Monitoring and Managing the Critically Ill Patient in the Intensive Care Unit

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Abstract

The need for better acquisition and monitoring of patient physiological information within and outside of healthcare settings is especially important, as our healthcare system prepares to care for an aging population of more critically ill patients. Monitors serve several purposes, including: identification of shock and abnormal cardiac physiology, evaluation of cardiovascular function, and/or to allow for optimizing titration of therapy. An important function of an effective monitoring device is the reliable detection of abnormal physiology. Despite much research on the use of monitoring techniques in critical care, there is little evidence to support improved outcome related to routine use of monitors. Mainstays of invasive monitoring in the ICU include central venous pressure monitoring and arterial pressure monitoring, with pulmonary arterial monitoring reserved for occasional patients with multisystem disease. Recent trends in monitoring have included development of less invasive monitoring techniques that yield a number of cardiovascular parameters potentially useful to clinicians. New noninvasive measures of tissue perfusion (e.g., StO_2) have significant potential for identification and treatment of pathophysiologic states resulting in inadequate tissue perfusion. Developers of new monitors, despite facing regulatory requirements that are less stringent than those of drug manufacturers, will increasingly be expected to demonstrate clinical efficacy of new devices. In the final analysis, the most important "monitor" is a caring healthcare provider at the patient bedside carefully evaluating the patient's response to intervention and therapy.

Keywords

ICU monitoring • Near-infrared spectroscopy • Pulse waveform contour analysis • Sublingual capnometry • Pulmonary artery catheter

All exact science is dominated by the idea of approximation (Bertrand Russell, 1870–1972)

23.1 History

The treatment of shock is closely related to healthcare workers' experience during times of war. Ambroise Pare, a French military surgeon practicing during the sixteenth century, first described ligature to control bleeding in 1545. Experiences during World War I resulted in a clear understanding of the need for operative interventions for bowel perforation, with this operative intervention available due to the accessibility of general anesthetics. The discovery of blood types by Karl Landsteiner in 1901 (for which he received the Nobel Prize in 1930) enabled the safe and practical use of blood transfusions by medical providers during World War II, thus allowing resuscitation of combat-injured casualties. Advances utilized in the Korean War included new surgical techniques such as vascular anastomosis and new medical therapies including renal dialysis.

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The use of positive pressure ventilation and renal dialysis was broadened during the Vietnam War due to the development of complications of resuscitation in patients with previously nonsurvivable injury, including acute respiratory distress syndrome and/or renal failure.

The first described use of an intensive care unit (ICU) as a separate area to care for patients was in the early 1950s, as a result of a poliomyelitis epidemic in Denmark. The first coronary care unit was established in Kansas City, KS, in the early 1960s with the observation that new techniques of cardiopulmonary resuscitation could reduce mortality in patients suffering myocardial infarction. Their use expanded to postsurgical patients during the mid-1960s, as more complicated surgery mandated a closer observation of patients and more aggressive interventions in the ICU. More specifically, physiological monitoring displays were introduced in the ICU in the 1970s, and, unfortunately, they have not changed substantially since then. In contrast, the last four decades have seen significant efforts and resources expended toward improving data display design in high-risk fields, such as aviation and power plant control. These efforts have yielded marked improvement in the safety and efficiency of air travel and nuclear power plant operations.

Our ability to care for sicker patients has also improved. The first "monitors" were the five senses of the physician. Lanneac described the first stethoscope as an extension of the sense of hearing in the late eighteenth century. The development of neurosurgery as a specialty in the early twentieth century and the need to monitor blood pressure during these operations led to development of the sphygmomanometer. The need to monitor the physiology of astronauts in space led to the capability of continuous EKG and other types of monitors. EKG was one of the very first technical approaches to monitor patient physiology and was clinically developed by the British cardiologist, Sir Thomas Lewis, in 1908. Some of today's most innovative monitors still employ elements of Lewis' original strip chart (for a more complete history of the EKG, see Chap. 19). ICU monitoring techniques developed over the last four decades have resulted in a significant improvement in our overall understanding of cardiac physiology and pathophysiology. The last three decades have seen a plethora of invasive and noninvasive monitoring tools developed for critical care use. Despite these tools, the most important tool available to the clinician remains his/her five senses, mandating a careful examination of patients on a daily routine basis.

23.2 Goals of Monitoring

23.2.1 Diagnosis of Shock

Table 23.1 Commonly used clinical end points of resuscitation

Heart rate
Blood pressure
Mentation
Skin perfusion
Urine output 50 cm^3/h
Normal lactate/acid base status
Appropriate response to therapeutic interventions

Many monitoring strategies relate to identification of shock; therefore, an important issue is the clinical definition of shock. In the final analysis, shock can be simply defined as inadequate oxygen delivery to a tissue bed, resulting in decreased adenosine triphosphate (ATP) production and flux at the mitochondrial level related to decreased oxidative phosphorylation. Therefore, the ideal monitor for diagnosis of shock would be able to identify the rate of ATP production and turnover. Unfortunately to date, such a monitor does not exist for routine clinical use; hence, clinicians use common clinical end points to identify shock and other associated abnormalities in patients. A list of commonly used clinical monitoring end points is listed in Table 23.1. It requires an astute clinician to balance the sometimes contradictory findings identified during evaluation of the patient and to develop an appropriate treatment strategy. An important component of this process is frequent reevaluation of the patient to assess results of the initial intervention. Importantly, a response to intervention contradictory to initial evaluation should prompt reconsideration of the initial diagnosis.

