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Invasive and non-invasive monitoring in the ICU

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ABSTRACT

Effective invasive and non-invasive monitoring, when coupled with good clinical decision making, can improve outcomes for critically ill patients. When deciding on the best monitoring technique, it is important to consider the specific information that is needed to guide critical care management, while balancing the reliability of the data obtained and the risks of invasive monitor placement. Here, we review invasive and non-invasive options for hemodynamic and neurologic monitoring in the Surgical Intensive Care Unit. Understanding how each monitoring device functions, its indications, risks, and limitations is key when deciding how to monitor bedside physiologic data that guide clinical decision making.

Level of evidence: Level IV

INTRODUCTION

Effective monitoring is the cornerstone of quality critical care management and allows the intensivist to make informed clinical treatment decisions. Depending on the patient's clinical status, monitoring may need to be continuous or occur at defined timepoints. Hemodynamic monitoring is often central to critical care management and can be non-invasive or invasive. When deciding on the best monitoring technique, it is important to consider the specific information that is needed to guide clinical decision making and to personalize the decision for invasive monitoring. Hemodynamic monitoring can achieve several goals including defining cardiovascular function to ensure optimal perfusion and end-organ function, monitoring volume status and the response to resuscitation, and potentially identifying cardiovascular dysfunction earlier.[1] Monitoring of cerebral function, intracranial pressure (ICP), and the effects of sedation are also frequently used in neurotrauma and neurocritical care patients. Here, we review common invasive and non-invasive monitoring techniques that are used in the surgical intensive care unit (ICU). Defining the clinical questions that can be addressed via each monitoring technique and whether these data will impact clinical decision-making is critical to ensure maximal benefit, while limiting the potential for iatrogenic injury.

HEMODYNAMIC MONITORING: NON-INVASIVE MODALITIES

Continuous cardiac monitoring

Continuous cardiac monitoring, sometimes called telemetry or continuous electrocardiograph (EKG), can detect arrhythmias, myocardial infarction, and their precursors such as premature atrial/ventricular complexes, prior to obtaining a formal EKG. Five EKG leads are placed on the patient's torso (four limb leads and a precordial lead) with wires connected to the monitor which converts the electrical impulses from the heart into the familiar waveform of each beat and calculating beats per minute.[2] Limitations include motion artifact and a high sensitivity to specificity ratio, which can create alarm fatigue when the technology is sensitive enough to detect (and generate an alarm regarding) even minor changes that are not always clinically relevant.[3]

Pulse oximetry

Possibly the most common non-invasive continuous monitoring modality used in hospitals is the pulse oximeter. Oxygen saturation of arterial blood is the second-most important factor of oxygen-carrying capacity, but through pulse oximetry it is also the easiest to obtain. As such, it is indispensable in the monitoring of ICU patients, especially those with respiratory failure. Finger, ear, or forehead probes use red and near-infrared (IR) light to determine the amount of oxyhemoglobin versus deoxyhemoglobin in peripheral capillaries and calculate the proportion of hemoglobin bound to oxygen.[4] The oxygen saturation reading appears as a waveform on a monitor which can also display both respiratory and heart rate. Limitations include inability to differentiate between hemoglobins other than oxy-hemoglobin and deoxy-hemoglobin (carboxyhemoglobin, sickle hemoglobin, methemoglobin), less accuracy in cases of very low oxygen saturation (below 70%), physiologic factors such as compromised perfusion to the extremities (severe hypotension, hypothermia, low cardiac output, vasoconstriction), and even certain nail polish colors (blue, black, green), which interfere with the sensor's ability to distinguish amounts of red and near-IR light passing from one side of the probe to the other.[5]

Oscillometric non-invasive blood pressure (NIBP) monitors

The NIBP cuff is another cornerstone of prehospital and in-hospital (including the ICU) vital signs. Oscillometry measures the amplitude of arterial pressure oscillations over time, by inflating the arm cuff with air to a pressure that can collapse the brachial artery, and then gradually deflating it down to atmospheric pressure. It is clinically relevant to note that this method of measuring blood pressure is most accurate in determining the mean arterial pressure, and less so the systolic or diastolic pressure, as the mean pressure is measured by the oscillometer, whereas the systolic/diastolic numbers are mathematically derived from proprietary algorithms.[6] Arguably the most important limitation of oscillometric NIBP monitoring is it requires an

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appropriately sized cuff relative to the patient's arm.[7] However, other limitations once thought to be clinically relevant in the decision to perform non-invasive versus invasive blood pressure monitoring may be less important than initially thought. These include NIBP use in cardiac arrhythmias such as atrial fibrillation,[8] and use on extremity sites other than the upper arm, such as the calf or thigh.[9] The intra-arterial line is considered the gold standard for accuracy in blood pressure measurement; however, the evidence that invasive blood pressure monitoring offers improved mortality to ICU patients with respiratory failure and sepsis is in question.[10–12] This suggests that the accuracy of invasive blood pressure monitoring alone is not necessary to provide quality care to ICU patients with blood pressure abnormalities, as long as clinicians understand the accuracy and limitations of the monitoring system of choice in a given setting.

