Monitoring Devices in the Intensive Care Unit

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KEYWORDS
- Monitors
- Pulmonary artery catheter
- Central venous pressure
- Pulse oximetry
- Capnography
- Intracranial pressure

KEY POINTS
- Cardiovascular monitors help determine if patients’ tissues are getting enough blood supply.
- The pulmonary monitors monitor the pulmonary mechanics of the patients’ respiratory system.
- Neurologic monitors are used to maintain adequate blood flow to the brain.

MONITORING IN THE INTENSIVE CARE UNIT

Monitoring devices are the cornerstone of the modern intensive care unit. Without these revolutionary devices, clinicians would not have the requisite information to care for the critically ill especially if patient status changes acutely. Monitors in the intensive care unit (ICU) are key to delivering treatment in the ICU. Current devices emphasize assessing cardiovascular (CV), pulmonary, and neurologic function. This article deals mostly with CV monitoring.

CV MONITORS

There are many different types of CV monitors. They can be broadly categorized into 2 types: those intrinsic to heart function and those that monitor blood or, more importantly, oxygen delivery to tissues.

TELEMETRY

Telemetry monitoring is the most common type of CV monitor in the ICU. It monitors the intrinsic electrical function of the heart. Every patient in the ICU has a telemetry monitor attached to them. Telemetry is a 2-lead continuous electrocardiogram. The leads II and
V1 are commonly used because the QRS complex in these leads is usually the largest of all leads and they have prominent P waves. Telemetry allows any arrhythmia to be detected immediately. Any new arrhythmia diagnosed gives a clue to many physiologic derangements of the patient. Electrolyte abnormalities, fluid shifts, and cardiac ischemia are the most common reasons for acute cardiac arrhythmias.1

Sinus tachycardia is the most common abnormality seen on telemetry and is usually a sign of cardiac excitability from many sources, including pain, hypoxia, sepsis, increased inflammation, increased adrenal output from trauma or other sources, or beta blocker withdrawal. Tachycardia may or may not need to be treated. Bradycardia is usually caused by medications but has many other causes. Bradycardia can be the first sign of severe hypoxia. Atrial arrhythmias are also common. Atrial fibrillation can be seen in surgical patients as they start mobilizing resuscitative fluids between 48 to 72 hours after resuscitation.2 Atrial flutter is less common. Ventricular arrhythmias are worse. Early diagnosis and treatment are critical. Subtle changes in the telemetry strip, in conjunction with information received from other monitors, can give clues to bigger problems. T waves are the most labile individual wave on a telemetry strip. As a result, when a T-wave abnormality occurs, the differential diagnosis is long. The most common T-wave abnormality is an inversion of the wave.3,4 As with any subtle telemetry change after assessing patients, the next step is a 12-lead electrocardiogram.

PULSE OXIMETER

The pulse oximeter is a useful tool in the ICU. It measures the percent saturation of oxygen on hemoglobin molecules in arterial blood. Without a pulse oximeter, a blood gas would be needed every time a physician wanted to know how well patients were being oxygenated. The development of the pulse oximeter took approximately 50 years. Starting in the 1930s, theory and crude instruments were developed, with the first commercially available device being used in hospitals starting in 1981.5 The machine displays the percent saturation of hemoglobin molecules in arterial blood with oxygen. It does this by taking advantage of the fact that the hemoglobin molecule that has oxygen attached to it absorbs and reflects a different wavelength of light than a hemoglobin molecule without an oxygen molecule attached to it. The percentage of oxygen is calculated only from the reflected light that has a pulsatile nature, which corresponds to the pulsatile blood in the artery. Carbon monoxide will falsely elevate the pulse oximeter reading because it reflects the same wavelength of light that oxyhemoglobin reflects. For a pulse oximeter to work well, the probe must be attached to skin that is well perfused.

The ICU monitor will display the pulse oximeter information as a number but also as a waveform. The wave is a display of the pulsing blood that the sensor is reading. It looks like a blood pressure tracing on the monitor. The characteristic of this waveform corresponds to how accurate the reading is. A dampened waveform indicates poor tissue perfusion and cannot be accepted as an accurate reading.