23.2.2 Evaluation of Cardiac Function

Another reason for consideration of advanced monitoring is for frequent evaluation of cardiac function. In particular, serious illness in patients with underlying cardiac disease (e.g., cardiomyopathy, congestive heart failure, congenital heart disease, etc.) may require a careful titration of therapy to prevent decompensation. Situations that commonly result in invasive monitoring of patients include serious infectious episodes, planned major operations, and/or decompensation of the underlying disease.

23.2.3 Titration of Vasoactive Therapy

Many patients receive advanced monitoring due to hemodynamic instability (i.e., hypotension or severe hypotension) or due to the need to titrate vasoactive therapy for other therapeutic purposes (e.g., optimization of cerebral perfusion in patients with neurologic insult). Most vasoactive agents have short half-lives, requiring frequent titration of therapy to achieve monitoring targets. This need mandates accurate, continuous monitoring of blood pressure (or other end point), typically via an invasive route.

Fig. 23.1 Different monitors used in the ICU. Heart rate, arterial blood pressure, and mechanical ventilation settings (*top*). Intravascular temperature manager, ECHO, and perfusion monitors (*below*)

An important, but frequently unstated, reason for invasive monitoring in the critically ill patient is to allow a more definitive diagnosis and/or end point for treatment. This more definitive observation after initial evaluation may allow ongoing management of the patient's issues with the clinician away from the bedside, allowing the clinician to perform other duties (Fig. 23.1).

23.3 Monitors: Do They Help?

Despite the common reliance on monitors in the modern ICU, a number of monitoring end points commonly used have not demonstrated consistent benefit with respect to patient outcome, including continuous EKG monitoring, pulse oximetry, pulmonary artery catheters, and/or intracranial pressure monitoring. For example, with regard to pulse oximetry, Pedersen et al. in the Cochrane database systems review of 2003 [1] noted that "the conflicting subjective and objective results of the studies, despite an intense methodological collection of data from a relatively large population (>20,000 patients) indicates that the value of perioperative monitoring with pulse oximetry is questionable in relation to improved quality outcomes effectiveness and efficacy."

Another randomized nonblinded study was performed in 2006 [2] which was designed to compare the effects of continuous and standard monitoring of pulse oximetry on patient outcomes in 1219 subjects. Ochroch and colleagues observed that there was no difference in the rate of ICU readmission from postcardiothoracic surgery care floor, mortality, or overall estimation of costs of hospitalization between the CPOX and standard monitor groups. The same can be said regarding pulmonary artery catheters. Shah et al. [3] noted that "despite almost 20 years of randomized controlled trials, a clear strategy leading to improved survival with a pulmonary artery catheter has not been devised." This has led to the near abandonment of the use of pulmonary artery catheters in many institutions.

One nuance with regard to monitors is that the use of such devices will not change the outcome for a fatal disease if there is no treatment available for the disease [4]. For instance, while you can monitor the progression of end-stage organ function in a patient with metastatic cancer, it is unlikely that utilizing a monitor to guide therapy in such a patient will affect the ultimate survival outcome of the patient.

On the other hand, one positive bit of evidence demonstrating beneficial effects for physiologic monitoring relates to the significant decrease in anesthesia-related deaths over the last two decades. Anesthesia care is currently highly dependent on multiple physiologic monitors. As monitors have become increasingly utilized during anesthesia, the anesthesia-related mortality rate of 1 per 20,000 anesthetics reported in the late 1970s has decreased to a rate of 1 in 300,000 anesthetics at the turn of the century. Most knowledgeable clinicians in this area would agree that much of this decrease in mortality is related to both better understanding of pathophysiology and more widespread use of continuous monitoring.

23.3.1 What About Telemedicine?

Telemedicine applied to the ICU is an innovative approach to providing critical care services and to treating critical ill patients, especially those residing in broad or remote geographic areas (Fig. 23.2). Rosenfeld et al. published, in 2000 [5], the first feasibility study of telemedicine. Their study

