# Hemodynamic Monitoring in the Cardiovascular Intensive Care Unit

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**KEYWORDS**

• Hemodynamic monitoring • Cardiovascular intensive care unit • Monitoring devices

**KEY POINTS**

- The cardiovascular intensive care unit relies on a multimodal, integrated approach to hemodynamic assessment that combines macrocirculatory and microcirculatory data with expert clinical judgment due to rapid, dynamic physiologic changes and shock heterogeneity.
- Mean arterial pressure (MAP) targets are not universally defined; while 60 to 65 mm Hg is a common threshold, evidence on higher or individualized goals is mixed, and MAP alone does not guarantee adequate oxygen delivery, necessitating perfusion-focused monitoring.
- A broad toolkit of monitoring modalities is used: invasive (arterial lines, pulmonary artery catheter) for continuous data and dynamic changes, and non-invasive/ultrasound-based methods (point-of-care ultrasound, transesophageal echocardiography, near-infrared spectroscopy, esophageal Doppler, non-invasive blood pressure) with specific strengths and limitations for bedside decision-making.
- Emerging technologies and artificial intelligence/machine learning (ML) (pulse wave transit time, bioreactance, non-invasive venous waveform analysis, wearables, ML-based hypotension prediction) hold promise to enhance early detection and management but require further validation and integration into care pathways.

## INTRODUCTION

Critically ill patients often experience rapid, dynamic changes in cardiovascular physiology, making accurate hemodynamic assessment essential for timely diagnosis and management. In the cardiovascular intensive care unit (CVICU), hemodynamic monitoring provides the foundation for evaluating tissue perfusion, guiding fluid resuscitation, titrating vasoactive medications, and assessing response to therapy. Over the past several decades, advances in monitoring technologies have expanded the clinician's ability to characterize both macrocirculatory and microcirculatory function with increasing precision.[1,2]

Despite this growing array of tools, the optimal approach to hemodynamic monitoring remains a subject of ongoing debate. Traditional invasive devices offer comprehensive physiologic data but carry procedural risks, while newer noninvasive

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**Abbreviations**

| | |
|---|---|
| AUC | area under the curve |
| CGM | continuous glucose monitoring |
| CRT | capillary refill time |
| CVICU | cardiovascular intensive care unit |
| ESICM | European Society of Intensive Care Medicine |
| HF–CS | heart–failure–related cardiogenic shock |
| MAP | mean arterial pressure |
| MCS | mechanical circulatory support |
| ML | machine learning |
| NIBP | non–invasive blood pressure |
| NIRS | near–infrared spectroscopy |
| NIVA | non–invasive venous waveform analysis |
| PAC | pulmonary artery catheter |
| POCUS | point–of–care ultrasound |
| PPV | proportion of perfused vessels |
| PPV | pulse pressure variation |
| SV | stroke volume |
| SVV | stroke volume variation |
| TEE | transesophageal echocardiography |

modalities promise improved safety yet may lack the robustness of established techniques in certain clinical contexts.[3] Furthermore, the heterogeneity of shock states, the complexity of ICU populations, and the evolving emphasis on individualized resuscitation underscore the need for thoughtful selection and interpretation of monitoring strategies.[4] Rather than relying on single metrics, contemporary critical care increasingly emphasizes an integrated, multimodal approach to hemodynamic assessment that combines static and dynamic parameters with expert clinical judgment.[5,6]

This article aims to provide a comprehensive overview of current hemodynamic monitoring modalities used in the ICU, highlighting their physiologic principles, strengths, limitations, and evidence-based applications. By examining both established and emerging technologies, we seek to clarify how these tools can be effectively incorporated into clinical decision-making to optimize patient outcomes for the critically ill patient.

## HEMODYNAMIC GOALS

Hypotension is common in critically ill patients, yet it is unclear below what level of systolic or mean arterial pressure (MAP) hypoperfusion and thereby organ dysfunction occur. Commonly, a MAP of 60 to 65 mm Hg is the threshold at which intervention is recommended. This is based partly on studies from the 1970s and 1980s that demonstrated that capillary pressure is maintained through autoregulation while the MAP is 60 to 65 mm Hg. This practice was reinforced by Rivers and colleagues' work on early goal-directed therapy in the early 2000s.[7] The Surviving Sepsis Campaign guidelines have incorporated a MAP goal of 60-65 mm Hg since 2004.[8,9]

