SH, Tonna JE, Nativi-Nicolau J, et al. Shock team approach in refractory cardiogenic shock requiring short-term mechanical circulatory support: a proof of concept. Circulation 2019;140(1):98–100. doi:10.1161/CIRCULATIONAHA.119.040654.

[6] Levy B, Bastien O, Karim B, Cariou A, Chouihed T, Combes A, et al. Experts' recommendations for the management of adult patients with cardiogenic shock. Ann Intensive Care 2015;5(1):52. doi:10.1186/s13613-015-0052-1.

[7] McDonagh TA, Metra M, Adamo M, Gardner RS, Baumbach A, Böhm M, et al. 2021 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure. Eur Heart J 2021;42(36):3599–726. doi:10.1093/eurheartj/ehab368.

[8] Cecconi M, De Backer D, Antonelli M, Beale R, Bakker J, Hofer C, et al. Consensus on circulatory shock and hemodynamic monitoring. Task force of the European Society of Intensive Care Medicine. Intensive Care Med 2014;40(12):1795–815. doi:10.1007/s00134-014-3525-z.

[9] Jentzer JC, van Diepen S, Barsness GW, Henry TD, Menon V, Rihal CS, et al. Cardiogenic shock classification to predict mortality in the cardiac intensive care unit. J Am Coll Cardiol 2019;74(17):2117–28. doi:10.1016/j.jacc.2019.07.077.

[10] Thiele H, Ohman EM, de Waha-Thiele S, Zeymer U, Desch S. Management of cardiogenic shock complicating myocardial infarction: an update 2019. Eur Heart J 2019;40(32):2671–83. doi:10.1093/eurheartj/ehz363.

[11] Gaubert M, Laine M, Resseguier N, Aissaoui N, Puymirat E, Lemesle G, et al. Hemodynamic profiles of cardiogenic shock depending on their etiology. J Clin Med 2020;9(11):3384. doi:10.3390/jcm9113384.
[12] Osman M, Syed M, Patel B, Munir MB, Kheiri B, Caccamo M, et al. Invasive hemodynamic monitoring in cardiogenic shock is associated with lower in-hospital mortality. J Am Heart Assoc 2021;10(18):e021808. doi:10.1161/JAHA.121.021808.
[13] Chioncel O, Parissis J, Mebazaa A, Thiele H, Desch S, Bauersachs J, et al. Epidemiology, pathophysiology and contemporary management of cardiogenic shock – A position statement from the Heart Failure Association of the European Society of Cardiology. Eur J Heart Fail 2020;22(8):1315–41. doi:10.1002/ejhf.1922.
[14] Zeymer U, Bueno H, Granger CB, Hochman J, Huber K, Lettino M, et al. Acute Cardiovascular Care Association position statement for the diagnosis and treatment of patients with acute myocardial infarction complicated by cardiogenic shock: a document of the Acute Cardiovascular Care Association of the European Society of Cardiology. Eur Heart J Acute Cardiovasc Care 2020;9(2):183–97. doi:10.1177/2048872619894254.
[15] Hiemstra B, Koster G, Wiersema R, Hummel YM, van der Harst P, Snieder H, et al. The diagnostic accuracy of clinical examination for estimating cardiac index in critically ill patients: the Simple Intensive Care Studies-I. Intensive Care Med 2019;45(2):190–200. doi:10.1007/s00134-019-05527-y.
[16] Boissier F, Bagate F, Mekontso Dessap A. Hemodynamic monitoring using trans esophageal echocardiography in patients with shock. Ann Transl Med 2020;8(12):791. doi:10.21037/atm-2020-hdm-23.
[17] Aissaoui N, Luyt CE, Leprince P, Trouillet JL, Léger P, Pavie A, et al. Predictors of successful extracorporeal membrane oxygenation (ECMO) weaning after assistance for refractory cardiogenic shock. Intensive Care Med 2011;37(11):1738–45. doi:10.1007/s00134-011-2358-2.
[18] Nagueh SF, Smiseth OA, Appleton CP, Byrd BF 3rd, Dokainish H, Edvardsen T, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography: an update from the American society of echocardiography and the European association of cardiovascular imaging. J Am Soc Echocardiogr 2016;29(4):277–314. doi:10.1016/j.echo.2016.01.011.
[19] McLean AS. Echocardiography in shock management. Crit Care 2016;20:275. doi:10.1186/s13054-016-1401-7.