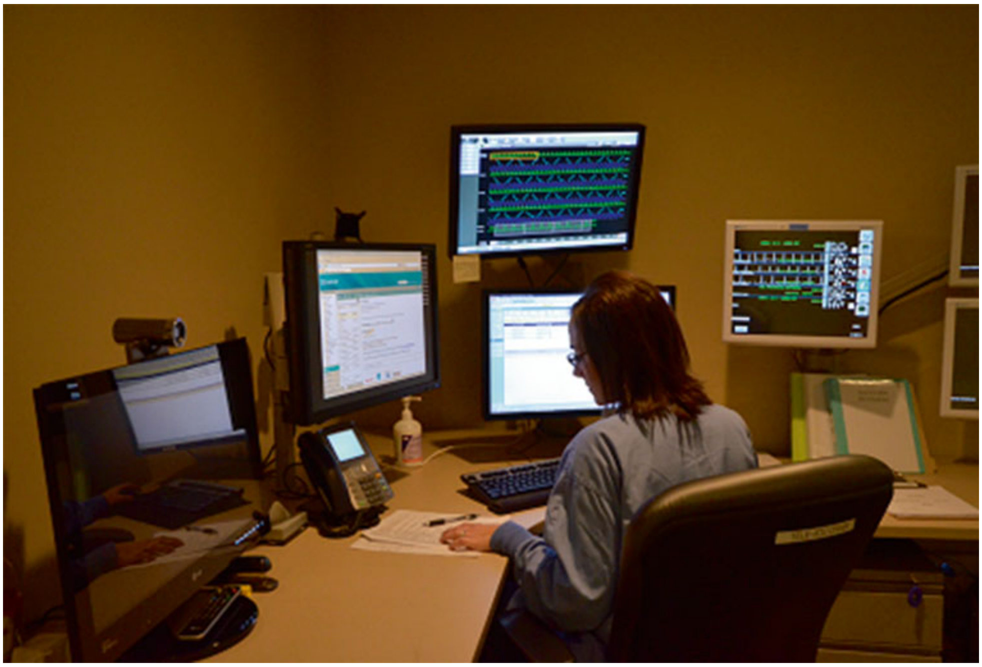

Fig. 23.2 Tele-ICU. The workstation arrangement in the tele-ICU may vary, but usually there are between 5 and 7 monitor screens displaying real-time patient data, including vital signs, medications, lab results, and the patient's entire medical history

looked at a single open model surgical ICU that, for a 16-week period, was provided with 24-h off-site monitoring. Compared with the baseline periods prior to the intervention, the mortality rate, length of stay, and costs were all reduced. In another study, one from a large university medical center, administrators retrospectively reviewed their data from 2011 to 2012, which showed a reduction in mortality rates from 6.5 % before to 4.9 % after the implantation of an enhanced monitoring system [6]. Subsequently, other larger trials have also identified similar improvements in mortality [7, 8]. Finally, it was also suggested that if the hospital is able to provide the initial capital and financing for the ongoing operation, a tele-ICU may positively benefit the hospital's profit margin [9].

23.4 Invasive Monitoring Techniques in the ICU

23.4.1 Central Venous Pressure (CVP) Monitoring

Pressure monitoring in a central venous location, using a large-bore catheter, is likely the most frequently utilized invasive monitoring technique in current ICUs. Central venous catheters allow an estimate of "cardiac preload" and are typically placed via the internal jugular or subclavian venous route (Fig. 23.3). These monitors are very accurate for the identification of situations in which cardiac output is affected by a low preload. However, the assumption is made when monitoring CVPs that this value is proportional to pulmonary artery pressure, which is proportional to left atrial pressure, which is proportional to left ventricular end-diastolic volumes. Unfortunately, there are many common conditions in ICU patients which may elevate CVP that do not relate to increased filling of the left ventricle. These include: pneumonia, positive pressure ventilation, acute respiratory distress syndrome, pulmonary emboli, and others. Thus, one should have a strong concern for the situation in which a high CVP does not correlate with the clinical condition of the patient.

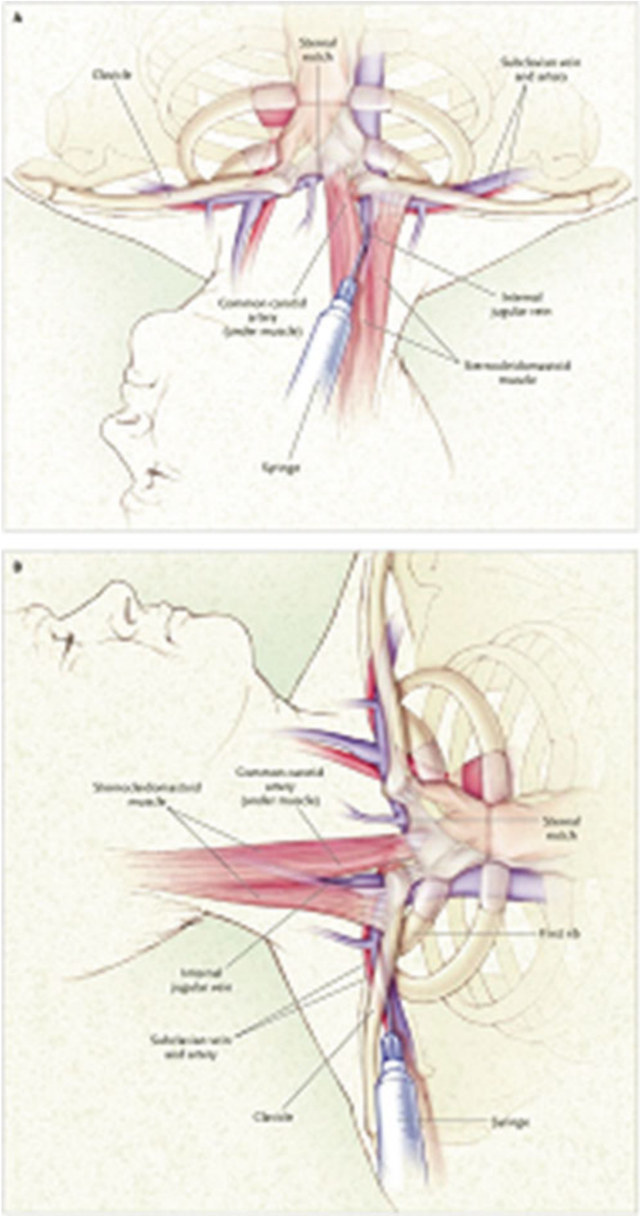

Fig. 23.3 Venous anatomy of subclavian (*top*) and internal jugular veins. Veins are in blue. Outline of clavicle and manubrium are in black (*upper panel*). Sternocleidomastoid muscle (*lower panel*) is in red

23.4.2 Arterial Blood Pressure Monitoring

Arterial blood pressure monitoring can be performed using both noninvasive and invasive techniques. Noninvasive monitors have progressed significantly over the years and currently allow a hands-off approach to intermittent measurement of blood pressure. Unfortunately, it is difficult to noninvasively measure blood pressure more frequently than every 5 min due to patient comfort and potential for inducing pressure sores. In situations where more frequent measures are necessary, invasive catheters placed percutaneously into a peripheral artery are utilized (Fig. 23.4). Typically, continuous beat-to-beat blood pressure is measured using an arterial catheter placed in one of several positions (most commonly radial or femoral arteries). However, this can be associated with injury, greater expense, and the need for required skills to acquire the data [10].