The transducer probe that emits and measures the pulse can be placed almost anywhere on the body, but the areas with thinner skin are better. The most common places are the fingers, toes, ears, nose, and forehead. Unfortunately, the perfusion of too many of these body locations is compromised in low-flow states or when vaso-pressors are being used.

A normal pulse oximeter reading for someone without lung disease on room air should be between 94% and 100%. Patients with chronic lung problems can have a pulse oximetry reading of greater than 86%, but it is usually less than 92% on room air. Most pulse oximeters are accurate down to a reading of 70%. When pulse
oximeters are providing consistent readings in the 70% range, it is recommended that an arterial blood gas be obtained to check the validity of the pulse oximeter. 6

**Tissue Hemoglobin Oxygen Saturation**

The tissue hemoglobin oxygen saturation (StO2) monitor is a device that allows us to determine how much hemoglobin is saturated with oxygen in tissues deeper than the skin by using near-infrared spectroscopy technology. Usually it is set up to determine the StO2 in skeletal muscle but the monitor can be set up to determine StO2 in organs that are close to the body’s surface, like a child’s kidney. The StO2 can be followed to determine if fluid resuscitation is successful by increasing oxygen delivery to tissue. Increasing StO2 correlates with improved outcome, and an acute decrease in StO2 can be a harbinger of poor outcome; but having an StO2 monitor set up does not seem to change outcomes any better than following base deficit, lactate levels, or oxygen delivery calculations. 7

**Arterial Lines**

Arterial lines give us access to arterial blood for sampling, measures blood pressure, and can help us determine if someone requires volume resuscitation or not. For patients who have CV instability requiring continuous blood pressure monitoring, an arterial line is indispensable. Continuous blood pressure measurement with an arterial line determines how effective our treatments are without continually recycling the blood pressure cuff, which can cause damage to the muscle and skin in patients. 8,9 Blood draws are frequently obtained from the arterial lines when in place. An arterial line does increase the number of blood draws and the volume of blood that is drawn when compared with patients without arterial lines. This increase in blood loss occurs without any measurable outcome benefit. 10

Correct calibration of an arterial line is key to successful readings. The first step is to zero the pressure in the transducer. This action is done with the transducer at the level of the heart. Once the arterial line tubing is attached to the transducer, a waveform should be displayed on the monitor. The appearance of the waveform will help the physician interpret the recorded pressure. An inaccurate waveform can be described as overdamped or underdamped. Overdamping will appear as a narrowed and flattened tracing. This appearance implies that the pressure is being dulled or artificially lowered and the most common cause is air in the system. Most of the time, this is an air bubble next to the transducer. The air needs to be bled out of the system and the system recalibrated to obtain an accurate tracing and blood pressure reading. An underdamped arterial line tracing will appear as very sharp changes (sawtooth appearance). If this tracing appears, a kink in the tubing or obstruction in the system will be giving this elevated abnormal reading. Flushing the tubing or removing the kink will improve this waveform.

To test if an arterial line is overdamped or underdamped, one should flush the arterial line rapidly with pressurized saline and then abruptly stop flushing the line while watching the monitor. An underdamped waveform will display greater than 4 narrow waves before returning to a more natural-appearing wave. An overdamped waveform will go right back to a more natural-appearing wave after this rapid flush without any narrow waves. If 2 narrow waves appear after this rapid flush followed by the normal blood pressure tracing, it is perfect. Figs. 1–3 show what the tracings should look like for these various scenarios.

Using the arterial line tracing to determine if patients will be fluid responsive is a nice technique. Patients’ blood pressure changes depending on what part of the respiratory cycle they are in. It has to do with the fact that intrathoracic pressure changes
with inspiration and expiration. This change in pressure will change the patients’ pre-
load, change the amount of blood in the pulmonary vasculature, and change the size
of the ventricles in diastole, which in turn will change the patients’ blood pressure
slightly. This variability can be seen in the arterial line tracing (Figs. 4 and 5). The ability
to see this in the tracing helps determine if someone may be fluid responsive. The
more variability in patients’ blood pressure during a respiratory cycle, the more the
blood pressure should increase for a given fluid bolus. When there is no variability,
patients will probably not be very fluid responsive.\(^{11}\)

