Hemodynamic Monitoring

Hemodynamic monitoring is a mainstay in the care of critically ill patients and remains a valuable adjunct to physical examination and diagnostics in the assessment, diagnosis, and management of shock (Rali et al., 2022). It involves using invasive and non-invasive methods to provide information about pump effectiveness, vascular capacity, blood volume, and tissue perfusion. The precise data obtained from hemodynamic monitoring helps to identify the type and severity of shock (cardiogenic, hypovolemic, distributive, or obstructive). When paired with clinical evaluation, hemodynamic monitoring is helpful in guiding the administration of fluids, in selecting and titrating vasoactive drugs, and in deciding when mechanical support might be necessary to treat refractory shock and allows for evaluation of the effectiveness of treatment in real time.

The Cardiac Cycle & Key Definitions

A thorough understanding of the cardiac cycle and key definitions provide a foundation for the interpretation of hemodynamics.

The Cardiac Cycle

Diastole

- Diastole begins when the musculature of the atria and ventricles relax. During this period, all four cardiac valves are closed.
- During diastole, blood returns to the atria from the venous system. The inferior vena cava and superior vena cava fill the right atrium with blood returning from the body and the four pulmonary veins fill the left atrium with blood returning from the lungs.
- The increasing pressure inside the filling atria push the atrioventricular (AV) valves open, allowing for passive ventricular filling. At this point in the cardiac cycle, the semilunar valves remain closed.
- At the end of diastole, the atria contract to forcibly fill the ventricles with extra volume of blood. Contraction of the atria is referred to as *atrial systole.*

Systole

- Shortly after atrial systole, ventricular systole begins. During ventricular systole, the ventricles contract, pushing the AV valves closed and forcing the semilunar valves open.
- Blood is ejected from the ventricles through the semilunar valves. The right ventricle moves blood into the pulmonary artery and the left ventricle pushes blood to the body.

Key Definitions		
	Definition	**Clinical Considerations**
Stroke volume (SV)	The volume of blood pumped out of the left ventricle with each contraction	Normal range is 60-90 mL. Calculation SV = End-diastolic volume (EDV) – end-systolic volume (ESV)
End diastolic volume (EDV)	Volume of blood in the right ventricle (RV) or	Normal is about 120 mL.

	LV at the end of diastole (filling)	
End systolic volume (ESV)	Volume of blood in the RV or LV at the end of systole (contraction)	Normal is about 50 mL.
Preload	The amount of ventricular stretch at the end of diastole	Also known as the left ventricular end-diastolic pressure (LVEDP)
Afterload	The amount of resistance the heart must overcome to open the aortic valve and push the blood volume out into the systemic circulation	Also known as the systemic vascular resistance (SVR)
Contractility	The ability of the heart to contract and generate force and blood flow	

Measuring Hemodynamics

Hemodynamic instability causes a mismatch between oxygen demand and delivery, ultimately leading to organ failure. Hemodynamic instability can typically be managed with clinical examination and monitoring of vital signs (heart rate, blood pressure, oxygen saturation, and respiratory rate) and urine output. However, when the patient does not improve, or deteriorates further, invasive hemodynamic monitoring is often needed to guide fluid management and vasopressor/inotropic support.

Clinical Assessment

A clinical examination is the fastest and least invasive hemodynamic monitor available.

- A patient with inadequate global perfusion often presents with signs of end organ dysfunction, such as tachypnea, tachycardia, confusion, weak peripheral pulses, skin mottling, and oliguria.
- Capillary refill time (CRT), which can be rapidly tested, is the time required for blood flow to return to the distal capillaries. CRT is measured by compressing and blanching the nailbed of a patient's fingertip for ten seconds, then releasing the pressure. The amount of time required for color to return to the nailbed is documented as CRT. The upper limit of a normal CRT is three seconds in adults. A longer CRT indicates reduced capillary perfusion and decreased peripheral blood flow.

Non-invasive Monitoring

Electrocardiogram (ECG)

- Heart rate is an important determinant of cardiac output (CO) (CO = HR X SV).
- A 12-lead ECG confirms cardiac rhythm and provides baseline information on ST segments and T waves.
- Continuous monitoring of heart rate, cardiac rhythm, and ST segments allow for early recognition of hypovolemia and myocardial ischemia.
- Tachyarrhythmias are a common finding in certain shock states. Bradycardia and/or heart block may indicate cardiogenic shock.