Recently, a continuous noninvasive arterial pressure (CNAP) measurement was made possible by using a finger cuff technology (Fig. 23.5). It has been shown to be superior to intermittent oscillometric measurements in detecting rapid changes in arterial pressure [11]. Such an approach employs

Fig. 23.4 Arterial line placed into radial artery. The line is attached to a pressure transducer which measures blood pressure and allows slow flush of intravenous fluid though the line. This line can also be utilized for sampling of arterial blood

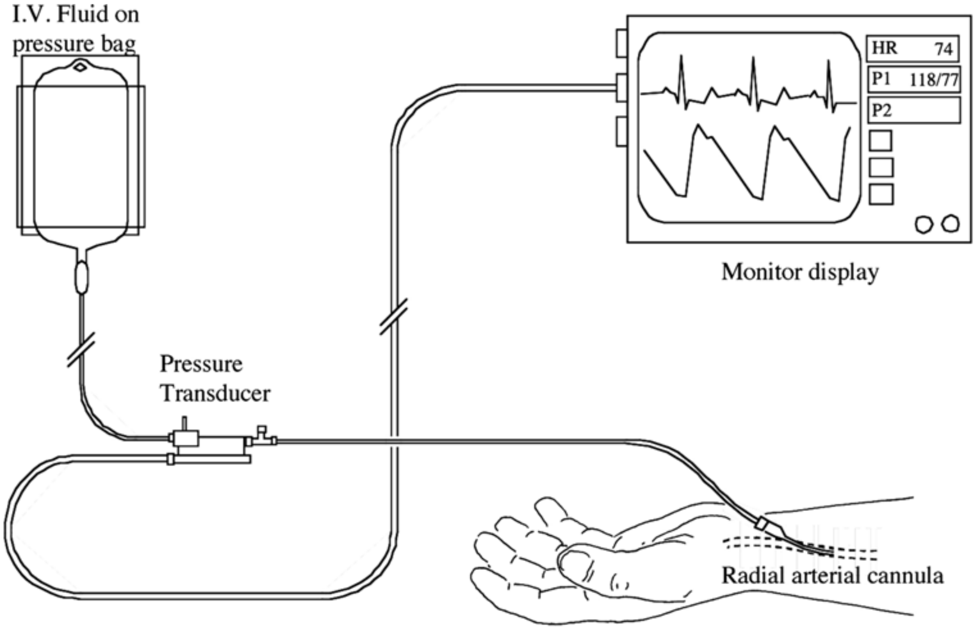

Fig. 23.5 Continuous noninvasive arterial blood pressure (CNAP) provides a continuous, beat-to-beat, blood pressure signal recorded from the fingers of a subject. The monitoring system uses a double finger cuff in three cuff sizes to accommodate small children through large adults. The system outputs a continuous blood pressure waveform that is similar to a direct arterial pressure waveform. Adopted from biopac.com

a double finger cuff that is easy to place on the patients' hand, a pressure transducer mounted on the forearm, and an upper arm oscillometric cuff for calibration. The system outputs a continuous noninvasive blood pressure waveform that is similar to a direct arterial blood pressure waveform and also displays values for systolic, diastolic, and mean blood pressures as well as heart rate.

CNAP is obtained by applying pressure via the finger cuffs such that the blood volume flowing through the finger arteries is held constant (i.e., volume clamping). The diameter of a finger artery under a cuff is "clamped," i.e., kept at a constant diameter in the presence of the changes in arterial pressure during each heart beat. The finger diameters are measured by means of an infrared photo-plethysmograph built into the finger cuff. The finger diameter is held constant by dynamically applying a counter pressure throughout the cardiac cycle. The pressure in the cuff that is needed to keep the volume constant during arterial pulsation corresponds to the relative arterial pressure. Recent studies have demonstrated comparable results to continuous invasive arterial blood pressure measurements [12]. For additional information on blood pressure monitoring, see Chap. 18.

Like CVP monitoring, there are assumptions built into blood pressure monitoring that are occasionally incorrect.

