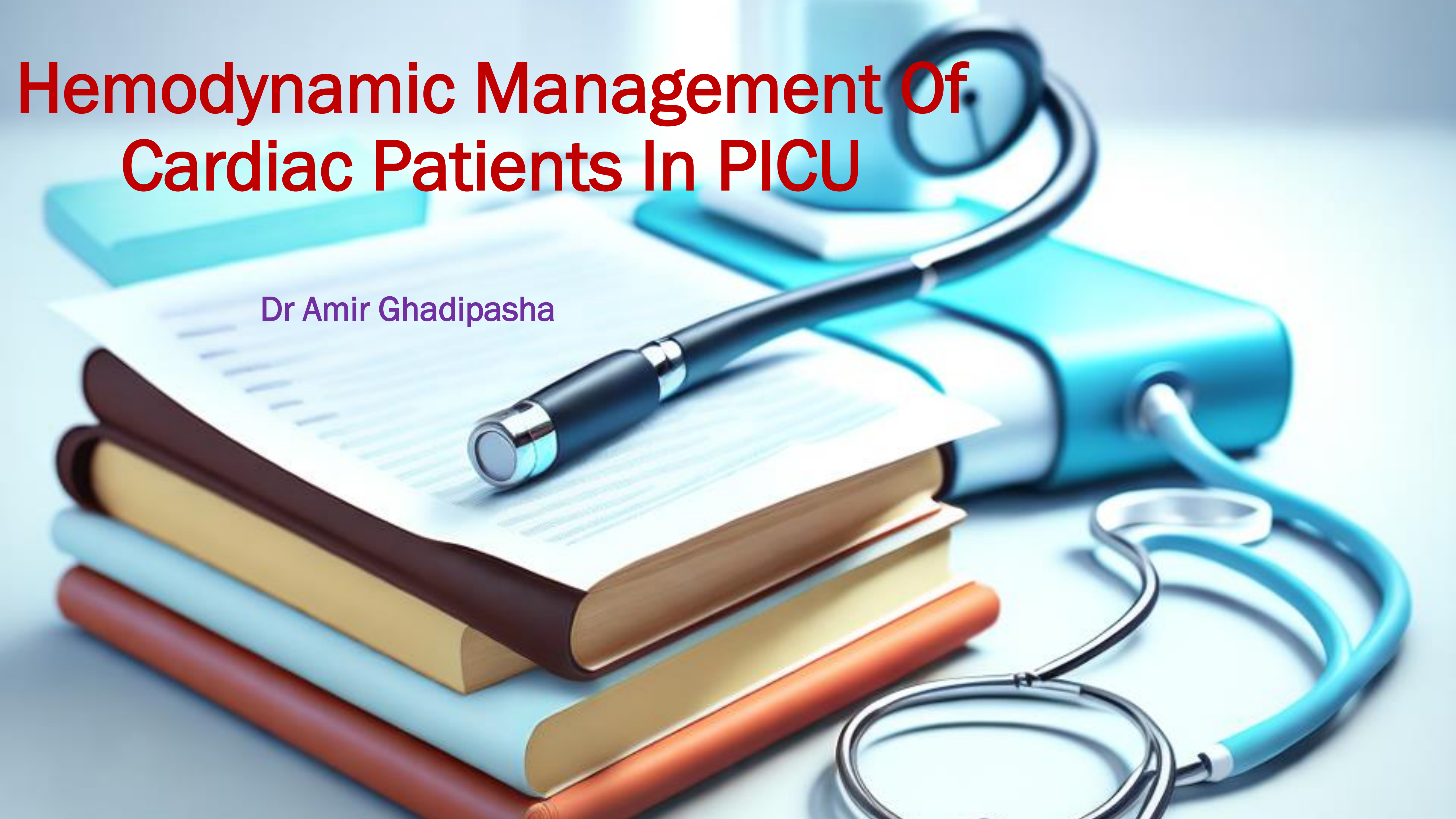

Hemodynamic Management Of Cardiac Patients In PICU

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introduction

- The fundamentals of hemodynamic monitoring have changed very little over the past years.
- The main goal of hemodynamic monitoring in the critically ill patient remains the correct assessment of the cardiovascular system and its response to tissue oxygen demands