Subsequent studies have examined other MAP goals, including individualized patient goals, with mixed results. Most notably, the SEPSISPAM trial compared high-target MAP of 80 to 85 mm Hg with a low-target MAP of 65 to 70 mm Hg with no difference in mortality at 28 or 90 days. However, there was an increase in the need for renal replacement therapy in patients with chronic hypertension randomized to the low-target group, and an increase in the rates of atrial fibrillation in the high target group, a possible consequence of the use of higher catecholamine vasopressors.[10] This has not been replicated, with several trials showing no difference in any of these outcomes based on MAP goals.[11] Specifically, the 65 Trial showed no difference in serious adverse events or mortality at 90 days with a MAP goal of 60 to 65 in older adults.[12] In contrast, a meta-analysis by D'Amico and colleagues demonstrated reduced mortality, atrial fibrillation, and transfusion requirements with lower rather than high blood pressure targets in critically ill patients.[13]

There are currently no randomized controlled trials regarding MAP goals in the CVICU or cardiogenic shock populations. Further, many studies exclude cardiac medical or surgical patients because of their unique pathophysiology. Because of this, providers in a CVICU must extrapolate from other patient populations and surrogate markers of perfusion to develop best practices regarding hypotension.

Intraoperative trials in high-risk patients undergoing major surgery provide one such comparative population. The IMPROVE trial found no difference in outcome when comparing an individualized approach to a MAP greater than or equal to 65 mm Hg.[14] However, there is some suggestion that MAP less than or equal to 80 mm Hg for 10 minutes results in organ injury, with increasing impact at thresholds below 70 and 65 mm Hg.[15] Any period of MAP less than or equal to 55 mm Hg was an independent risk factor for organ disfunction.[15] The INPRESS trial likewise showed no difference in severe adverse events or mortality when comparing standard of care and an individualized blood pressure management strategy.[16] Interestingly, the peri-operative cohort of the D'Amico meta-analysis did not demonstrate a difference in mortality between the low and high blood pressure target groups.[13] Given this, no consensus recommendation was identified for an optimal MAP or systolic blood pressure.

Ultimately, there is no clear consensus on what MAP should be defined as "normal" or

standardized among all patients. Further, it should be noted that whatever the threshold, MAP does not necessarily equal adequate oxygen delivery. As such, surrogate markers for perfusion including targeted tissue perfusion and aortic pulsatility are being examined.[17–19]

## MICROCIRCULATION VERSUS MACROCIRCULATION

In patients with mal-perfusion due to shock, it is critically important to distinguish pressure from flow when aiming to improve oxygen delivery. This has become increasingly emphasized with the emergence of literature demonstrating a lack of correlation between MAP and pressure in the microcirculation, that is the end-capillaries, in critical illness.[20] The microcirculation represents approximately 10% of the circulating blood volume and is the component of the vasculature in direct contact with the parenchyma of end-organs, thus arguably the primary driver of effective tissue perfusion.[21]

The dissociation between the macrocirculation and microcirculation, however, demands that physicians manage two potentially competing systems and prioritize or differentially optimize them.[21] For example, vasopressors may improve the vasodilatory component of shock while also constricting the distal microvasculature and impeding flow to vulnerable peripheral tissues. Similarly, while fluid resuscitation may optimize cardiac output, it may also lead to edema through third-spacing and thus increased venous tone, leading to capillary congestion and diminished arteriolar flow. Conversely, in prioritizing the microcirculation, vasodilators may be effective, but with obvious potential impact on systemic perfusion (**Fig. 1**).[21]

Further complicating this predicament is the relative difficulty in effectively monitoring the microcirculation as compared with the so-called "macro-circulation" of the larger vasculature. A most fundamental examination component, capillary refill time (CRT), has been used as a surrogate marker and may be the link between macrodynamics and microdynamics. CRT-guided resuscitation has been extensively studied in septic shock. It is an excellent tool that does not require any sophisticated monitoring devices and can be implemented in all care settings, including low-resource international settings. CRT has been shown to be equivalent to lactate as a surrogate for global oxygen delivery management.[21] Specifically, in the ANDROMEDA-SHOCK trial, targeting CRT was associated with faster improvement in peripheral perfusion and less organ dysfunction at 72 hours.[22] More recently, ANDROMEDA-SHOCK-2 demonstrated that incorporating CRT into a structured, personalized resuscitation algorithm reduced the duration of organ support compared with usual care.[23]

Alternate technologies including microvascular flow index and proportion of perfused vessels (PPV) exist, most reliably via sublingual monitoring, but are limited in their availability and generalizability among all tissue beds (ie, adequate sublingual perfusion may represent renal or mesenteric flow).[24]

While no unified approach has been identified or promoted, it has been suggested that the most logical approach to optimizing both macro and microcirculatory perfusion is to first prioritize systemic blood pressure goals and secondarily monitor for consequences of microvascular dysfunction, including lactic acidosis, end-organ dysfunction, and even localized tissue damage due to poor perfusion. With evidence of the latter, goals may be reassessed, and alternative monitoring and/or therapies can be applied.[21]

## HEMODYNAMIC MONITORING DEVICES

While diagnostic modalities like transesophageal echocardiography (TEE) and transpulmonary thermodilution provide only instantaneous assessments of loading conditions, pathology, and shock phenotype, continuous monitoring modalities such as arterial pressure waveforms, central venous pressure trends, and continuous cardiac output sensors track dynamic changes and allow early detection of deterioration or monitoring of treatment response.[25–29]

Effective ICU management relies on integrating both approaches to efficiently and accurately establish the underlying pathology and guide ongoing therapy.