One of the newer benefits of arterial lines is the ability to infer the cardiac index with
a device called the FloTrac (Edwards Lifesciences Corp, Irvine, CA, USA). The FloTrac
sensor is attached to the arterial line and connected to its corresponding monitor. It
takes 2000 blood pressure measurements every 20 seconds. This information, along
with patient demographic information, is used to calculate the stroke volume index
and cardiac index. This device correlates well with pulmonary artery (PA) catheter
measurements for stroke volume index and cardiac index when patients have normal
hemodynamics. Unfortunately, this correlation degrades as patients’ hemodynamics
become more abnormal.\(^ {12}\)

Complications from arterial lines tend to be low. There is always a possibility of
infection similar to any invasive vascular line. The risk of infection is one infection for
every 1000 line days, which breaks down to about 1% of lines developing an infec-
tion.\(^ {13}\) The more common complication is arterial insufficiency, which can occur in
25% of radial artery catheters. Arterial insufficiency is a complete spectrum from
emboli to partial or complete arterial occlusion. The bleeding risk from an arterial
line site is approximately 3%.\(^ {14}\)
Central Venous Pressure

Central venous lines have a long history of use in the ICU. They are used for good intravenous access, total parenteral nutrition, and central venous pressure (CVP) monitoring. CVP measurement is used to help determine patients’ fluid status. In a person with normal hemodynamics, a higher CVP indicates a higher preload and, therefore, a higher intravascular volume, with the contrary also being true. Low CVPs usually indicate that someone is volume depleted and their blood pressure will increase with fluid boluses. Placing a central venous line and monitoring CVP is the easiest method to obtain a snapshot of patients’ volume status. Current surviving sepsis guidelines recommend getting the CVP of patients with sepsis between 8 and 12 mm Hg by fluid resuscitation. However, CVP monitoring is not always as reliable as we wish it to be. Many comorbidities make CVP monitoring unreliable. Many disease processes elevate CVP, yet patients may still need volume expansion. These disease processes include pulmonary embolism, pulmonary hypertension, right heart failure, and right heart valve disease. Ascites and abdominal hypertension are 2 other conditions that can falsely elevate CVP measurements. Most problems with CVP interpretation occur when the CVP is elevated and when the CVP is low, and it almost always means that patients’ are volume depleted and more fluid is needed. Another way to interpret CVP values is to remember that the trend over time is the most valuable aspect of CVP monitoring.

If the CVP changes during the respiratory cycle or with a fluid challenges it usually indicates that patients are intravascularly depleted. Intrapleural pressures should be equal to atmospheric pressure at end expiration whether patients are on positive pressure ventilation or breathing room air. This observation suggests that the CVP should
be measured at end expiration. In a spontaneously breathing patient CVP is higher at end expiration where in a ventilated patient CVP is lowest at end expiration (see Fig. 5).

As with any invasive device, there are complications associated with the central line used to measure CVP. Complications are commonly divided into those occurring during placement and those secondary to the catheter being maintained. Pneumothorax or arterial injuries are the 2 most common types of complications when placing a central line. The risk of any complication on insertion is between 6% and 12%.18 The most common complication is arterial puncture, which can be reduced for jugular insertion with ultrasound.19,20 Pneumothorax is more common with subclavian access and is reported to occur 1% to 3% of the time. Femoral central line placement is not recommended for CVP monitoring and has the highest complication rate of any access site.21,22 A chest radiograph is needed after placement to make sure the central line is at the superior vena cava–right atria junction before accurate measurements can be made.

Maintaining the catheter is also associated with complications. Ventricular perforation is an uncommon complication associated with a catheter that is placed too deep so that the tip resides at the atrial ventricular junction or actually into the ventricle. Arm movement can make this catheter move and puncture the ventricle. The major complication during catheter maintenance is blood stream infection. The risk of a blood stream infection from a central line in the jugular or subclavian position is 2 per 1000 patient-days. This risk goes up with increasing length of time the catheter is in place.23,24 The best prevention for catheter-related blood stream infection is to remove the catheter as soon as it is no longer needed.

**PA Catheter**

The PA catheter is one of the most invasive monitors in the ICU and can be difficult to place. It should be used only when absolutely necessary. A PA catheter is used when patients are in severe shock; do not respond to normal interventions; and need more intense therapies, including multiple vasoactive drug drips and intense fluid management. With the introducer catheter ideally placed in the right jugular vein or left...
subclavian vein, the catheter is floated through the right side of the heart and placed into the PA and then wedged into a terminal branch of the PA.