End-tidal capnography

Capnography is a measurement of carbon dioxide concentration during the respiratory cycle, displayed as a waveform on a monitor.[13] Also known as end-tidal CO_2 ($ETCO_2$), this non-invasive monitoring modality is used in cardiopulmonary resuscitation, postanesthesia care, conscious sedation, and general hospital ward monitoring of patients receiving opioid pain medications, in addition to other scenarios. In the ICU, there are several indications for capnography. Confirmation of successful endotracheal intubation with $ETCO_2$ has become a standard of care in both the ICU and the emergency department, with the goal of identifying inadvertent intubation of the esophagus expeditiously. $ETCO_2$ monitoring of mechanically ventilated patients can be used to assess ventilation, and although the difference between $PaCO_2$ and $ETCO_2$ in certain ICU patients (Acute Respiratory Distress Syndrome (ARDS), Chronic Obstructive Pulmonary Disease (COPD), V/Q mismatch) does not allow for close approximation of $PaCO_2$, $ETCO_2$ can still be useful for trending ventilation over time or detecting acute, extreme changes.[13 14] Finally, $ETCO_2$ can be used in non-intubated ICU patients who are on close watch for respiratory failure and need for intervention with non-invasive or invasive ventilation strategies. Of note, many clinicians are most familiar with time capnography (plot of exhaled CO_2 against time), while the less-frequently used and understood *volume* capnography (plot of exhaled CO_2 against total exhaled volume) can provide more data regarding pulmonary mechanics and gas exchange but requires additional training for interpretation than the simple representation of exhaled CO_2 against time.[14]

Point-of-care ultrasound (POCUS)

Ultrasound is increasingly being used by practitioners at the bedside to provide clinical data to guide bedside decision-making. Improved technology and increased availability of portable, mobile ultrasound have increased the deployment of this tool in the care of critically ill patients. POCUS is useful to get a bedside snapshot of cardiac function using echocardiography. Although POCUS does not replace the formal echocardiogram, global assessment of cardiac function including systolic function can be estimated.[15] POCUS can also be used to evaluate volume status and fluid responsiveness by measuring the diameter of the inferior vena cava (figure 1).[16] In addition to the traditional trauma extended Focused Assessment with Sonography for Trauma, POCUS can also be useful in evaluating for pericardial effusion, pleural effusion or pneumothorax in non-trauma patients. Ultrasound is generally widely available in the intensive care unit, cost-effective, and can provide immediate results and

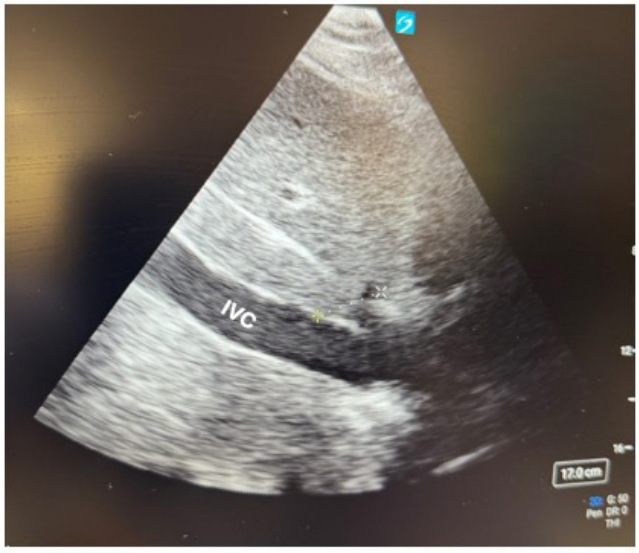

Figure 1 Point-of-care ultrasound can be used to assess volume status by measuring the diameter of the IVC. IVC, inferior vena cava.

does not require review by the radiologist. Obtaining quality images that can guide decision-making does require proficiency of the ultrasound operator to access the appropriate windows to obtain imaging that can guide clinical management.[17]