### *Physical Examination*

Bedside assessment remains an important component of hemodynamic evaluation in the CVICU.[30] Peripheral findings such as cool extremities, mottling, and a prolonged CRT can indicate impaired perfusion, help identify early circulatory compromise, and contribute to cardiogenic shock classification frameworks.[31]

Exam-based assessment of fluid responsiveness is a highly complementary modality to point-of-care ultrasound (POCUS) and other invasive monitors. Dynamic indices such as pulse pressure variation (PPV), stroke volume variation (SVV), and passive leg raise induced changes in cardiac output are more reliable predictors of fluid responsiveness than static measures like CVP.[32,33] It should be noted, however, that the validation for these metrics, particularly PPV and

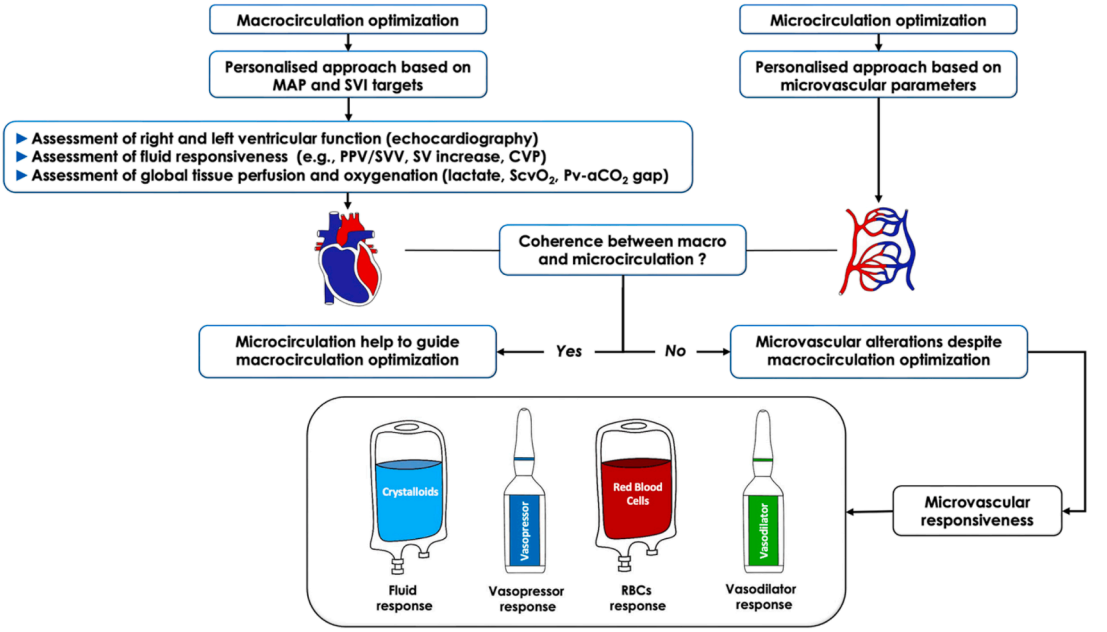


**Fig. 1.** Approach to optimizing microcirculation and macrocirculation. (Duranteau, J., De Backer, D., Donadello, K. et al. The future of intensive care: the study of the microcirculation will help to guide our therapies. Crit Care 27, 190 (2023). https://doi.org/10.1186/s13054-023-04474-x.)

SVV, include assumptions regarding patient sedation and ventilation which are frequently no longer deployed, including large tidal volume mechanical ventilation (10 mL/kg), thus impacting the applicability in today's patients.[34,35]

## *Noninvasive Monitoring*

Patients admitted to the CVICU often present with unstable cardiovascular conditions, including acute coronary syndromes, cardiogenic shock, acute and chronic heart failure, arrhythmias, pulmonary hypertension, status post cardiac surgery, or mechanical circulatory support. In this environment, the elements of standard physiologic monitoring (continuous ECG, non-invasive blood pressure, NIBP, pulse oximetry, respiratory rate, temperature, and capnography, when applicable) form the initial framework for hemodynamic assessment. These core parameters are consistent with both the American Society of Anesthesiologists and the Association of Anaesthetists UK guidelines standard monitoring.[36,37] These noninvasive measures help detect early changes in perfusion and oxygen delivery and determine when more advanced monitoring is required.[5,38]