Placing the PA catheter is a bedside procedure that requires an understanding of the pressure waveforms as the catheter is passed from the superior vena cava to the pulmonary artery (Figs. 6–9). The catheter is floated with the aid of a balloon at its tip, which allows the catheter to be guided by the blood flow and helps avoid irritating the heart as the catheter is passed through the right ventricle into the PA. The waveforms are followed, and advancement is stopped when the wedge pressure is visualized. The balloon is deflated and the pressure tracing should revert to the PA pressure waveform. If the wedge pressure persists, the catheter should be withdrawn slightly and the balloon inflated again to achieve a wedge pressure. Deflating the balloon should give the PA pressures at this time.

When properly placed and verified by chest radiograph, the PA catheter will give you a massive amount of information about patients’ CV function. The main parameter is the cardiac output. The cardiac output is determined by a thermodilution technique and is normalized to patients’ body surface area giving the cardiac index. Most manipulations we use are used to optimize the cardiac output or index. Our goal with fluids and vasoactive drugs is to improve cardiac output, which should improve tissue perfusion and organ function.

Other parameters obtained via the PA catheter include the CVP, the PA pressures, and the wedge pressure. The catheter can also be used to obtain a mixed venous gas, or some PA catheters can actually measure mixed venous oxygen saturation (SvO₂) continuously. Other calculated parameters include stroke volume and systemic vascular resistance. The wedge pressure is used to assess left atrial filling pressure and, by inference, the left-sided filling volume. This relationship is usually correlated, and low values indicate the need for fluid administration. High values commonly indicate cardiac dysfunction, which suggests that the treatment should be aimed at improving myocardial function and not administering more fluid. Mixed venous oxygen content is used with peripheral arterial oxygen content to determine how much oxygen the body is consuming. Stroke volume, which is calculated, is used by some to determine how efficient each beat of the heart is. Systemic vascular resistance is calculated by using Ohm’s law ([mean arterial pressure – central venous pressure]/cardiac output). It can be used to communicate how well a vasoactive drug is working.

Because the catheter tip of the PA catheter sits in the PA, it is an ideal instrument to obtain SvO₂ readings. This reading can either be done by taking a blood sample from the tip or by using a PA catheter that is equipped to directly measure the oxygen saturation at the tip fiber optically. An SvO₂ reading is very useful in determining how well

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**Fig. 6. CVP pressure waveform.**
the body tissues are receiving and using oxygen. The normal SvO₂ is between 65% and 75%.²⁵,²⁶ A decrease in this number usually means that not enough oxygen is being delivered to tissue or more oxygen than normal is being taken out of the blood.

The extraction ratio is a relatively quick calculation that helps determine if patients are getting and using an adequate amount of oxygen. The extraction ratio is calculated using the SvO₂ and the arterial oxygen saturation. The following set of equations show how the extraction ratio equation is derived.

The oxygen delivery equation is as follows:

\[
(\text{DO}_2) \text{ (mL/min)} = (\text{CO}) \times \text{blood oxygen content}
\]

\[
\text{DO}_2 = \text{CO} \times \left( 13.4 \times \text{Hgb} \times \frac{\text{SaO}_2}{100} + 0.031 \times \text{P}_a\text{O}_2 \right)
\]

where \(\text{CO}\) is cardiac output, \(\text{DO}_2\) is oxygen delivery, \(\text{Hgb}\) is the patients’ hemoglobin, \(\text{SaO}_2\) is arterial oxygen saturation in percent, and 13.4 and 0.031 are conversion factors for oxygen carried by hemoglobin and plasma A normal cardiac output is 5 L/min, hemoglobin is 15, arterial oxygen saturation is 97%, and \(\text{P}_a\text{O}_2\) is 100. This calculation gives a normal oxygen delivery of 1000 mL/min. The body only uses or consumes about 250 mL/min.