Goals of monitoring

- To assure the adequacy of perfusion.
- Early detection of an inadequacy of perfusion - decision making: is monitoring sufficient, or does the patient need active intervention?
- To titrate therapy to specific hemodynamic endpoints in unstable patients.
- To differentiate among various organ system dysfunction's

Hemodynamic monitoring

- Hemodynamic monitoring combined with oxygen transport assessment has been used to differentiate the relative magnitude of pulmonary and cardiovascular dysfunction that contribute to hypoxemia,
  - which is of critical importance because therapy directed to correct pulmonary dysfunction (raising the airway pressure) may have adverse effects on venous return and cardiac output.

Hemodynamic monitoring (cont.)

- All patients admitted to the ICU require standard basic hemodynamic monitoring (ECG, heart rate, blood pressure, central venous pressure, temperature, peripheral venous oxygen saturation, blood gas analysis).
- All critically ill patients need monitoring of intravascular volume status, and intake and output must regularly be observed.
- Urinary output should be measured quantitatively on a regular basis as well.
- For surgical patients monitoring includes observation of wounds for bleeding or suture disruption, and any drainage systems should be observed for fluid loss as well as for any sign of new or continuing bleeding.
- Beyond that the specific clinical situation of the individual patient will dictate further requirements

Monitoring techniques

- Hemodynamic monitoring using invasive techniques is the mainstay of today's practice of critical care and allows precise frequent determinations of cardiorespiratory variables. However, noninvasive measures should not be forgotten!

ECG monitoring

- Continuous ECG monitoring allows the registration of beating frequency, cardiac rhythm and ischemic episodes (depression of ST-segment).
- One must, however, be aware that ischemia detection is incomplete when monitoring only either the anterior (lead V_4) or the posterior/inferior region (lead II) of the left ventricle.
- Furthermore, ECG does tell us nothing about electromechanical coupling of the heart.

Central venous pressure

- The central venous pressure (CVP) reflects the pressure in the central veins - usually measured in the thoracic cavity - when they enter the right atrium. CVP fluctuates with respiration, so the time of measurement can be important. Normally CVP should be measured in the endexspiratory state. CVP (right atrial pressure) indicates pressure and not volume.
- *Indications* for CVP measurements include:
- Diagnostic measurements.
- Monitoring and guiding fluid management.
- Monitoring and guiding pharmacological interventions.

- The relationship between the right heart side pressure and the intravascular volume is unpredictable and is affected by many factors (e.g. the tone of the systemic circulation).

Central venous pressure (cont.)

- The problems in *interpreting CVP* as an volume indicator can be summarized as following:
  - *Shocked patients*: low intravascular volume with compensatory vasoconstriction: CVP low.
  - *Rapid resuscitation*: fluid poured into a constricted patient will increase blood pressure and push CVP up rapidly, but the vasculature may still be constricted.
  - *Redistribution*: normally the patient's vasculature will dilate a little and the fluid will redistribute slowly. CVP falls to zero but the patient remains constricted.
  - *Anesthesia*: the constricted patient is given general anesthesia.
- Acute vasodilation occurs and the fluid redistributes instantly, exposing a large volume deficit. Blood pressure and CVP plummet.

❑ Kidney function

- Diuresis depends strongly on heart function. Oliguria due to prerenal failure is an early indicator of pump failure of the heart.

❑ Pulse oximetry

- Pulse oximetry monitors oxygenation. Simultaneously, beating frequency is recorded, as well as - in combination with the ECG - an eventual pulse deficit. A strong variation in the amplitude may indicate volume deficiency.