### *Electrocardiography*

Continuous ECG monitoring is essential in the CVICU and multi-lead monitoring improves detection of arrhythmias and conduction delays that may reflect myocardial strain or impaired coronary perfusion.[39] Further, reduced heart rate variability has been associated with higher physiologic stress and an increased risk of post-operative arrhythmias and hemodynamic instability in cardiac surgical patients.[40]

### *Pulse oximetry*

Pulse oximetry is likewise a critical monitor in CVICU patients, though its accuracy is denuded in low-flow states, peripheral vasoconstriction, hypothermia, and when true arterial saturation is below 80%, where $SpO_2$ often overestimates $SaO_2$.[41] Instability and loss of accuracy are also common in patients receiving high-dose vasopressors, during significant shock, or in the early post-operative period.

Similarly, mechanical circulatory support (MCS) may alter $SpO_2$ reliability. VV-ECMO via a single-lumen cannula shows the greatest tendency for $SpO_2$ to overestimate $SaO_2$ and is most often associated with occult hypoxemia.[42] In contrast, central VA-ECMO frequently shows the opposite pattern, with $SpO_2$ underestimating $SaO_2$.[42] Hemolysis and high vasopressor requirements further widen the $SpO_2$–$SaO_2$ discrepancy in these patients.[42] In extracorporeal cardiopulmonary resuscitation, an $SpO_2$–$SaO_2$ discrepancy greater than or equal to 4% early after cannulation is associated with increased mortality, highlighting the need for arterial confirmation of oxygenation in this setting.[43]

### *Non-invasive blood pressure*

Oscillometric NIBP is commonly used for initial blood pressure assessment in the CVICU. MAP is generally the most reliable value, whereas systolic and diastolic readings depend on device algorithms and lose accuracy in arrhythmias, low peripheral perfusion, marked vasoconstriction, or obesity. In a large ICU cohort, the median difference between cuff-derived and arterial MAP was approximately 6 mm Hg, with wider discrepancies in older patients, those on higher vasopressor doses, and in low-perfusion states.[44] In patients with septic shock, NIBP is noninferior to early arterial catheterization for 28 day mortality and avoids catheter-related complications.[45] Overall, oscillometric NIBP is a practical first step in the CICU, but values should be interpreted alongside perfusion status, vasopressor dose, and technical factors, with escalation to invasive monitoring when hemodynamic instability requires tighter precision.[46]

### *Near-infrared spectroscopy*

Near-infrared spectroscopy (NIRS) provides an estimate of regional tissue oxygen saturation ($rSO_2$), reflecting the balance between local oxygen delivery and consumption.[46] In CVICU patients, decreases in cerebral $rSO_2$ may indicate low cardiac output, impaired cerebral perfusion, or increased oxygen extraction.[47] Postoperative and critically ill patients with sustained reductions in $rSO_2$ have shown higher rates of delirium and organ dysfunction.[48,49]

Similarly, somatic NIRS applied to the lower extremities can detect early limb mal-perfusion during peripheral VA-ECMO. Routine calf monitoring has been associated with fewer ischemic complications and timelier placement of distal-perfusion catheters.[50]

## *Invasive Monitoring*

Particularly in the CVICU patient, where hemodynamic changes may be rapid and frequent and confounding variables like shock, hypoxia, and vasopressor administration are numerous, traditional noninvasive monitoring devices are often less reliable. Further, intermittent rather than continuous monitoring leaves gaps in vital sign monitoring and thus intervention, and therefore continuous monitoring is often favored in critically ill patients. In most cases, this requires employment of invasive monitoring techniques.

### *Arterial line*

The 2025 European Society of Intensive Care Medicine (ESICM) guidelines recommend arterial catheterization in shock that does not respond to initial measures or when vasopressors are required.[51] Interpretation requires attention to waveform quality and proper transducer leveling, as damping, catheter kinking, or air in the line can distort measured pressures.[52]

Radial cannulation is generally preferred because of its ease of placement and low complication risk. Brachial access can be considered when anatomy is favorable, while femoral and axillary cannulation are useful when peripheral perfusion is poor or radial waveforms are inconsistent with the clinical picture.[53] Although generally safe, arterial catheterization carries risks including bleeding, infection, thrombosis, and distal ischemia.