Clinical decision support

Advances in artificial intelligence and deep learning algorithms allow for the synthesis of large, complex datasets in the medical record that may be beneficial for identifying patients at risk for decompensation before clinical signs appear. These early warning systems have been developed to predict adverse events including sepsis[18] and acute kidney injury. Deep learning algorithms have also been developed to help predict complications and mortality in critically ill patients.[19] Although prior early detection algorithms suffered from poor positive predictive value due to poor data quality, more recent deep learning algorithms have demonstrated improved performance and fewer false alarms. For instance, a recent study monitored patients with a deep-learning model in the electronic medical record to predict sepsis. Patients who were identified at risk for sepsis generated a 'Best Practice Advisory' that prompted the provider to assess the patients risk of sepsis and resulted in reduced in-hospital sepsis mortality and increased sepsis bundle compliance.[18] Machine learning algorithms have also been developed to analyze data from continuous hemodynamic monitoring of patients in the ICU.[20 21] In the future, the real-time analysis of continuous ICU monitoring data paired with data from the electronic medical record may allow for the development of improved early detection systems and clinical decision support at the bedside in the ICU. Ongoing development and validation of the deep-learning algorithms is needed to improve positive predictive value and increase generalizability across diverse populations and clinical scenarios.

HEMODYNAMIC MONITORING: INVASIVE MODALITIES

Arterial lines

Arterial lines are frequently used for continuous blood pressure monitoring. Arterial lines have advantages over NIBP measurement including more precise measurements and continuous monitoring. Arterial lines also allow for frequent blood

gas sampling which can help guide clinical decision making. Most commonly, arterial lines are placed in the radial artery or femoral artery; however, alternate sites including the brachial artery, dorsalis pedis artery, and axillary artery can be used if vascular access is limited. In addition to real-time measurement of blood pressure, arterial lines can also demonstrate pulse pressure variation.[22] Limitations to arterial line use for blood pressure monitoring include variations in systolic pressure based on the location of placement.[23] Arterial line access is safe, but not without risk. Risks include arterial injury, bleeding, thrombosis, arterial insufficiency, distal tissue ischemia, and bloodstream infection.[24] New innovations in technology have allowed for the development of non-invasive continuous blood pressure monitoring; however, these are not yet widely in use.[25]

Central venous pressure (CVP) monitoring

Central venous access is commonly obtained in the ICU and allows for the administration of certain medications, frequent venous blood sampling, and monitoring. Central lines placed in the internal jugular vein or subclavian vein can be used to measure CVP by transducing the pressure in the superior vena cava. CVP is used to assess volume status, approximate preload, and provide information on heart function.[26] Although CVP can help guide clinical decision making, it is important to realize its limitations.[27] CVP often does not have a clear relationship with volume status and can be influenced by factors including positive pressure ventilation and intra-abdominal pressure.[28] Since CVP monitoring requires central venous access, its risks include those inherent to central venous catheter placement and maintenance including central line-associated blood stream infection (CLABSI), central line-associated venous thrombosis, and air embolism.

Pulmonary artery catheter (PAC)

PACs are placed via central venous access and terminate in the right ventricle. These catheters allow for continuous measurement of pulmonary artery pressure and pulmonary capillary wedge pressure, and allow for the measurement of mixed venous oxygen saturation. PACs can be used to measure cardiac output via the thermodilution technique.[29] Although PACs have been used to guide vasopressors or ionotrope therapy for many years, their use has greatly diminished over the past two decades.[30] The PAC-Man trial demonstrated that though the use of PACs was safe, they did not improve outcomes in critically ill patients.[31] Placement of a PAC brings potential risks including cardiac arrhythmia, thrombosis, pulmonary artery rupture, and CLABSI. Based on improvements in non-invasive techniques to measure hemodynamic status, PACs are largely limited to patients undergoing cardiac surgery, those with right heart failure/pulmonary hypertension, or patients with undifferentiated shock.