Arterial pressure monitoring

- Peripheral arterial lines (A. radialis) offer several advantages in comparison of monitoring blood pressure with a cuff. The line provides continuous measurement of blood pressure and can be used for sampling of blood gases. A strong variation in the amplitude may indicate volume deficiency.
- In the setting of marked vasoconstriction or hypotension, the arterial line gives more accurate pressure values than a blood pressure cuff; however, in case of strong centralization of circulation, blood pressure measurements done with peripheral arterial lines may considerably differ from the core hemodynamics.
- *Indications* include

• Rapidly changing clinical circumstances in critically ill patients (e.g. hemorrhage, sepsis).

• Monitoring and guiding the use of vasoactive drugs with rapid cardiovascular effects.

• Monitoring and guiding acute interventions (e.g. major surgery, resuscitation).

• Blood sampling.

Pulmonary artery catheter

- The pulmonary artery catheter offers several advantages over central venous pressure monitoring.
- When the balloon tip of a Swan Ganz catheter is properly wedged in a branch of the pulmonary artery, the pressure sensed by the catheter tip represents that in the left atrium, taking aside a specific problem of pulmonary capillary wedge pressure monitoring in the septic patient. Left atrial pressure, which equals left ventricular filling pressure in the absence of mitral stenosis, is an excellent indicator of the adequacy of fluid resuscitation done.
- If the pressure is low (less than 12 mmHg), additional fluid resuscitation is indicated. If the pressure is high (greater than 20 mmHg), additional fluid is unlikely to improve cardiac performance further, and vasopressors are probably indicated for circulatory support.
- Although the catheter can yield a vast amount of information, the distinction between the need of fluids or vasopressors is its most useful application.

Profiles of hemodynamic emergencies in the critically ill patient

Condition	HR	MAP	CO	CVP/RAP	PAP/PAWP	Notes
LV Failure	↑	↓	↓	↑	↑	
Cardiogenic pulmonary edema	↑	normal or ↓	↓	↑	↑ PAWP > 25 mmHg	
Pulmonary embolism	↑	↓ or varies ^	↓	↑	↑PAD > PAWP by > 5 mmHg	↑ PVR
Cardiac tamponade	↑	↓	↓	↑	↑CVP, PAD and PAW equalized	↓ RVEDVI
RV Failure	↑ or varies	↓ or varies	↓	↑	PAP ↑, PAWP normal/↓/↓	↑ RVEDVI
Hypovolemic shock	↑	↓	↓	↓	↓	↑ SVR, ↑O_2 extraction
Cardiogenic shock	↑	↓	↓	↑	↑	↑ SVR, ↑O_2 extraction
Septic shock	↑	↓	↑,↓	↓,↑	↓,↑	SVR changes, ↓O_2 extraction, ↓SVR#

HR - heart rate, MAP - mean arterial pressure, CO - cardiac output, CVP - central venous pressure
RAP - right arterial pressure, PAP - pulmonary artery pressure
PAWP - pulmonary arterial wedge pressure, RVEDVI - right ventricular enddiastolic volume index.

Pulmonary artery catheter (cont.)

- PA catheters may be used for both diagnosis and therapy. Clinical indications include:
- Postmyocardial infarction: to assess hemodynamic status and monitor and guide therapy.
- Cardiac surgery: to monitor cardiac function.
- Major surgery: in the presence of myocardial dysfunction or for preoperative optimization of hemodynamics.
- Resuscitation: in case of hemodynamic instability during fluid replacement: to assess left ventricular function.
- Septic shock: assessment of LV function and fluid status.
- Diagnosis of high and low pressure pulmonary edema.
- Measurement of oxygen transport, enabling optimization of ventilation and perfusion.
- Pre-eclampsia and eclampsia: to monitor fluid status and assess intravascular volume.