In patients on MCS, the arterial line provides a stable reference for systemic pressure as device flow and native cardiac function fluctuate. It assists with confirming inflation-deflation timing during counter-pulsation, tracking changes in native output during percutaneous ventricular assist support, and recognizing the return of pulsatility during recovery on VA-ECMO.[54]

### *Arterial line-derived data*

Derived from the arterial line waveform, SVV and PPV have been proposed as variables to guide fluid administration in critical care settings. However, data validating these metrics are largely limited to the intraoperative setting or critical care patients under deep sedation, on mechanical ventilation, and without cardiac arrhythmias.[55–57] In order to make these principles more widely applicable to critically ill patients and based on the principles of SVV/PPV, algorithm-based technology has emerged which uses existing invasive monitors to calculate and continually present various cardiac indices.

**Pulse contour analysis** Pulse contour analysis devices utilize the area under the curve (AUC) of the arterial waveform to derive CO (**Fig. 2**). The stroke volume (SV) is determined through calculation of the AUC and then multiplied by pulse rate to determine the CO (see **Fig. 2**).[58]

These devices utilize a proprietary algorithm that continuously assesses multiple variables as a representation of SV and vascular tone. Collectively, these produce a conversion factor (Khi), which is then multiplied by the standard deviation of the arterial pressure to calculate SV in mL/beat.[58] As opposed to typical SVV technology, patients with dysrhythmia can still be monitored with this device, as the algorithm uses pulse rate, that is, perfused beats, rather than the electrically determined heart rate for calculation. This device does not require external calibration and is validated in spontaneously breathing patients.[58]

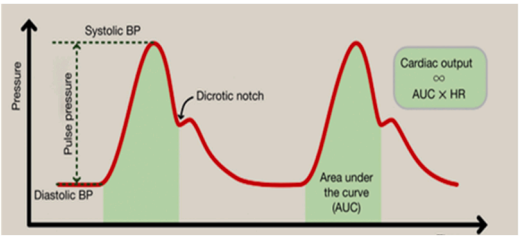


**Fig. 2.** Pulse contour analysis. AUC of systolic upstroke calculated to produce SV, then multiplied by HR to produce cardiac output. AUC, area under the curve; HR, heart rate; SV, stroke volume. (*Adapted from* Betteridge N, Armstrong F. Cardiac output monitoring. Anaesth Intensive Care Med 2025;26(1):31–40. https://doi.org/10.1016/j.mpaic.2024.09.013. Copyright Elsevier 2025 (9). https://doi.org/10.1016/j.mpaic.2024.09.013.)

Unfortunately, these devices are unreliable in vasodilatory shock and susceptible to dampening of the arterial waveform.[59,60]

**Transpulmonary thermodilution** Based on the initial systems of transpulmonary dye dilution with lithium, many current CCO systems utilize transpulmonary thermodilution. Using peripherally inserted thermistor-tipped arterial catheters placed in the axillary, femoral, or brachial arteries, these systems utilize arterial pressure waveform analysis to generate CCO data. The system is calibrated with cold injectate thermodilution using an existing central line. Subsequently, an algorithm analyzes the pulse contour and biometric data to generate CO. It can also derive other parameters including global end diastolic volume, global ejection fraction, and SVR.[58] These devices are found to correlate well with PAC data, but some require frequent recalibration and are affected by arrhythmia and spontaneous ventilation. While theoretically less invasive than a PAC, it does require a more proximally placed arterial line, which harnesses inherently more risk.[58,61]

**Ultrasound flow dilution: COstatus** The COstatus system utilizes an extracorporeal arteriovenous loop between existing arterial and central venous catheters with a small roller pump circulating blood from artery to vein; 2 ultrasound flow-dilution sensors are attached at either end. After transcardiopulmonary flow, a dilution curve is recorded. CO is calculated from this curve using the Stewart-Hamilton principle (CO = indicator/area under concentration-time curve). It is validated in both adult and pediatric patients. Recalibration is necessary in unstable conditions.[58,62] There are very limited data on CO status use in post-cardiac surgery ICU patients, but it has been found to correlate well with PA catheter readings in these patients.[63]

**Artificial intelligence and machine learning algorithms** Machine learning algorithms are a subset of artificial intelligence (AI) technology that allow computers to learn patterns and provide feedback by analyzing data. A few systems have been introduced which use proprietary algorithms to forecast hypotension from arterial line data with strong sensitivity and specificity and thereby facilitate early intervention.[61,64]

Isolated data for post-operative patients in CVICU are limited, but peri-operative use combined with standard care for cardiac surgery patients was shown to significantly reduce duration and severity of hypotension in the recent HYPE-2 trial. However, there were no significant differences in organ dysfunction or ICU length of stay.[65]

### *Pulmonary artery catheter*

Pulmonary artery catheters (PACs) provide direct measurement of intracardiac pressures and saturations, allowing calculation of derived indices such as cardiac output, cardiac index, and pulmonary and systemic vascular resistance (PVR, SVR). In the CVICU, it is typically reserved for patients whose hemodynamics are complex or unclear and in whom management requires precise characterization of right-sided and left-sided filling pressures, forward flow, and pulmonary vascular loading conditions.[66,67]

Early randomized trials in mixed ICU and advanced heart failure populations, including PAC-Man and ESCAPE, did not demonstrate a mortality benefit for routine PAC use and contributed to a substantial decline in utilization.[68,69] These studies, however, largely excluded patients with true cardiogenic shock or those being considered for mechanical circulatory support (**Table 1**).