The oxygen consumption equation is as follows:

\[
\text{VO}_2 = \text{CO} \times (\text{CaO}_2 - \text{CvO}_2)
\]

where \(\text{CO}\) is cardiac output, \(\text{CaO}_2\) is arterial oxygen content, \(\text{CvO}_2\) is mixed venous oxygen content, and \(\text{VO}_2\) is oxygen consumption.
\[ \text{VO}_2 = \text{CO} \times (13.4 \times \text{Hgb} \times \text{S}_a\text{O}_2 - 13.4 \times \text{Hgb} \times \text{S}_v\text{O}_2) \]

where \( \text{CO} \) is cardiac output, \( \text{Hgb} \) is the patients’ hemoglobin, \( \text{S}_a\text{O}_2 \) is arterial oxygen saturation in percent, \( \text{S}_v\text{O}_2 \) is mixed venous oxygen saturation, and \( \text{VO}_2 \) is oxygen consumption

or

\[ \text{VO}_2 = \text{CO} \times 13.4 \times \text{Hgb} \times (\text{S}_a\text{O}_2 - \text{S}_v\text{O}_2) \]

where \( \text{CO} \) is cardiac output, \( \text{Hgb} \) is the patients’ hemoglobin, \( \text{S}_a\text{O}_2 \), is arterial oxygen saturation in percent, \( \text{S}_v\text{O}_2 \) is mixed venous oxygen saturation, and \( \text{VO}_2 \) is oxygen consumption

The \( \text{S}_v\text{O}_2 \) is normally about 75%.

By combining oxygen delivery and consumption, an oxygen extraction ratio can be calculated. The equation is as follows:

\[ \text{OER} = \frac{\text{VO}_2}{\text{DO}_2} \]

where \( \text{DO}_2 \) is oxygen delivery, \( \text{OER} \) is oxygen extraction ratio, and \( \text{VO}_2 \) is oxygen consumption

Plugging in the aforementioned equations for oxygen consumption and oxygen delivery are canceling terms, the following simplified equation based solely on mixed venous saturation and arterial oxygen saturation is reached:

\[ \text{OER} = \frac{(\text{S}_a\text{O}_2 - \text{S}_v\text{O}_2)}{\text{S}_a\text{O}_2} \]

where \( \text{OER} \) is oxygen extraction ratio, \( \text{S}_a\text{O}_2 \), is arterial oxygen saturation in percent, and \( \text{S}_v\text{O}_2 \) is mixed venous oxygen saturation

An extraction ratio of 25% to 30% is normal. Anything less may indicate a need for intervention. Treatment is either to increase delivery by increasing cardiac output, increasing oxygen in blood, or increasing hemoglobin or to decrease consumption by decreasing the work of breathing, sedation, decreasing heart rate, eliminating fever, or even paralyzing patients.

The PA catheter is a very useful tool in the treatment of critically ill patients if used properly and on carefully selected patients. It carries the same general complications that a central venous line has, including mechanical complications during placement and catheter-related blood stream infection during maintenance. It has other complications because it passes through the heart. It causes multiple types of arrhythmias as a result of irritating the conducting system of the heart. The most alarming is asystole, which happens if patients already have baseline left heart block and the PA catheter
causes right heart block. Pulling the catheter back will usually resolve this situation. Another potentially devastating complication is rupture of the PA. This complication happens if the catheter tip is too far in a distal branch of the PA and the balloon ruptures the small vessel it is in. A free rupture of a PA requires quick attention from a surgeon adept in thoracic surgery because this is a potentially fatal problem.

**Pulmonary Monitors**

Monitoring respiratory status in the ICU is just as important as monitoring the CV system. Most of the patients in the ICU will not have an endotracheal tube in place, at least at some point. In these patients, pulse oximetry and respiratory rate are the only continuous monitors that really need to be observed.

Transthoracic impedance measuring is the technique that is used most commonly to continuously measure respiratory rate in ICU patients. This measuring is done with the telemetry leads. A small current is passed from one of the left-sided leads to one of the right-sided leads and the voltage is measured. This voltage will change with each breath as a result of the change in electrical resistance of the chest with each breath. The resulting rate of voltage cycles then corresponds to the patients’ respiratory rate.