Transesophageal Echocardiography (TEE)

- Echocardiography is making major inroads into the critical care units. In general, physical examination of critically ill cardiac patients is limited in its accuracy in predicting measured physiologic data.
- Available studies suggest that protocol-driven pulmonary artery catheter management will modify central venous pressure driven management some 40% of the time, with strong suggestions of improvement in outcome.
- Recent data suggest that in patients with pulmonary artery catheter-driven care, the use of TEE modifies management another 40% of the time.
- Diagnosis of many disease processes and pathophysiologic derangements are beyond the capabilities of routine invasive monitoring techniques and can only be made by bedside echocardiography.

Transesophageal Echocardiography (TEE) (cont.)

- Since its introduction in the early eighties, echocardiography has undergone a huge technological and clinical evolution.
- The indications of echocardiography as a diagnostic and monitoring tool in the peri-operative and critical care setting have increased exponentially because of its potential to accurately assess cardiovascular dynamics.
- TEE is able to assess global and regional left ventricular function and can reliable evaluate the different determinants of ventricular function such as preload, contractility and afterload.
- The short axis view of the left ventricle is a basic and readily available part of this imaging technique. Moreover, its adequate visualization of the great vessels leads to an appreciation of cardiovascular interaction and helps to differentiate between cardiac and vascular causes of hemodynamic disturbances.

Selected cardiovascular agents and their hemodynamic effects

Drug	HR	MAP	CO	PAWP	SVR	PVR
Dopamine	↑	↑	↑	↓	↑	0
Dobutamine	0 / ↑	↑	↑	↓	↓	↓
Epinephrine	↑	↑	↑	↑	↑	↑
Norepinephrine	0 / (↓,↑)	↑	↑		↑	0 / ↑
Amrinone	0 / ↑	0 / ↑	↑	↓	↓	↓
Milrinone	↓	↓	↑	↓	↓	↓
Esmolol	↓	↓	0 / ↓	0 / ↑	↓	↓
Sodium Nitroprusside	0	↓	↑	↓	↓	↓
Nitroglycerine	0	↓	0 / ↑	↓	↓	↓
Phentolamine	↑	↑	↑	↓	↑	0 / ↑
Atropine	↑	↑	↑	0	0	0
Digoxin	0 / ↓	0 / ↑	↑	0 / ↓	0	0
Verapamil	↓	↓	0	↓	↓	↓

HR - heart rate, MAP - mean arterial pressure, CO - cardiac output, CVP - central venous pressure
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Standard Hemodynamic Parameters
Pulse Rate

- The field of critical care medicine evolved from the treatment and resuscitation of wounded soldiers in Normandy and Korea in the 1940s and 50s.
- In the Mobile Army Surgical Hospital (MASH) units, physician caring for critically ill patients discovered the importance of monitoring vital signs. Perhaps the most basic and fundamental of vital signs is pulse rate.
- While a single solitary heart rate can offer a glimpse of the patient’s clinical state, monitoring trends and changes in heart rate are essential to the cardiac intensivist in their determination of the patient’s hemodynamic state and trajectory.
- Changes in heart rate can be indicative of but not specific for changes in ventricular preload, function and output, as well as be reflective of a change in metabolic demand.
- Because changes in heart rate are generally nonspecific they need to be considered within the clinical context.
- Heart rate trends may be useful for example in determining the optimal ventricular filling pressure, as discussed below.
- An assessment of cardiac rhythm is an essential part of the management of the critically ill patient where electrocardiographic monitoring is routinely used in the cardiac intensive care unit to survey for arrhythmias that may occur, particularly following cardiac surgery.

Systemic Arterial Blood Pressure

- Systemic arterial blood pressure monitoring is another mainstay of standard hemodynamic monitoring.
- Noninvasive blood pressure monitoring is usually obtained using oscillometric devices such as the Dinamap (Device for Indirect Measurement of Blood Pressure).
- Studies have shown that oscillometric devices such as Dinamap give comparable blood pressure readings when measured against indwelling arterial catheters
- Nonetheless, they are not without their limitations. Studies have found that noninvasive oscillometric devices are less reliable for diastolic blood pressure and are also less accurate at lower blood pressure and during clinical shock
- An additional limitation is the intermittent nature of non-invasive pressure monitoring.
- Indwelling arterial catheters are considered the standard of care for the management of hemodynamically unstable patients, providing a continuous display of the arterial waveform and additional information not available with the noninvasive modality

Systemic Arterial Blood Pressure (cont.)