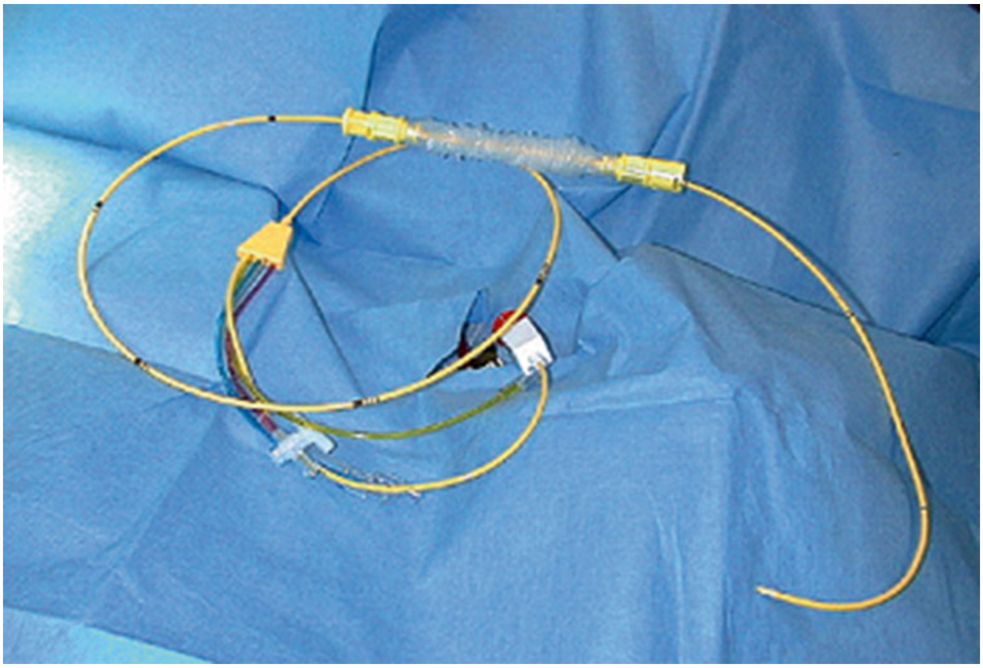

Fig. 23.6 Pulmonary artery catheter. This catheter has an inflatable balloon at the tip, allowing the catheter to be carried through the right heart and into the pulmonary artery during insertion

Table 23.2 Calculations for invasive hemodynamic measurements

Hemodynamic formula	Normal
$CI = CO/BSA$	2.8–4.2 $l/min/m^2$
$SV = CO/HR$	60–90 ml/beat
$MAP = DBP + 1/3\ (SBP - DBP)$	80–120 mmHg
$SVR = [(MAP - CVP)/CO] \times 80$	900–1400 dynes cm s^3
$SVRI = [(MAP - CVP)/CI]$	1900–2400 dynes cm m^3
$PVR = [(MPAP - PAOP)/CO] \times 80$	100–250 dynes cm s^3
Arterial oxygen content: $CaO_2 = (SaO_2)\ (Hb \times 1.34) + PaO_2\ (0.0031)$	21 ml/100 ml
Venous oxygen content: $CvO_2 = (SvO_2)\ (Hb \times 1.34) + PvO_2\ (0.0031)$	15 ml/100 ml
Oxygen consumption: $VO_2 = CO\ (CaO_2 - CvO_2) \times 10$ (VO_2 not indexed, indexed by weight, BSA)	225–275 ml/min, 3.5 ml/kg/min; 110 $ml/min/m^2$
Oxygen delivery: $DO_2 = CO(CaO_2) \times 10$	1000 ml/min
Oxygen extraction ratio: $O_2ER = VO_2/DO_2$	22–30 %

BSA body surface area, *CI* cardiac index, *CO* cardiac output, *CVP* central venous pressure, *DBP* diastolic blood pressure, *Hb* hemoglobin, *HR* heart rate, *MAP* mean arterial pressure, *MPAP* mean pulmonary artery pressure, *PAOP* pulmonary artery occlusion, *PVR* peripheral vascular resistance, pressure, *SBP* systolic blood pressure, *SV* stroke volume, *SVR* systemic vascular resistance, *SVRI* systemic vascular resistance index

Importantly, the assumption that a normal arterial blood pressure has excluded the presence of shock may be false, since afterload may be increased due to low cardiac output. This results in a normal blood pressure but inadequate oxygen delivery to tissues.

23.4.3 Pulmonary Artery Catheter

Since pulmonary artery catheterization was first described in 1970 by Drs. Swan and Ganz [13], it has been widely used as a diagnostic tool and to understand the physiology of the cardiovascular system during critical illness. The pulmonary artery catheter is inserted via central venous access through the femoral, subclavian, or internal jugular route. A balloon at the tip of the catheter allows the catheter to be “floated” to the right side of the heart and into the pulmonary artery, where it wedges into a smaller branch of the pulmonary artery (Fig. 23.6). It allows the measurement of stroke volume, cardiac output, mixed venous saturation, and pressures on the right side of the heart (Table 23.2). This catheter allows for a more accurate measure of intravascular volume than CVP because it bypasses the situations that can falsely elevate CVP; additionally, the information it provides can be utilized to distinguish among the various types of shock (Table 23.3). Since the pulmonary artery system is a high

Table 23.3 Changes in cardiac preload (PAOP), systemic vascular resistance, and cardiac output in various causes of shock

Type of shock	PAOP	SVR	CO	Prime mover
Hemorrhagic	Decreased	Increased	Decreased	Decreased preload
Septic	Unchanged	Decreased	Increased	Decreased SVR
Cardiogenic	Increased	Increased	Decreased	Decreased CO
Neurogenic	Unchanged	Decreased	Increased	Decreased SVR

CO cardiac output, *PAOP* pulmonary capillary wedge pressure, *SVR* systemic vascular resistance, *prime mover* variable primarily responsible for shock in clinical syndrome