[20] Ortuno S, Delmas C, Diehl JL, Bailleul C, Lancelot A, Naili M, et al. Weaning from veno-arterial extra-corporeal membrane oxygenation: which strategy to use? Ann Cardiothorac Surg 2019;8(1):E1–8. doi:10.21037/acs.2018.08.05.
[21] Garcia YA, Quintero L, Singh K, Lakticova V, Iakovou A, Koenig SJ, et al. Feasibility, safety, and utility of advanced critical care transesophageal echocardiography performed by pulmonary/critical care fellows in a medical ICU. Chest 2017;152(4):736–41. doi:10.1016/j.chest.2017.06.029.
[22] Arntfield R, Lau V, Landry Y, Priestap F, Ball I. Impact of critical care transesophageal echocardiography in medical-surgical ICU patients: characteristics and results from 274 consecutive examinations. J Intensive Care Med 2020;35(9):896–902. doi:10.1177/0885066618797271.
[23] Merz TM, Cioccari L, Frey PM, Bloch A, Berger D, Zante B, et al. Correction to: continual hemodynamic monitoring with a single-use transesophageal echocardiography probe in critically ill patients with shock: a randomized controlled clinical trial. Intensive Care Med 2019;45(9):1330. doi:10.1007/s00134-019-05700-3.
[24] Jentzer JC, Tabi M, Wiley BM, Singam NSV, Anavekar NS. Echocardiographic correlates of mortality among cardiac intensive care unit patients with cardiogenic shock. Shock 2022;57(3):336–43. doi:10.1097/SHK.0000000000001877.
[25] Mayo PH, Narasimhan M, Koenig S. Critical care transesophageal echocardiography. Chest 2015;148(5):1323–32. doi:10.1378/chest.15-0260.
[26] Lakhal K, Macq C, Ehrmann S, Boulain T, Capdevila X. Noninvasive monitoring of blood pressure in the critically ill: reliability according to the cuff site (arm, thigh, or ankle). Crit Care Med 2012;40(4):1207–13. doi:10.1097/CCM.0b013e31823dae42.
[27] Seidlerová J, Tůmová P, Rokyta R, Hromadka M. Factors influencing the accuracy of non-invasive blood pressure measurements in patients admitted for cardiogenic shock. BMC Cardiovasc Disord 2019;19(1):150. doi:10.1186/s12872-019-1129-9.
[28] Burstein B, Tabi M, Barsness GW, Bell MR, Kashani K, Jentzer JC. Association between mean arterial pressure during the first 24 h and hospital mortality in patients with cardiogenic shock. Crit Care 2020;24(1):513. doi:10.1186/s13054-020-03217-6.
[29] Teboul JL, Monnet X, Chemla D, Michard F. Arterial pulse pressure variation with mechanical ventilation. Am J Respir Crit Care Med 2019;199(1):22–31. doi:10.1164/rccm.201801-0088CI.
[30] Muller G, Kamel T, Contou D, Ehrmann S, Martin M, Quenot JP, et al. Early versus differed arterial catheterisation in critically ill patients with acute circulatory failure: a multicentre, open-label, pragmatic, randomised, non-inferiority controlled trial: the EVERDAC protocol. BMJ Open 2021;11(9):e044719. doi:10.1136/bmjopen-2020-044719.
[31] Levy B, Desebbe O, Montemont C, Gibot S. Increased aerobic glycolysis through beta2 stimulation is a common mechanism involved in lactate formation during shock states. Shock 2008;30(4):417–21. doi:10.1097/SHK.0b013e318167378f.
[32] Andersen LW, Mackenhauer J, Roberts JC, Berg KM, Cocchi MN, Donnino MW. Etiology and therapeutic approach to elevated lactate levels. Mayo Clin Proc 2013;88(10):1127–40. doi:10.1016/j.mayocp.2013.06.012.
[33] Geri G, Hernandez G, Vieillard-Baron A. Lactate kinetics in critically ill: a new prognostic marker or just another brick in the wall? Intensive Care Med 2019;45(1):113–14. doi:10.1007/s00134-018-05507-8.
[34] Revelly JP, Tappy L, Martinez A, Bollmann M, Cayeux MC, Berger MM, et al. Lactate and glucose metabolism in severe sepsis and cardiogenic shock. Crit Care Med 2005;33(10):2235–40. doi:10.1097/01.ccm.0000181525.99295.8f.