- The upstroke of the arterial waveform provides information about cardiac function. If the rate of rise of the pressure wave is rapid, contractile function is good.
- A slow upstroke can be indicative of poor cardiac function but is also seen in aortic stenosis and with elevations in systemic vascular resistance.
- The area under the systolic portion of the waveform is proportional to the stroke volume. A low pulse pressure may reflect a low stroke volume.
- A widened pulse pressure is seen in states characterized by diminished vascular tone, in patients with an aorta to pulmonary arterial runoff and in patients with aortic insufficiency.
- Indwelling catheters also facilitate the titration of vasoactive medications, particularly afterload reducing agents; allow for an assessment of the response to volume expansion; and they permit frequent arterial blood gas sampling to assess the adequacy of gas exchange.
- An important limitation of blood pressure is that it is the product of cardiac output and systemic vascular resistance, thus it may not be an accurate indicator of cardiac output

Central Venous Pressure

- Central venous pressure monitoring allows for the continuous assessment of ventricular filling pressures and pressure waveforms and is commonly used in the cardiac intensive care unit.
- Because ventricular compliance is affected by a number of conditions including positive pressure ventilation and cardiac disease, a determination of the optimal ventricular filling pressure is indicated.
- If volume administration increases stroke volume then the ventricle is operating on the ascending portion of its pressure stroke volume curve and preload reserve is present. The presence of preload reserve is reflected in a prompt decrease in heart rate, increase in the systolic blood pressure or improvement in venous oximetry following volume administration

Central Venous Pressure (cont.)

- If there is no improvement in these parameters, preload reserve is exhausted and additional fluid will only increase pulmonary congestion without improving output.
- Its worth noting that the determination of the optimal ventricular filling pressure is an on-going exercise, as ventricular compliance may vary over time due to changes in respiration (see cardiopulmonary interactions) and ventricular function
- Further confounding the determination of the optimal ventricular filling pressure is the fact that there is no correlation between the central venous or right atrial pressure and left atrial pressure in patients with cardiac and or pulmonary disease
- Finally, it is worth noting that studies have shown that there is a very good correlation between femoral venous and central venous pressures so long as there is a continuous column of fluid between the two sites of measurement

End-tidal CO_2 Monitoring

- The concentration of CO_2 in expired gas is predicated on tissue CO_2 production, pulmonary blood flow and alveolar ventilation.
- In capnography, infrared devices measure the concentration of CO_2 in inhaled and exhaled gases over time.
- The normal baseline on the capnogram should have a CO_2 concentration of zero, reflecting inspiratory as well as early expiratory gas; this is followed by a sharp upstroke reflecting mid-exhalation and increasing alveolar gas; this is followed by the plateau phase, which represents a leveling off of alveolar gas; the capnogram then abruptly falls to zero, as the expiratory phase is terminated and inspiratory gas dilutes out the remaining CO_2.

End-tidal CO2 Monitoring (cont.)

- There is a minimal difference between measured arterial CO2 (PaCO2) and the end tidal CO2 level (PETCO2) in normal subjects due to minor abnormalities in the relationship between alveolar ventilation to perfusion.
- However, when pulmonary perfusion is limited lung units with large ventilation to perfusion ratios may be created, particularly in the setting of positive pressure ventilation. This leads to an inefficiency in CO2 removal or wasted ventilation and the creation of a large arterial to end tidal CO2 gradient.
- Increasing ventilator support will be of limited benefit in improving CO2 removal and may very well worsen the extent of wasted ventilation.
- Strategies that decrease airway pressure and improve pulmonary perfusion will decrease the extent of wasted ventilation, improve CO2 removal and improve cardiac output (see cardiopulmonary interactions elsewhere is this issue)