More recent data focused on cardiogenic shock suggest a different signal. In a large multicenter analysis, complete hemodynamic profiling with a PAC in cardiogenic shock was associated with lower in-hospital mortality compared with incomplete or no PAC assessment.[70] In a separate cohort of patients with heart-failure-related cardiogenic shock (HF-CS), early PAC use (within 6 hours of admission) was associated with lower adjusted in-hospital mortality compared with delayed or no PAC insertion.[67] CICU-based registries similarly report that PAC use in cardiogenic shock is associated with improved survival after adjustment for illness severity.[66] These findings are reflected in recent cardiology society guidance (SCAI, ACC/AHA), which supports invasive hemodynamic monitoring in moderate-to-severe cardiogenic

**Table 1**
**Key studies on pulmonary artery catheter use in heart failure and cardiogenic shock**

| Study, Year | Design/Setting | Population | PAC Exposure | Main Findings |
|---|---|---|---|---|
| ESCAPE Trial (JAMA), 2005 | RCT, 26 HF centers | Advanced HF without cardiogenic shock ($n$ = 433) | PAC-guided therapy vs clinical assessment | No difference in mortality, LOS, or days alive; more adverse events with PAC. |
| PAC-Man Trial (Lancet), 2005 | Pragmatic RCT, mixed ICU | Mixed critically ill adults ($n$ = 1014) | PAC vs no PAC | No mortality difference; 10% insertion-related complications. |
| Garan et al,[70] JACC HF (CSWG), 2020 | Multicenter CS registry (8 sites) | Cardiogenic shock undergoing MCS evaluation ($n$ = 1414) | Complete vs incomplete vs no PAC hemodynamics | Complete PAC profiling before MCS associated with lowest mortality. |
| Kadosh et al,[66] JACC HF (CCCTN), 2023 | Prospective CICU registry (34 sites) | CICU admissions with shock ($n$ = 3827) | PAC vs no PAC; institutional variability studied | PAC associated with lower adjusted mortality; large center variability. |
| Kanwar et al,[67] J Card Fail, 2023 | Multicenter HF-CS registry (15 sites) | Heart failure-related cardiogenic shock ($n$ = 1055) | PAC vs no PAC; early PAC $\leq$ 6 h | PAC and especially early PAC associated with lower in-hospital mortality. |

shock, especially when evaluating patients for temporary MCS, durable LVAD, or transplant.[31,71]

### *Point-of-Care Ultrasound*

POCUS serves as a well-validated and rapidly deployed bedside tool for hemodynamic assessment in unstable CICU patients.[72–74] It provides rapid, targeted information that complements formal echocardiography and invasive monitoring. It facilitates rapid diagnosis of obstructive processes such as tamponade, acute RV failure from pulmonary embolism, or pneumothorax, focused assessment of LV and RV systolic function, flow velocities, and for major valve lesions.[74,75]

Lung ultrasound is highly sensitive for pulmonary edema and pleural effusion and often outperforms chest radiography in accuracy.[76,77] POCUS-based volume assessment combines findings from the IVC, lung ultrasound, and venous Doppler when available.[78] The VExUS score, which grades venous congestion using IVC size and Doppler patterns in the hepatic, portal, and renal veins, can help identify clinically significant congestion.[79] VExUS is increasingly used in advanced heart failure and post-operative cardiac patients to guide fluid removal or avoid additional volume. These ultrasound findings can also clarify PAC data, especially in patients with RV dysfunction, elevated right-sided pressures, or suspected organ congestion.[80]

Extracardiac ultrasound, including diaphragm evaluation, hepatic and renal venous Doppler, and focused abdominal views, is valuable in complex CICU cases.[80] These modalities help assess diaphragmatic weakness, venous congestion, and organ perfusion, especially in patients with RV failure, high intrathoracic pressures, or those status post cardiac surgery.[81–83]

POCUS is useful in patients on temporary or durable mechanical support. Bedside imaging can confirm cannula position, assess LV and RV unloading, and help identify problems such as malposition, tamponade, or inadequate forward flow. It is also valuable during ECMO cannulation and troubleshooting when hypoxemia or low-flow states occur.[84,85] POCUS may also be useful during cardiac arrest to identify reversible causes such as tamponade or tension pneumothorax, but its use must not prolong CPR pauses.[86]

### *Transesophageal Echocardiography*

Most frequently used in the cardiac operating room, TEE is an important imaging option in the CVICU when transthoracic windows are limited or when more detailed structural assessment is required.[84,87] It provides stable, high-quality visualization regardless of body habitus, ventilation, dressings, or post-operative changes, and can be performed at the bedside without interrupting ongoing care. In unstable patients, this advantage allows rapid clarification of hemodynamic problems when initial evaluation or TTE is inconclusive.[88,89] A comparison of TTE and TEE in the CICU is shown in **Table 2**.