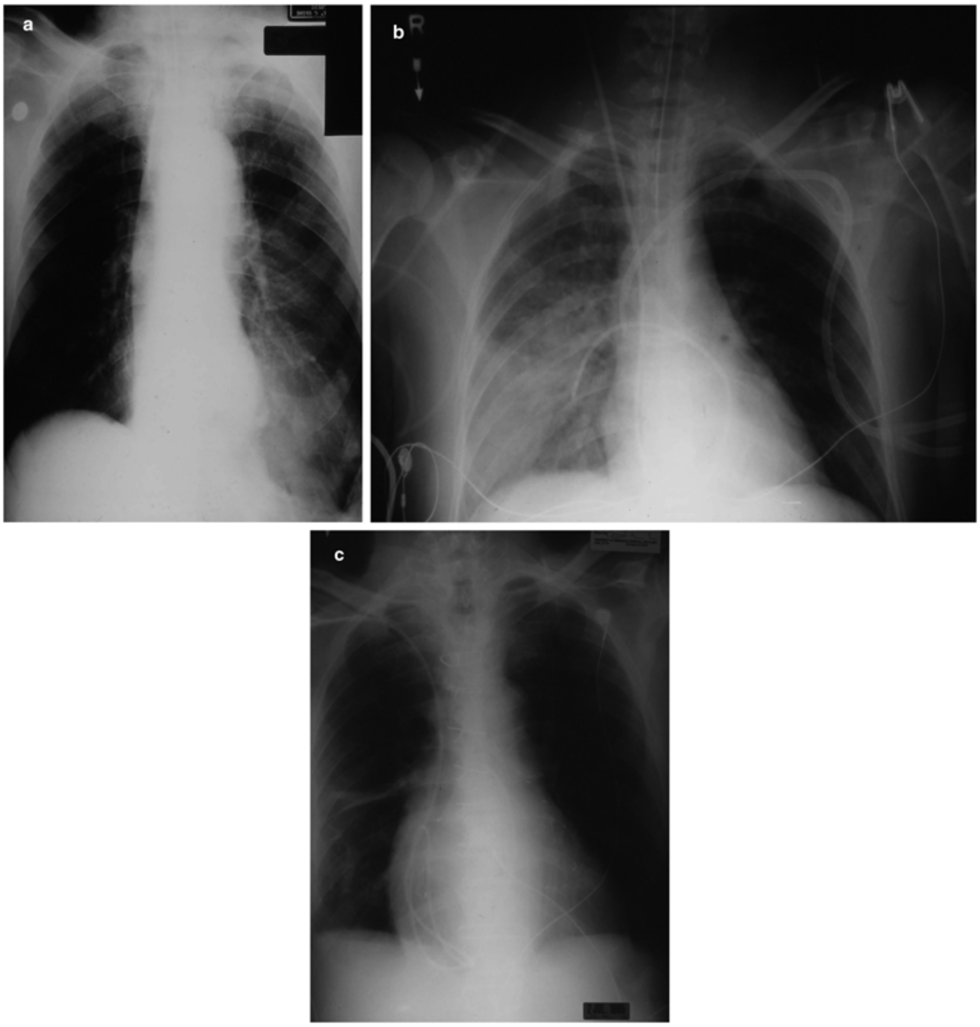

Fig. 23.7 Complications associated with insertion of central access and pulmonary artery catheter including: (**a**) right pneumothorax, (**b**) pulmonary hemorrhage due to distal migration of pulmonary artery catheter, and (**c**) knotting of pulmonary artery catheter in right ventricle

flow, low resistance system, those conditions which falsely elevate pulmonary artery pressure do not affect pulmonary artery wedge pressure. As noted previously, the use of this catheter has significantly declined in the last decade due to paucity of data supporting improved mortality, general ICU or hospital length of stay, or cost for adult patients in intensive care [14, 15]. Despite the decreased use, the pulmonary artery catheter can still be indispensable to assist in the evaluation and titration of therapy of the patient with multisystem disease.

23.4.4 Complications of Invasive Monitors

A major issue with all invasive monitors involves complications such as those related to insertion, infectious complications, and/or problems associated with an indwelling catheter. Insertion complications can result when the catheter: (1) is placed in the wrong vessel, (2) creates a pneumothorax, or (3) causes bleeding related to coagulopathy or inappropriate dilation of a vessel (Fig. 23.7). Furthermore, centrally placed catheters can allow air within the central circulation, occasionally resulting in stroke [16]. Unfortunately, catheter-associated central line infections are common and represent a major and expensive source of hospital morbidity. Typical infection rates for central venous catheters are in the range of 3–5 infections per 1000 patient catheter days. Thus, it is important to remove central venous catheters at the point where they are no longer necessary. Since indwelling catheters are made of a foreign material, there is risk of thrombosis and embolus [17]. Both of these risks are well described in the literature, and attempts to decrease these risks with heparin bonding or using other coatings are prevalent.

23.5 Less Invasive Monitoring Techniques

There are many new monitors making their way into daily clinical use. The utility of these monitors varies widely depending on clinician experience and understanding of monitoring end points, patient populations chosen for study of these monitors, and the clinical relevance of these monitors. The two questions clinicians should ask themselves when evaluating any new monitoring strategy are as follows: (1) Does this monitoring system provide the information needed to make a decision about the patient's status that is clinically relevant? (2) How should the clinician intervene related to the results of the monitor? If results from the monitoring system are not clinically relevant or do not allow decisions to be made with respect to intervention, then the monitor is likely not useful for patient care.

23.5.1 Cardiac Hemodynamics

There are several new measurements available allowing less invasive measurement of cardiac hemodynamics.