Limitations of the Standard Assessment of Cardiac Function and Cardiac Output

- While the physical examination and the interpretation of standard hemodynamic parameters (heart rate, central venous pressure, blood pressure) is essential to the management of the critically ill patient, estimations of cardiac function, cardiac output and the adequacy of tissue oxygenation based on an analysis of these standard clinical parameters are often discordant from measured values.
- This has been shown to be the case in numerous studies and is present across disciplines and levels of experience with the most senior care providers fairing no better than more junior care providers.
- These findings provide the rationale for enlisting additional tools for monitoring cardiovascular function

Serum Lactate Levels

- When metabolic demand exceeds oxygen delivery serum lactate will rise as lactate production outpace its clearance.
- The constant formation of lactate during glycolysis and it continuous conversion back to pyruvate is called lactate shuttle, and it is believe to be a part of cellular signaling in addition to its role in cellular metabolism
- The normal serum lactate level is less than 1.5 mmol/L. An elevated or rising lactate level is often seen as an indicator of inadequate oxygen delivery and cellular hypoxia in the intensive care unit. Nonetheless, studies have found that there are nonhypoxic reasons for elevated serum lactate.
- Hyperlactemia may be encountered after cardiopulmonary bypass in the post-operative setting and may not be associated with tissue hypoxia but rather may be reflective of a “washout” phenomenon after resumption of the normal circulation

Serum Lactate Levels (cont.)

- In any case, sustained or rising serum lactate level should not be assumed to be the result of a “washout” and should be promptly addressed.
- The association between hyperlactemia and morbidity and mortality following surgery is well known.
- In a prospective study, Charpie and colleagues monitored serum lactate levels in 46 patients who were less than 1 month old following cardiac surgery. With the primary outcome defined as need for extracorporeal membrane oxygenation (ECMO) or death, 9 patients required ECMO or died and 37 patients did not. In those whose postoperative course resulted in ECMO or death, the average initial serum lactate level was significantly higher (9.4 ± 3.8 mmol/L vs. 5.6 ± 2.1 mmol/L; P = .03) However, the positive predictive valve for the initial postoperative lactate level was only 38%. But when changes in lactate level were trended overtime, an increase in the lactate level of 0.75 mmol/L per hour or more was strongly associated with a poor outcome (P < .0001) such as the need for ECMO and death and the positive predictive valve was 100%.

Venous Oximetry

- The Fick principle states that when there is a decrease in oxygen delivery to the tissues, the arteriovenous oxygen content difference increases due to an increase in oxygen extraction.
- Furthermore, it is only when cardiac output and oxygen delivery drops below a critical level that an increase in oxygen extraction can no longer fully compensate, resulting in anaerobic metabolism and elevated serum lactate levels
- Therefore, venous oximetry provides an earlier indication of a waning cardiac output and oxygen delivery than serum lactate levels.

Venous Oximetry (cont.)

- As oxygen delivery falls, the oxygen extraction ratio rises [**Oxygen Extraction Ratio:** O_2ER = SaO_2 – $ScvO_2$ / SaO_2]
  - *SaO_2 and $ScvO_2$ are **Arterial** and **Central Venous Oxygen Saturations**, respectively.*
- The normal O_2ER is 25-30%, and as it rises above 50-60% anaerobic metabolisms ensues, defining the critical O_2ER. When the critical O_2ER is exceeded serum lactate production begins to exceed its clearance and levels begin to rise.
- An assessment of the O_2ER is not an exercise in determining cardiac function, cardiac output or systemic oxygen delivery
- The O_2ER is however an indicator of the relationship between oxygen supply and demand. Because the mixed venous saturation is rarely available outside the cardiac catheterization lab, alternative sites (central venous) are used to monitor venous oxygenation saturations and include: the jugular vein; superior vena cava; right atrium, so long as there is no left to right atrial shunting; and the inferior vena cava right atrial junction
- The utility of venous oximetry in managing patients at risk for or in a state of shock has been demonstrated by studies in adults and children with septic shock and well as in neonates following the Norwood procedure for the hypoplastic left heart syndrome