**Table 2**
**Comparison of transthoracic echocardiography (TTE) and TEE in the cardiovascular intensive care unit (CICU)**

| | TTE | TEE |
|---|---|---|
| Image quality | Variable; limited by ventilation, dressings, obesity, edema | Consistently high-quality images in most ICU patients |
| Invasiveness | Noninvasive | Semi-invasive; requires probe insertion |
| Use during CPR | Requires pauses; often poor windows | Continuous imaging without interrupting compressions |
| Clinical use | Initial assessment; routine monitoring; good acoustic windows | When TTE is inadequate; unclear shock mechanism; MCS/ECMO guidance; cardiac arrest |
| Visualization | Limited posterior views; may miss loculated effusions or thrombi | Excellent visualization of atria, valves, aorta, and posterior structures |
| Hemodynamic assessment | Feasible but window-dependent | Reliable Doppler and structural assessment in difficult windows |
| Procedural guidance | Limited for cannulation or devices | Useful for ECMO cannulation and device positioning (Impella, TandemHeart) |
| Risks | Minimal | Rare esophageal injury or bleeding; requires airway protection |
| Availability | Widely available | Limited by probe access and trained operators |
| Training | Basic and advanced TTE skills | Advanced TEE training required |

Doppler measurements such as LVOT VTI can be obtained reliably and correlate with changes in SV. TEE also detects findings that may not be visible on transthoracic views, including posterior or loculated pericardial effusions, intracardiac thrombus, and acute valvular abnormalities.[90] TEE also has value in cardiac arrest. Continuous imaging during CPR allows the identification of reversible conditions such as tamponade, massive PE, or aortic dissection, and helps distinguish true from pseudo-PEA.[91]

In patients on MCS, TEE has utility in cannulation as well as confirming cannula position and appropriate ventricular unloading and for troubleshooting.[92,93] TEE also contributes to weaning decisions on VA-ECMO by assessing aortic valve opening, recovery of systolic function, and changes in LVOT VTI.[94]

### *Esophageal Doppler*

Though infrequently deployed in the era of improving ultrasound technology, esophageal Doppler remains a reliable option for semi-invasive continuous, beat-to-beat assessment of aortic flow and SV.[95] Although it does not provide structural imaging, it allows estimation of SV, cardiac output, and flow variation during ventilation, helping guide fluid administration and evaluate the response to therapy. Esophageal Doppler often detects preload changes earlier than pressure-based measures, and correlates reasonably well with thermodilution for trending cardiac output.[96] Its limitations include the need for correct probe positioning, reduced accuracy with aortic pathology or poor alignment, and limited tolerance in awake patients.[61]

## EMERGING TECHNOLOGIES

Thanks to ongoing investigation and development, new and improved monitoring technologies continue to be deployed in the critical care population.

### *Pulse Wave Transit Time (Estimated Continuous Cardiac Output)*

Using the least invasive and commonly deployed monitors, estimated continuous cardiac output devices utilize algorithmic processing of heart rate, peripheral oxygen saturation, and NIBP to generate a pulse wave transit time.[97,98] This time, when multiplied by heart rate, generates cardiac output measurements, though these are truly estimated and thus poorly validated at this juncture, particularly in the cardiac surgery population.[58]

### *Thoracic Bioimpedance and Bioreactance*

Thoracic impedance technology uses skin electrodes to detect changes in voltage that are correlated with tissue impedance as a surrogate for

thoracic fluid content.[99,100] Once baseline impedance is established, small fluctuations from baseline are presumably due to respiratory variability or the variation of the cardiac cycle and thus are extrapolated to estimate SV and cardiac output.[58] While potentially promising as a minimally invasive technology, application in the CVICU population is particularly confounded by lung edema and pleural effusions and as well as changes in SVR.[58,99,100]

### *Non-invasive Venous Waveform Analysis Devices*

While further validation in the CVICU population is required to facilitate broader utility, non-invasive venous waveform analysis (NIVA) technology is another emerging tool. NIVA is designed to noninvasively reflect intrasvascular volume status. Recently, NIVA utilizes has been correlated with acute blood loss in porcine and human models.[101,102] It has also been validated as a surrogate for volume status in patients on hemodialysis and pulmonary capillary wedge pressure (PCWP) in patients with heart failure.[103,104]