**Capnography**

The ventilator has many monitors to help care for intubated patients. Continuous capnography measures the amount of carbon dioxide that is exhaled with each breath. It is displayed as a waveform and looks like a square wave (Fig. 10). The plateau of the wave measures the amount of carbon dioxide made, and the shape of the wave corresponds more to the flow of air through the lungs. The more the wave looks like a square, the less restrictive the airway; the more the wave looks like a shark fin, the more obstructed the airway is, as in asthma (Fig. 11). Changes in the amount of exhaled carbon dioxide can be one of the first signs of a change in physiologic status in critically ill patients. A decrease in exhaled carbon dioxide could indicate decreased production or increased minute ventilation. An increase in the difference between the expired carbon dioxide and the partial pressure of carbon dioxide measured in an arterial blood gas indicates an increase in dead space ventilation (Figs. 10–12). Continuous capnography is not commonly used in ventilated patients but is used to confirm the placement of an endotracheal tube using a simple carbon dioxide monitor attached to the endotracheal tube after intubation.

**GASTRIC TONOMETRY**

Gastric tonometry is used to measure the mucosal carbon dioxide levels of the mucosa in the stomach. As blood flow to the stomach decreases, the carbon dioxide

![Fig. 10. Normal capnography.](image-url)
levels of the tissues will increase. The theory is that by measuring this increase in carbon dioxide and reacting to its change, interventions can be done to improve the patient outcome.

The probe of the device is similar to a nasogastric tube and it is inserted in the same way. It measures mucosal carbon dioxide by allowing it to diffuse through a semipermeable membrane into a balloon that is on the distal part of the nasogastric tube. The machine then continuously measures the partial pressure of carbon dioxide in the balloon. If the partial pressure of carbon dioxide has increased by more than 8 mm Hg compared with an arterial blood gas, there is some form of mucosal ischemia.30

There are only a small number of studies that investigate this device. Of these studies, there are a few that are observational and show that patients who have a worse outcome do have an increase in gastric carbon dioxide concentrations.30,31 There are few randomized trials using gastric tonometry. One trial showed that if gastric carbon dioxide was normal on admission to the ICU, patients that had care with gastric tonometry had better outcomes than those without. However, the same study showed no difference in the groups if gastric carbon dioxide was high on admission to the ICU.32 No other randomized trials showed any difference, but there are trends toward gastric tonometry being another helpful tool in your ICU monitoring arsenal especially in extremely sick patients.33–35

ABDOMINAL COMPARTMENT PRESSURE MONITORING

Abdominal compartment hypertension and subsequent compartment syndrome are ominous entities and are a result of a few pathologic processes. While the intrabdominal contents remain consistent, the volume of fluid in the abdomen can increase. An increase in fluid within the abdominal compartment occurs secondarily

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**Fig. 11.** Restrictive capnography (shark-fin wave).

**Fig. 12.** Capnography with increased dead space.
to several situations, including bleeding into the abdomen from trauma or a ruptured aneurysm, third space fluid shift from organ edema, or ascites. Normal intra-abdominal pressure (IAP) remains relatively constant, around 10 mm Hg. As fluid accumulates, the abdominal wall initially expands, but when it cannot stretch anymore the pressure starts to increase. Intra-abdominal hypertension (IAH) is defined as IAP greater than 12 mm Hg. IAH has 4 grades (Table 1).

The first sign of IAH is abdominal distention. The physiologic consequences of IAH are decreased urine output and increased peak airway pressures in ventilated patients. As IAH occurs abdominal organ ischemia increases.

The way to monitor IAP is by measuring urinary bladder pressures via a Foley catheter. The IAP is measured directly through the Foley catheter. The catheter is attached to a standard pressure transducer; 50 mL of saline are injected through the catheter into the bladder, and then the catheter is clamped so that the transducer will measure the pressure in the bladder. This procedure is done every hour for patients whose pressure is greater than 15 mm Hg. Medical management is recommended until IAP reaches 25 mm Hg. It is currently recommended that once the IAP is greater than 25 mm Hg, the abdomen needs decompression.

### Intracranial Pressure Monitoring

Cerebral blood flow depends on both blood pressure and intracranial pressure (ICP). For blood to circulate through the brain the pressure in the skull has to be less than mean arterial pressure. Cerebral perfusion pressure (CPP) is calculated as mean arterial pressure minus ICP. If ICP increases to approximate mean arterial pressure, blood will not flow into the brain and brain death will begin. There are many conditions that will cause an increase in ICP. Traumatic brain injury is the most common reason in the surgical ICU, but other causes include hydrocephalus, meningitis, brain tumor, stroke, or reperfusion of the brain after anoxia. If an increase in ICP is suspected by disease process, physiologic signs, or imaging and patients have altered mental status, an ICP monitor might be warranted. These monitors are placed at the bedside by drilling a hole through the skull. A bolt is placed snugly through the hole and a transducer is then placed through the bolt into the subdural space to directly transduce ICP.