Near-infrared Spectroscopy

- Similar to pulse oximetry near infrared spectroscopy (NIRS) assesses the concentration of oxygenated and deoxygenated hemoglobin by analyzing the absorption and scatter of near infrared light.
- However, unlike pulse oximetry, which analyzes the pulsatile signal in the circulation, NIRS samples the nonpulsatile component. And because a majority of blood in the microcirculation is venous (upwards of 75- 80%) the oxygen saturation derived by NIRS is used as a surrogate for venous saturations for the viscera interrogated [23]. Studies have demonstrated a very good correlation between jugular saturations and cerebral NIRS derived oxygen saturations.
- Cerebral oxygen saturations are also used as a surrogate for central venous oxygen saturations and as such are used to assess the global relationship between oxygen supply and demand

Near-infrared Spectroscopy (cont.)

- As with pulse oximeters, NIRS oximeters rely on a complex algorithm to convert the change in absorbance of at least two wavelength of light to an absolute saturation value. It is not a measurement of oxygen saturations.
- Thus, while the correlation of pulse and NIRS oximetry with measured values is very good the derived values may vary from measured values. Due to technical constraints such as these, the technology is limited to relative quantitation and is thus useful for tracking changes in a given patient.
- Not surprisingly, studies have found that low cerebral oxygen saturation are associated with worse long term neurological outcomes. A prospective observational trial conducted by Dent et al found that new or worsened MRI lesions were found in infants whose cerebral NIRS were below 45% for longer than 180 minutes during cardiac surgery.
- Other studies have also demonstrated a significant correlation between depressed cerebral oxygenation intra- and postoperatively and the development of new or worsened neurologic injury and adverse neurodevelopmental outcomes

The Pulmonary Arterial Catheter and Emerging Technologies

- The pulmonary arterial catheter (PAC) provides continue measurements of right atrial and left atrial pressures, the latter obtained via a **Pulmonary Artery Occlusion Pressure** (PAOP).
- The PAOP is quite useful as studies have demonstrated a poor correlation between right and left atrial pressures in patients with underlying cardiopulmonary disease.
- The PAOP also distinguishes between cardiogenic and permeability pulmonary edema. The PAC also allows for an assessment of pulmonary arterial pressures, which in conjunction with the PAOP enables the clinician to determine the etiology of the pulmonary hypertension (ie., left sided heart disease versus pulmonary arterial hypertension).

The Pulmonary Arterial Catheter and Emerging Technologies (cont.)

- The PAC may be used to measure cardiac output by utilizing the principles of thermodilution. A measurement of cardiac output also allows for a calculation of systemic and pulmonary vascular resistance.
- Controversy has arisen in recent years with regard to the use of the pulmonary arterial catheter in the adult and pediatric setting.
- Proponents extol its ability to give hemodynamic data not available elsewhere while its opponents highlight the risks associated with its insertion and prolong use.
  - *In either case the information gleaned from the PAC may be essential in guiding therapy in patients who despite all efforts fail to progress and in whom additional hemodynamic data is essential to directing therapy*
- PACs in pediatric and adult patients:
  - *new technologies are emerging.*
  - *A relatively new technology that may be used to measure cardiac output is **Pulse Contour Analysis.***

The Pulmonary Arterial Catheter and Emerging Technologies (cont.)

- Pulse Contour Analysis
- This technology is based on the principle that the area under the curve of a central arterial waveform correlates with stroke volume.
- The PiCCO system (Pulsion Medical systemic, Munich, Germany) relies on a standard central venous catheter and a thermistor-tipped arterial catheter to generate a transpulmonary thermodilution-derived cardiac output.

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