23.5.1.1 Pulse Contour Wave Processing

Recently, several investigations have validated the benefits of employing less invasive measures of hemodynamics, including pulse contour wave processing and the ability to predict whether a patient is going to respond to fluid boluses as the initial step of the hemodynamic resuscitation. Some of these commonly used methods (e.g., PiCCO, LiDCO, FloTrac) are based on assessing changes in left ventricular output during positive pressure ventilation, e.g., pulse pressure variation (PPV) and stroke volume variation (SVV). Underlying these measures, intrathoracic pressure increases during respiration, causing right arterial pressure to increase as a consequence; cardiac preload will decrease, leading to a decrease in right ventricular output and thus left ventricular output after few beats. The PiCCO monitor utilizes intermittent arterial thermodilution with beat-to-beat analyses of the arterial pulse waveforms to provide several hemodynamic parameters. This monitoring approach requires both a central arterial line (femoral or axillary) and a central venous line [18]. The LiDCO monitor also uses pulse contour analysis and is calibrated using a dye dilution technique employing lithium chloride as an indicator. This approach requires only a peripheral venous line and arterial catheter [19]. The aforementioned techniques also allow evaluation of preload using different calculated measures including SVV, PPV, and others. Importantly, these measures of preload have been demonstrated to be well correlated with fluid responsiveness in a number of clinical settings [20].

It should be noted that the previous measures have some general and specific limitations, one being that the results become inaccurate in the setting of atrial fibrillation, frequent premature ventricular contractions, and/or intra-aortic balloon central pulsation. They also require the patient to be heavily sedated and to be receiving mechanical ventilation with a tidal volume of >6 ml/kg for obtaining accurate PPV and SVV values. Therefore, their use becomes more challenging during periods of hemodynamic instability, requiring frequent recalibration of the system. An additional limitation of the LiDCO monitor approach is that some nondepolarizing muscle relaxants (e.g., vecuronium) will interfere with the sensor [21].

A new pulse contour method, the FloTrac/Vigileo™ system (Edwards LifeSciences, Irvine, CA, USA), has been recently introduced. It uses intra-arterial pressure waveform-based pulse contour analyses to measure cardiac output and SVVs, without the need for continual calibration. For estimation of the cardiac output, the standard deviation of pulse pressure sampled in 20 s is related to normal stroke volume based on the patient's demographic data (height, weight, age, and gender). Unlike PiCCO which requires femoral or brachial arterial cannulation to estimate SVV, the FloTrac/Vigileo system uses only a peripheral arterial pressure waveform without any other invasive monitoring. SVV measured by the FloTrac/Vigileo™ system (SVV-FloTrac) has been reported to have acceptable sensitivity and specificity for the prediction of fluid responsiveness [22].

23.5.1.2 Ultrasonography/Echocardiography

Ultrasonography and echocardiography have been used to measure flow volume and diameter of the aorta and left ventricular function as a noninvasive hemodynamic evaluation (Fig. 23.8). The described methods include transthoracic or transesophageal echocardiograms (TEE). Transthoracic methods are less invasive but significantly less accurate, while transesophageal techniques require a sedated and/or mechanically ventilated patient. Subramaniam and co-authors suggest a method of rapid echocardiographic assessment using a standardized algorithm [23]. This approach uses transesophageal echocardiography for assessment but requires an experienced operator to prevent misinterpretation

Fig. 23.8 Bedside ultrasound machine commonly used in the ICU setting and easy to move and handle (three different probe sizes)

of findings. Over the last few years, several studies within different ICU and critical care settings have demonstrated the feasibility of utilizing TEE in the management of hemodynamic instability. It is now clear that this semi-invasive tool can provide critical information about the heart. Further, even when invasive continuous monitoring by a pulmonary artery catheter is used, TEE can further help define a patient's diagnosis by acquiring morphological and functional information that can be integrated with the pulmonary artery catheter data. Several recent reports have demonstrated the potential utility of this semi-invasive approach in the ICU patient [24–26].

Preload can also be evaluated by measuring left ventricular end-diastolic area (which correlates well with end-diastolic volume) and also by evaluating respiratory variation in the diameter of the inferior vena cava or the collapsibility of the superior vena cava and then sampling the velocity time integral of the aortic valve flow during inspiration. To date, this technique is finding limited, but increasing, use in ICUs in the United States, in part due to lack of training and experience with this technique for many ICU physicians.

23.5.1.3 CO_2 Partial Rebreathing Technique

The CO_2 partial rebreathing technique can be used via a modified Fick technique in mechanically ventilated patients. The NiCO device (Respironics, Murrysville, PA, USA) allows measurement of cardiac output using this method. The technique involves measurement of end-tidal CO_2 obtained before and during rebreathing periods. The ratio of the change in end-tidal CO_2 allows a noninvasive estimate of cardiac output [27]. To achieve optimal results with the NiCO monitor, the patient should be maintained under fully controlled mechanical ventilation. This technique is limited by the fact that the calculation includes blood flow perfusing ventilated portions of the lung and bypassing any blood flow bypassing ventilated alveoli. Therefore, these results can be a significant underestimation of cardiac output, corrected by making an estimate of shunt fraction (the amount of blood flow bypassing ventilated alveoli). Compared with conventional cardiac output methods, the partial CO_2 rebreathing technique is noninvasive, can easily be automated, and can provide real-time and continuous cardiac output monitoring [28, 29].