[35] Valente S, Lazzeri C, Vecchio S, Giglioli C, Margheri M, Bernardo P, et al. Predictors of in-hospital mortality after percutaneous coronary intervention for cardiogenic shock. Int J Cardiol 2007;114(2):176–82. doi:10.1016/j.ijcard.2006.01.024.
[36] Rossini R, Ferlini M. Arterial lactate assessment in cardiogenic shock: it is high time to beat the clock. JACC Cardiovasc Interv 2020;13(19):2217–19. doi:10.1016/j.jcin.2020.07.019.
[37] Fuernau G, Desch S, de Waha-Thiele S, Eitel I, Neumann FJ, Hennersdorf M, et al. Arterial lactate in cardiogenic shock: prognostic value of clearance versus single values. JACC Cardiovasc Interv 2020;13(19):2208–16. doi:10.1016/j.jcin.2020.06.037.
[38] Harjola VP, Parissis J, Brunner-La Rocca HP, Čelutkienė J, Chioncel O, Collins SP, et al. Comprehensive in-hospital monitoring in acute heart failure: applications for clinical practice and future directions for research. A statement from the Acute Heart Failure Committee of the Heart Failure Association (HFA) of the European Society of Cardiology (ESC). Eur J Heart Fail 2018;20(7):1081–99. doi:10.1002/ejhf.1204.
[39] Vahdatpour C, Collins D, shock Goldberg SCardiogenic. J Am Heart Assoc 2019;8(8):e011991. doi:10.1161/JAHA.119.011991.
[40] Singh S, Kanwar A, Sundaragiri PR, Cheungpasitporn W, Truesdell AG, Rab ST, et al. Acute kidney injury in cardiogenic shock: an updated narrative review. J Cardiovasc Dev Dis 2021;8(8):88. doi:10.3390/jcdd8080088.
[41] Tarvasmäki T, Haapio M, Mebazaa A, Sionis A, Silva-Cardoso J, Tolppanen H, et al. Acute kidney injury in cardiogenic shock: definitions, incidence, haemodynamic alterations, and mortality. Eur J Heart Fail 2018;20(3):572–81. doi:10.1002/ejhf.958.
[42] Abadeer AI, Kurlansky P, Chiuzan C, Truby L, Radhakrishnan J, Garan R, et al. Importance of stratifying acute kidney injury in cardiogenic shock resuscitated with mechanical circulatory support therapy. J Thorac Cardiovasc Surg 2017;154(3) 856–64.e4. doi:10.1016/j.jtcvs.2017.04.042.
[43] Jung C, Fuernau G, Eitel I, Desch S, Schuler G, Kelm M, et al. Incidence, laboratory detection and prognostic relevance of hypoxic hepatitis in cardiogenic shock. Clin Res Cardiol 2017;106(5):341–9. doi:10.1007/s00392-016-1060-3.
[44] Zweck E, Thayer KL, Helgestad OKL, Kanwar M, Ayouty M, Garan AR, et al. Phenotyping cardiogenic shock. J Am Heart Assoc 2021;10(14):e020085. doi:10.1161/JAHA.120.020085.
[45] Mebazaa A, Combes A, van Diepen S, Hollinger A, Katz JN, Landoni G, et al. Management of cardiogenic shock complicating myocardial infarction. Intensive Care Med 2018;44(6):760–73. doi:10.1007/s00134-018-5214-9.
[46] Vincent JL, De Backer D. Oxygen transport-the oxygen delivery controversy. Intensive Care Med 2004;30(11):1990–6. doi:10.1007/s00134-004-2384-4.
[47] Gattinoni L, Brazzi L, Pelosi P, Latini R, Tognoni G, Pesenti A, et al. A trial of goal-oriented hemodynamic therapy in critically ill patients. SvO2 Collaborative Group. N Engl J Med 1995;333(16):1025–32. doi:10.1056/NEJM199510193331601.
[48] Magder S. More respect for the CVP. Intensive Care Med 1998;24(7):651–3. doi:10.1007/s001340050640.
[49] Whitehead EH, Thayer KL, Burkhoff D, Uriel N, Ohman EM, O'Neill W, et al. Central venous pressure and clinical outcomes during left-sided mechanical support for acute myocardial infarction and cardiogenic shock. Front Cardiovasc Med 2020;7:155. doi:10.3389/fcvm.2020.00155.
[50] Jubran A, Mathru M, Dries D, Tobin MJ. Continuous recordings of mixed venous oxygen saturation during weaning from mechanical ventilation and the ramifications thereof. Am J Respir Crit Care Med 1998;158(6):1763–9. doi:10.1164/ajrccm.158.6.9804056.