ICP in supine patients should be less than 20 mm Hg. Once ICP pressures start to exceed 20 mm Hg, complication rates start to increase. Maintaining a lower ICP is more important in patients with unilateral mass effect from tumors or trauma because these patients are more likely to herniate their brain compared with those patients with global brain edema. CPP is what is really important, so as ICP increases one can attempt to increase mean arterial pressure to maintain CPP.

An external ventricular drain is a type ICP monitor where a catheter is placed through the previously mentioned bolt into one of the lateral ventricles of the brain.

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<tr>
<th>Grades of intra-abdominal hypertension</th>
<th>Grade of Intra-abdominal Hypertension</th>
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<tr>
<td>Intra-abdominal Pressure (mm Hg)</td>
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<tr>
<td>12–15</td>
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<td>16–20</td>
<td>II</td>
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<td>21–25</td>
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In this position, it can measure ICP but can also be used to drain cerebral spinal fluid (CSF). By draining CSF, one can directly reduce ICP. This reduction can be of great importance, especially if that ventricle cannot drain naturally as a result of blood or some other obstruction.

**TRANSCRANIAL DOPPLER ULTRASONOGRAPHY**

Transcranial Doppler monitoring is a noninvasive monitoring technique used to measure the velocity of blood flow through the major blood vessels off of the circle of Willis. The transducer is placed on the side of the head and can determine the velocity, direction, and the depth of the artery that it is transducing. It is mainly used to monitor vasospasm, stenosis flow, flow in a subarachnoid hemorrhage, or to determine flow in possible brain death. A major drawback to transcranial Doppler monitoring is the requirement of a skilled technician to perform the examination and a skilled person to interpret the results.

The transducer uses a 2 MHz wave. This frequency is relatively low for ultrasound, but this is required to penetrate the bone and have a signal that can be received from 3 major arteries in the brain. The normal velocities from the middle cerebral artery, anterior cerebral artery, and posterior cerebral artery are 62, 51, and 44 cm/s, respectively. Once the velocities start to increase more than 120 cm/s, mild vasospasm is considered, and severe vasospasm is considered after 200 cm/s. However, these velocities are arbitrary, and clinical assessment is key to determining if the results indicate ischemia. Some investigators advocate using flow acceleration and the pulsatility index as more accurate measurements.

Transcranial Doppler examination can also be used to confirm brain death. The caveat is that a prior transcranial Doppler study is required because 8% of patients do not have an acoustic window where flow can be obtained.

**Jugular Venous Bulb Oximetry**

Jugular venous bulb oximetry is a technique to measure the mixed venous oxygen content in the blood leaving the brain. It is used to help determine if there is enough oxygen being delivered to the brain or if too much oxygen is being used. A catheter is placed in the jugular vein and directed cephalad to the jugular venous bulb. The catheter should be placed on the side with the dominant venous drainage. This side is usually the right side and can be determined if an intracranial bolt is present by occluding each side with manual pressure. The jugular occlusion should increase the ICP, and the side with the greatest pressure increase is the dominant side. Mixed venous blood gases can be acquired via the catheter, or continuous jugular bulb oximetry can be used. Common practice is to treat a mixed venous jugular saturation of less than 50% either by decreasing oxygen demand or by increasing oxygen delivery to the brain.

**Continuous Transesophageal Echocardiography**

Transesophageal echocardiography is a very useful tool to determine the functionality of the heart. It is commonly used in the operating room during cardiac surgery. It can be used to determine the cardiac parameters and fluid status of patients in the ICU, similar to the information obtained from a PA catheter; however, this was historically seen as a single-point-in-time invasive test. Continuous transesophageal echocardiography has recently become available. The disposable probe is small and is placed in the esophagus and will continuously monitor cardiac function for up to 72 hours, at which time the probe is removed. This new technology may or
may not change how we monitor patients in the ICU, but it does illustrate that there are many different ways to monitor patients in the ICU and there are probably many more to come.

REFERENCES