FloTrac sensor–Vigileo monitor

The FloTrac sensor (Edwards Lifesciences (Irvine, California, USA)) collects data via an arterial catheter and uses pulse contour analysis to calculate cardiac output, stroke volume, systemic vascular resistance, and stroke volume variation.[32] Continuous data are displayed on the Vigileo monitor and provide real-time bedside hemodynamic data (figure 2). A benefit of the FloTrac sensor is that it does not require calibration. Limitations in the data quality provided by the FloTrac–Vigileo can occur with arrhythmias, spontaneous respiration, an open abdomen, and vasopressor therapy; these scenarios can result in poor cardiac output estimates.[33]

Pulse contour cardiac output system (PiCCO)

PiCCO requires an arterial line as well as a central venous catheter and allows for continuous measurement of cardiac output, cardiac index, stroke volume, and stroke volume variation, and estimates end-diastolic volume.[32] The system is calibrated using the central venous catheter to perform thermodilution. PiCCO allows for bedside data analysis to guide fluid therapy and manage patients with hemodynamic failure. Limitations include the requirement to perform an accurate thermodilution to calibrate the system. Measurements can be altered by cardiac arrhythmias or changes in the waveform generated by the arterial catheter.[34]

NEUROMONITORING: NON-INVASIVE MODALITIES

Brain activity monitoring

Monitoring patient sedation levels in the ICU can be helpful to prevent oversedation. Non-invasive monitors including the Sedline and Bispectral Index (BIS) monitors use electrodes placed on the skull to measure EEG activity in real-time with algorithms that provide an objective measurement of sedation level.[35] While monitoring brain activity levels in the ICU has not been conclusively shown to improve outcomes or decrease resource usage, they can be helpful in sedation management, especially during deep sedation.[36] Following brain activity levels using these monitors can help limit oversedation, prevent undersedation during periods of neuromuscular blockade, and potentially minimize sedative use with the goal of reducing delirium. One study has shown, for example, that lower BIS monitor scores are associated with the development of delirium.[37]

Automated pupillometry

Automated pupillometry is the measurement of pupil size and reactivity and serves as a non-invasive tool for monitoring neurologic status in patients with brain injury. Subtle changes in pupil size and reactivity can be detected and measured with an automated device. These devices can calculate the Neurologic Pupil Index and provide objective data to suggest changes in

Figure 2 Example of hemodynamic data from FloTrac displayed on Vigileo monitor.

Table 1 Monitorin devices commonly used in the ICU setting

Monitoring modality	Invasive or non-invasive?	Parameters measured	Most accurate for	Risks of placement/use	Limitations
Arterial line	Invasive	SBP, DBP, MAP*, PPV*	SBP; DBP	Vessel injury, thrombosis, bleeding, infection	Positional, dampened waveform, clotting off
Central venous pressure	Invasive	CVP	Static pressure measurement	Risks inherent to central line, misinterpretation	PPV, intra-abdominal hypertension
Pulmonary artery catheter	Invasive	PAP, PCWP, SvO_2, CO*, CI*, thermodilution	PAP, SvO_2, thermodilution	Risks inherent to central line, cardiac arrhythmia, PA perforation	More invasive without improving outcomes
FloTrac	Invasive	SBP, DBP, MAP*, PPV*, CO*, SV*, SVR*, SVV*	SBP, DBP	Risks inherent to arterial line, misinterpretation	Arrhythmia, spontaneous respiration, open abdomen, vasopressors
Pulse contour cardiac output system	Invasive	Arterial line parameters, CVP, thermodilution, CO*, CI*, SV*, SVV*, EDV*	Arterial line parameter, CVP	Risks inherent to arterial line, risks inherent to central line	Must be calibrated with thermodilution, cardiac arrhythmia alters measurements, limitations inherent to arterial lines
ICP monitor	Invasive	ICP	ICP	Infection, parenchymal injury	Credentialing/specialization for placement
Continuous cardiac monitoring	Non-invasive	Electrical impulses, HR*	Electrical activity	Skin tears, skin irritation, misinterpretation, alarm fatigue	Motion artifact, high volume of clinically irrelevant information
Pulse oximetry	Non-invasive	Percentage of red and near-IR light absorbed between probe, SpO_2*, HR*, RR*	Oxyhemoglobin, deoxyhemoglobin	Minimal	Rare hemoglobinopathies, hemoglobin bound to molecules other than oxygen, low blood flow to extremities, arrhythmia (limits accuracy of HR), very low SpO_2, some nail polish colors
Oscillometric blood pressure monitor	Non-invasive	SBP*, DBP*, MAP	MAP	Discomfort to the patient with repeated measurements in the same place	Inappropriate cuff size, intermittent measurements only
Point of care ultrasound	Non-invasive	Direct distance between structures, size of structures, echogenicity of structures/fluid, direction of flow when using Doppler	Direct distance measurements and size measurements	Small amount of discomfort depending on the exam performed, hemodynamic changes with turning or moving the patient to obtain the window	Operator error or inexperience, air between probe and target structure, patient body habitus
Brain function monitors	Non-invasive	Electroencephalography*, level of sedation	Electroencephalographic waveforms	Skin irritation where electrodes are placed	Time delay between administration of new medication and calculation of new monitored value (not immediately concurrent), interference from other medical devices, hypothermia
Automated pupillometry	Non-invasive	Pupil size*, pupil reactivity, NPI	Pupil size	Misinterpretation	Cataracts, certain medications, inability to detect reactivity in very small pupils
Clinical decision support	Non-invasive	Dependent on the learning algorithm	Dependent on the learning algorithm	Alarm fatigue or 'click' fatigue	Patient populations not used in the learning or validation models