[51] Leach RM, Treacher DF. Oxygen transport-2. Tissue hypoxia. BMJ 1998;317(7169):1370–3. doi:10.1136/bmj.317.7169.1370.
[52] Kandel G, Aberman A. Mixed venous oxygen saturation. Its role in the assessment of the critically ill patient. Arch Intern Med 1983;143(7):1400–2. doi:10.1001/archinte.143.7.1400.
[53] Connors AF Jr, Speroff T, Dawson NV, Thomas C, Harrell FE Jr, Wagner D, et al. The effectiveness of right heart catheterization in the initial care of critically ill patients. SUPPORT investigators. JAMA 1996;276(11):889–97. doi:10.1001/jama.276.11.889.
[54] Sakr Y, Vincent JL, Reinhart K, Payen D, Wiedermann CJ, Zandstra DF, et al. Use of the pulmonary artery catheter is not associated with worse outcome in the ICU. Chest 2005;128(4):2722–31. doi:10.1378/chest.128.4.2722.
[55] Harvey S, Harrison DA, Singer M, Ashcroft J, Jones CM, Elbourne D, et al. Assessment of the clinical effectiveness of pulmonary artery catheters in management of patients in intensive care (PAC-Man): a randomised controlled trial. Lancet 2005;366(9484):472–7. doi:10.1016/S0140-6736(05)67061-4.
[56] Saxena A, Garan AR, Kapur NK, O'Neill WW, Lindenfeld J, Pinney SP, et al. Value of hemodynamic monitoring in patients with cardiogenic shock undergoing mechanical circulatory support. Circulation 2020;141(14):1184–97. doi:10.1161/CIRCULATIONAHA.119.043080.
[57] Cavaliere F, Giovannini I, Chiarla C, Conti G, Pennisi MA, Montini L, et al. Comparison of two methods to assess blood CO2 equilibration curve in mechanically ventilated patients. Respir Physiol Neurobiol 2005;146(1):77–83. doi:10.1016/j.resp.2004.11.008.
[58] Jensen FB. Comparative analysis of autoxidation of haemoglobin. J Exp Biol 2001;204(Pt 11):2029–33. doi:10.1242/jeb.204.11.2029.
[59] McHardy GJ. The relationship between the differences in pressure and content of carbon dioxide in arterial and venous blood. Clin Sci 1967;32(2):299–309.
[60] Vallée F, Vallet B, Mathe O, Parraguette J, Mari A, Silva S, et al. Central venous-to-arterial carbon dioxide difference: an additional target for goal-directed therapy in septic shock. Intensive Care Med 2008;34(12):2218–25. doi:10.1007/s00134-008-1199-0.
[61] Ospina-Tascón GA, Umaña M, Bermúdez WF, Bautista-Rincón DF, Valencia JD, Madriñán HJ, et al. Can venous-to-arterial carbon dioxide differences reflect microcirculatory alterations in patients with septic shock. Intensive Care Med 2016;42(2):211–21. doi:10.1007/s00134-015-4133-2.
[62] McDonald CI, Brodie D, Schmidt M, Hay K, Shekar K. Elevated venous to arterial carbon dioxide gap and anion gap are associated with poor outcome in car-

diogenic shock requiring extracorporeal membrane oxygenation support. ASAIO J 2021;67(3):263–9. doi:10.1097/MAT.0000000000001215.
[63] Ellouze O, Nguyen M, Missaoui A, Berthoud V, Aho S, Bouchot O, et al. Prognosis value of early veno arterial PCO2 difference in patients under peripheral veno arterial extracorporeal membrane oxygenation. Shock 2020;54(6):744–50. doi:10.1097/SHK.0000000000001554.
[64] Vallet B., Pinsky M.R., Cecconi M. Resuscitation of patients with septic shock: please "mind the gap"! Intensive Care Med 2013;39(9):1653–5. doi: 10.1007/s00134-013-2998-5.
[65] Fincke R, Hochman JS, Lowe AM, Menon V, Slater JN, Webb JG, et al. Cardiac power is the strongest hemodynamic correlate of mortality in cardiogenic shock: a report from the SHOCK trial registry. J Am Coll Cardiol 2004;44(2):340–8. doi:10.1016/j.jacc.2004.03.060.
[66] Lim HS, Gustafsson F. Pulmonary artery pulsatility index: physiological basis and clinical application. Eur J Heart Fail 2020;22(1):32–8. doi:10.1002/ejhf.1679.