23.5.2 Perfusion Monitors

There are a number of recently developed noninvasive measures of regional tissue perfusion including near-infrared spectroscopic measurement of StO_2, sublingual and other capnometry methods, and the use of the $ScvO_2$ catheter.

23.5.2.1 Reflectance Near-Infrared Spectroscopy

Tissue hemoglobin saturation (StO_2) is derived from near-infrared spectroscopy and is a potentially useful, noninvasive adjunct for monitoring critically ill patients. StO_2 reflects changes in microcirculatory tissue perfusion. Unlike pulse oximetry signal (SpO_2), which measures oxygen contents in large, pulsatile vessels, StO_2 measures the oxygen content in vessels less than 1 mm in diameter (i.e., arterioles, capillaries, and venules) and describes the oxygen content at the tissue level; thus, it alerts the clinician that peripheral blood flow is being redistributed to vital organs, as the normal balance between the proportion of oxyhemoglobin and deoxyhemoglobin in the peripheral tissues undergoes adverse changes. There are several studies that have showed correlations between StO_2 and multiple organ failure, ICU admission, ICU outcome, and mortality [30, 31]. In patients with septic shock, StO_2 has been shown to correlate with higher mortality [32]. Additionally, one study conducted on 158 emergent cancer patients who presented to the emergency department with hypotension and/or systemic inflammatory response syndrome found that a SpO_2 less than 70 % significantly increased the risk of ICU admission [31]. Iyegha et al. [33] concluded, in a study of 620 ICU patients, that low StO_2 (<70 %) is common and associated with poor outcomes in SICU patients. However, no studies to date have utilized a randomized sampling or established a cause-and-effect relationship between a specific intervention that aimed toward normalization of StO_2 and specific patient outcomes.

23.5.2.2 Capnometry

In shock states, it is common to see redistribution of flow away from the gastrointestinal tract, resulting in increased gastrointestinal mucosal pCO_2. Many investigators have demonstrated this effect in both septic and hemorrhagic shock [34, 35]. Unfortunately, techniques to measure pCO_2 in the gastrointestinal tract have been limited by the efforts involved in appropriate placement of catheters within that area. This has led to the development of sublingual capnometry, capitalizing on the fact that the oral tissues are embryologically continuous with the gastrointestinal tract. This technique has the potential to allow rapid information regarding adequacy of tissue perfusion in critically ill patients; however, clinical studies utilizing this technology are lacking at this time.

23.5.2.3 Central Venous O_2 Saturation Monitors

The measurement of mixed venous oxygen saturation in either the pulmonary artery (SvO_2) or in the right atrium ($ScvO_2$) has been studied as a reflection of resuscitation of patients in a variety of settings [36–38]. It has also been used to guide the treatment of shock [39]. This technique has the potential advantage of yielding both an end point for resuscitative efforts and intravenous access. Since a decreased cardiac output and a resultant decrease in oxygen delivery to tissues will result in increased peripheral tissue extraction of oxygen from circulating blood, a low $ScvO_2$ in a critically ill patient has typically carried the implication that the patient is suffering from inadequate cardiac output. One potential shortcoming of this technique is the lack of sensitivity related to mixing of venous blood returning from organs with high and low metabolic needs, resulting in a falsely high reading. Despite these theoretic concerns, a recent study by Rivers and colleagues [36] used $ScvO_2$ as an end point of resuscitation in a group of septic patients presenting to an emergency department and demonstrated improved survival in patients who received interventions designed to improve $ScvO_2$ levels to greater than 70 % (defined as early goal-directed therapy). These findings have resulted in incorporation of early goal-directed therapy into protocols for treatment of patients with severe sepsis or septic shock.

23.5.3 Subcutaneous Continuous Glucose Monitoring

Hyperglycemia is common in acutely ill patients, especially within the ICU population [40]. Tight glucose control has been proposed to be crucial in these critically ill patients, especially for reduction in morbidity and mortality in the SICU populations. However, recent studies showed no evidence that intensive insulin therapy and tight glycemic control in ICU patients has led to decreased 28-day mortality; on the other hand, it can be associated with a high incidence of hypoglycemia and death [41, 42].

23.5.4 Conclusions

The need for monitoring of the critically ill patient has grown as the healthcare system has developed the ability to care for progressively more compromised and elderly patients. Monitors serve several purposes including: (1) the identification of shock and abnormal cardiac physiology, (2) the evaluation of cardiovascular function, and (3) to allow titration of therapy. An important function of an effective monitoring device is reliable detection of abnormal physiology. Despite much research on the use of monitoring techniques in critical care, there is little evidence of improved outcome related to routine use of monitors. To date, the mainstays of invasive monitoring in the ICU include CVP monitoring and arterial pressure monitoring, with pulmonary arterial monitoring reserved for occasional patients with multisystem disease. Recent trends in monitoring have included development of less invasive monitoring techniques that yield a number of cardiovascular parameters potentially useful to clinicians. New noninvasive measures of tissue perfusion (StO_2, sublingual capnometry) and semi-invasive techniques (TEE) have significant potential in identification and treatment of pathophysiologic states resulting in inadequate tissue perfusion. Tele-ICU is a new trend that has so far proven to reduced mortality and morbidity. Developers of new monitors (despite facing regulatory requirements that are considered less stringent than those of drug manufacturers) will increasingly be expected to demonstrate clinical efficacy of new devices. In the final analysis, the most important "monitor" is a caring healthcare provider at the patient bedside evaluating the patient's response to intervention and therapy.

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