*Indicates directly measured values, other parameters are calculated based on monitor algorithms or calibration.
CI, cardiac index; CO, cardiac output; CVP, central venous pressure; DBP, diastolic blood pressure; EDV, end diastolic volume; HR, heart rate; ICP, intracranial pressure; ICP, intracranial pressure; IR, infrared; IR, infrared; MAP, mean arterial pressure; NPI, neurologic pupil index; NPI, Neurologic Pupil Index; PAP, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; PPV, pulse pressure variation; RR, respiratory rate; SBP, systolic blood pressure; SpO2, oxygen saturation of peripheral blood; SV, stroke volume; SvO2, central venous oxygen saturation; SVR, systemic vascular resistance; SVV, stroke volume variation.

pupil function. There is some debate whether changes in pupil function accurately represent changes in ICP[38 39]; however, the data can still be useful as part of a comprehensive neurologic assessment in sedated or intubated patients. Automated pupillometry also minimizes interobserver variability and can help standardize measurement across the care team.[40] Therefore, serial measurements using an automated pupillometer can help identify changes in neurologic function in critically ill patients.

NEUROMONITORING: INVASIVE MODALITIES

ICP monitoring

A neurologic examination or, in the case of trauma, the Glasgow Coma Scale (GCS), is the foundation for monitoring patients with neurologic dysfunction in the ICU. In cases of patients who cannot participate in these clinical examinations, some intensivists and surgeons will monitor surrogate measures of neurologic function. This may include tracking ICP via an invasive monitoring device.[41] A hollow sensor alone attached to a monitor is often referred to as an ICP bolt (or simply 'a bolt'), while the external ventricular drain is attached to a reservoir with tubing that leads into the ventricles allowing for both diagnostic (ICP monitoring) and therapeutic (draining cerebrospinal fluid to relieve ICP) maneuvers.[42] ICP monitoring is recommended for patients with a GCS score ≤8 with evidence of structural brain injury on imaging.[43] ICP monitoring should also be considered for patients with GCS score >8 with structural injury on imaging who are at high risk of progression or who require urgent extracranial surgery or sedation that prevents serial neurologic

examination.[44] While there is debate over the clinical indications and even the clinical benefits of these devices,[45] they do provide data otherwise impossible to obtain in the obtunded ICU patient who is unable to participate in neurologic examinations.

Brain tissue oxygen monitoring

Secondary brain injury after traumatic brain injury (TBI) can lead to brain tissue hypoxia due to elevated ICP, cerebral edema, or lack of cerebral autoregulation. Brain tissue hypoxia can occur even when using protocolized management of ICP and cerebral perfusion pressure.[46] To better monitor cerebral oxygenation, brain tissue oxygen monitors (ie, Licox, Integra LifeSciences (Princeton, New Jersey, USA)) have been developed and can be deployed as an invasive monitor in the ICU. These devices use a small electrode that is placed into the brain parenchyma that can measure tissue oxygen partial pressure in addition to local temperature and can be placed concurrently with an ICP monitor. Clinical interventions can be performed to attempt to improve brain tissue oxygenation, including increasing the percentage of inspired oxygen (FiO_2), improving cerebral perfusion using vasopressor support, or by decreasing brain metabolic demand using sedation.[47] Limitations of brain tissue monitoring include its localized measurement that may not reflect brain tissue oxygenation in other anatomic regions, risk of infection, and cost of the device. While low brain tissue oxygenation has been correlated with poor neurologic outcomes, goal-directed therapies aimed at optimizing brain tissue oxygenation have not demonstrated improved outcomes compared with current standard of care for TBI.[48 49]

CONCLUSIONS

A wide range of invasive and non-invasive monitoring modalities are available to the intensivist for application to each unique clinical scenario encountered in the ICU. Understanding how each modality works, its indications, its risks, and its limitations is essential in improving patient care and outcomes (table 1).

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