[67] Garan AR, Kanwar M, Thayer KL, Whitehead E, Zweck E, Hernandez-Montfort J, et al. Complete hemodynamic profiling with pulmonary artery catheters in cardiogenic shock is associated with lower in-hospital mortality. JACC Heart Fail 2020;8(11):903–13. doi:10.1016/j.jchf.2020.08.012.
[68] Bertaina M, Galluzzo A, Rossello X, Sbarra P, Petitti E, Prever SB, et al. Prognostic implications of pulmonary artery catheter monitoring in patients with cardiogenic shock: a systematic review and meta-analysis of observational studies. J Crit Care 2022;69:154024. doi:10.1016/j.jcrc.2022.154024.
[69] Sorajja P, Borlaug BA, Dimas V, Fang JC, Forfia PR, Givertz MM, et al. Executive summary of the SCAI/HFSA clinical expert consensus document on the use of invasive hemodynamics for the diagnosis and management of cardiovascular disease. Catheter Cardiovasc Interv 2017;89(7):1294–9. doi:10.1002/ccd.27036.
[70] Sakka SG, Reinhart K, Meier-Hellmann A. Comparison of pulmonary artery and arterial thermodilution cardiac output in critically ill patients. Intensive Care Med 1999;25(8):843–6. doi:10.1007/s001340050962.
[71] Hadian M, Pinsky MR. Evidence-based review of the use of the pulmonary artery catheter: impact data and complications. Crit Care 2006;10(Suppl 3):S8 Suppl 3. doi:10.1186/cc4834.
[72] Combes A, Berneau JB, Luyt CE, Trouillet JL. Estimation of left ventricular systolic function by single transpulmonary thermodilution. Intensive Care Med 2004;30(7):1377–83. doi:10.1007/s00134-004-2289-2.
[73] Jabot J, Monnet X, Bouchra L, Chemla D, Richard C, Teboul JL. Cardiac function index provided by transpulmonary thermodilution behaves as an indicator of left ventricular systolic function. Crit Care Med 2009;37(11):2913–18. doi:10.1097/ccm.0b013e3181b01fd9.
[74] De Hert SG, Robert D, Cromheecke S, Michard F, Nijs J, Rodrigus IE. Evaluation of left ventricular function in anesthetized patients using femoral artery dP/dt(max). J Cardiothorac Vasc Anesth 2006;20(3):325–30. doi:10.1053/j.jvca.2005.11.006.
[75] Perny J, Kimmoun A, Perez P, Levy B. Evaluation of cardiac function index as measured by transpulmonary thermodilution as an indicator of left ventricular ejection fraction in cardiogenic shock. Biomed Res Int 2014;2014:598029. doi:10.1155/2014/598029.
[76] Monnet X, Teboul JL. Transpulmonary thermodilution: advantages and limits. Crit Care 2017;21(1):147. doi:10.1186/s13054-017-1739-5.
[77] Rali AS, Buechler T, Van Gotten B, Waters A, Shah Z, Haglund N, et al. Non-invasive cardiac output monitoring in cardiogenic shock: the NICOM study. J Card Fail 2020;26(2):160–5. doi:10.1016/j.cardfail.2019.11.015.
[78] Thiele H, Zeymer U, Neumann FJ, Ferenc M, Olbrich HG, Hausleiter J, et al. Intraaortic balloon support for myocardial infarction with cardiogenic shock. N Engl J Med 2012;367(14):1287–96. doi:10.1056/NEJMoa1208410.
[79] Ouweneel DM, Eriksen E, Sjauw KD, van Dongen IM, Hirsch A, Packer EJ, et al. Percutaneous Mechanical Circulatory Support Versus Intra-Aortic Balloon Pump in Cardiogenic Shock After Acute Myocardial Infarction. J Am Coll Cardiol 2017;69(3):278–87. doi:10.1016/j.jacc.2016.10.022.
[80] Thiele H, Akin I, Sandri M, Fuernau G, de Waha S, Meyer-Saraei R, et al. PCI Strategies in Patients with Acute Myocardial Infarction and Cardiogenic Shock. N Engl J Med 2017;377(25):2419–32. doi:10.1056/NEJMoa1710261.
[81] McDonagh TA, Metra M, Adamo M, Gardner RS, Baumbach A, Böhm M, et al. 2021 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure. Eur Heart J 2021;42(36):3599–726. doi:10.1093/eurheartj/ehab368.