### *Wearable Continuous Monitoring Devices*

Predicated upon the continuous monitoring technology frequently encountered in the ICU and driven by efforts for early mobility, wearable medical devices are increasingly encountered in the ambulatory and medical settings. The ability to capture and intervene in hypotension, tachycardia, and opioid-induced respiratory depression have led to substantial reductions in harm, particularly in the non-ICU ward.[105,106] Wireless devices are now emerging as an excellent option for removing the literal tethers of ICU hospitalization, though currently hindered by interference and inaccuracy. Specifically, new wearable continuous NIBP and continuous cardiac output monitoring devices are showing promise in the critical care setting.[107,108]

A notable subset of these devices includes continuous glucose monitoring (CGM) devices, which allow for more frequent glucose measurement and thus improved glycemic control and reduction of both hypoglycemia and hyperglycemia. While they are not yet FDA-approved for inpatient ICU use, convincing data are available from ICUs that temporarily deployed CGMs under a period FDA enforcement discretion during COVID.[109,110] In fact, reassuring outcomes and positive patient and provider feedback during this time have even led some to suggest that CGMs should be considered the 5th vital sign in critical care patients.[111]

Finally, as previously described as a component of multiple existing technologies, but particularly for wearable monitoring devices, artificial intelligence is emerging as a key resource to use in automating and integrating hemodynamic monitors into notification and intervention systems. These systems have promise for facilitating systematic early intervention while also diminishing inappropriate alerts and thus improving alarm fatigue.

## SUMMARY

Care for patients in the CVICU is fraught with rapid, dynamic changes in hemodynamics that make effective monitoring critical. Both noninvasive and invasive monitors as well as ultrasound-based technologies are now components of the armamentarium of an intensivists' tools. Advances in these technologies, including mechanical learning and artificial intelligence continue to facilitate improved data capture and thus intervention. With continued refinement, limitations including reliability, generalizability, data interference, and optimization of alarm thresholds, will hopefully continue to decline, thus further improving the ability to comprehensively and continuously capture the hemodynamic picture of our patients.

## CLINICS CARE POINTS

- Contemporary hemodynamic assessment requires an integrated, multimodal approach that combines static and dynamic parameters with expert clinical judgment.
- While a MAP goal of 60-65 mmHg is commonly used, there is no definitive MAP below which hypoperfusion and organ dysfunction definitively occur and thus no consensus recommendation on MAP goal.
- Other MAP goals, including individualized goals, have shown mixed results for several outcomes, and no RCTs have been done in the CVICU population.
- There is dissociation between the macrocirculation and microcirculation in shock and MAP does not correlate with pressure in the microcirculation.
- Capillary refill time (CRT) is a surrogate marker for microcirculatory perfusion and equivalent to lactate as a surrogate for oxygen delivery.
- Titration of vasopressors to CRT is associated with improved outcomes and is now a recommended component of resuscitation algorithms.
- PPV, SVV, and passive leg raise are more reliable predictors of fluid responsiveness than static measures like CVP, but application

may be limited based on differences from initially validated study populations.

- NIBP has been shown to be noninferior to arterial catheterization in septic patients.
- However, arterial catheterization is still currently recommended in shock which does not respond to initial measures or when vasopressors are required.
- Arterial line-derived data via pulse contour analysis, transpulmonary thermodilution, and ultrasound flow dilution may generate continuous cardiac output data, but reliability in shock and CVICU patients is variable.
- While PACs have not been shown to have a mortality benefit in mixed ICU and heart failure populations, they may portend improved patient outcomes in cardiogenic shock, particularly in patients who may be candidates for advanced heart failure therapies and MCS.
- POCUS, TEE, and esophageal doppler are widely validated tools in the CVICU population.
- While pulse wave transit time and thoracic bioimpedance and bioreactance have shown promise in some populations, cardiac surgical and CVICU patients have multiple confounders which decrease reliability and applicability.
- Wearable continuous monitoring devices are an emerging technology which may systematically improve care, particularly when integrated with AI-mediated intervention systems.

## DISCLOSURES

A.K. Khanna consults for Medtronic, Edwards Lifesciences, Philips Research North America, Bayer Corporation, AOP, GE Healthcare, Innoviva Therapeutics, Viatris, SERB Pharmaceuticals, Pharmazz Inc., SCCM (council member), SCCM Surviving Sepsis Campaign (Research Committee member), SCCM ESICM consensus definition of refractory septic shock (co-chair). Ongoing support Wake Forest University: RAAS dysfunction in septic shock and NIH/NHLBI R01HL177834-01: Dysfunctional Renin Angiotensin System in Septic Shock. None of the other authors have conflicts of interest to disclose.

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