Non-Invasive Blood pressure (NiBP)

- The definition of hypotension (low blood pressure) is patient-specific and interpreted in the context of the patient's usual BP.
- Hypotension is a common feature of most shock states.
- Blood pressure typically shows the pressures in the systemic vasculature during left ventricular systole (SBP) and diastole (DBP). It is shown in the format SBP/DBP.
- Mean arterial blood pressure (MAP) is an average of the systolic and two times the diastolic pressures (the heart spends twice as much time in diastole as it does in systole). MAP can be used as an approximation of organ perfusion pressure.
- Severely elevated BP, especially if acute, is associated with increased vascular resistance and may be associated with inadequate tissue perfusion, for example hypertensive encephalopathy or acute renal failure.

Pulse oximetry (SpO_2)

- Continuous SpO_2 monitoring enables detection of a reduction in arterial oxygen saturation, which is an integral part of oxygen delivery.
- The SpO_2 signal is often inaccurate in the presence of decreased peripheral perfusion. The inability to measure SpO_2 is itself an indicator of abnormal peripheral perfusion.

Echocardiography

- An echocardiogram provides visualization of the cardiac chambers, valves, pericardium, and overall cardiac function.
- It allows for measurement of left ventricular ejection fraction (LVEF) and estimation of SV and CO based on measurement of LV outflow tract (LVOT), LVOT velocity, and heart rate.

Fluid responsiveness

- Fluid resuscitation is a key treatment strategy for hemodynamically unstable patients. Although rapid optimization of volume status has been shown to improve outcomes, volume overload is associated with increased morbidity and mortality.
- A fluid challenge is necessary to determine whether fluid administration will benefit the patient.
- Fluid responsiveness is frequently defined as an increase in cardiac output (greater than or equal to 10% from baseline) with a fluid challenge (250-500 mL administered over 10-15 minutes).

- An alternative to a fluid challenge is to perform a *passive leg raise (PLR)* maneuver. This produces an 'autotransfusion' of blood from the venous compartments in the abdomen and lower limbs. To perform a PLR:
  - Position the patient in the semi-recumbent position with the head and torso elevated at 45 degrees.
  - Obtain a baseline blood pressure measurement.
  - Lower the patient's upper body and head to the horizontal position and raise and hold the legs at 45 degrees for one minute.
  - Obtain subsequent blood pressure measurement.
  - A 10% or greater increase in cardiac output (CO) indicates that the patient is fluid responsive. Note: Although not considered a validated measure, we often use blood pressure as a surrogate marker of CO in evaluating response to the PLR.
  - Only patients who are fluid responsive after a fluid bolus or passive leg raise should receive additional fluids.

Invasive Monitoring

Intra-arterial blood pressure (ABP)

- Arterial cannulation (usually the radial artery) allows for accurate continuous blood pressure measurement. Arterial line BP monitoring is the standard of care for patients on vasopressor/inotrope infusions.
- Arterial lines facilitate frequent blood draws for blood gases or other lab studies.

Central venous pressure (CVP)

- The CVP is the blood pressure in the vena cava/right atrium; normal range is 2-6 mm Hg.
- The CVP reflects venous return to right side of heart, or right ventricular preload, which is a key component of RV function.
- CVP is measured via a catheter positioned in the vena cava.

Pulmonary artery pressure (PAP)

- PAP is the blood pressure in the pulmonary artery. Normal systolic PAP range is 15-25 mm Hg, normal diastolic PAP is 8-15 mm Hg, and the mean PAP is 10-22 mm Hg.
- PAP may be measured during right heart catheterization or via introduction of a catheter into the pulmonary artery (e.g., Swan Ganz Catheter).

Mixed venous oxygen saturation (SvO_2)

- SvO_2 measures the percentage of oxygen bound to hemoglobin in mixed venous blood from the entire body and requires the placement of a pulmonary artery catheter.
- SvO_2 reflects the balance between oxygen delivery and oxygen consumption (VO_2).
- It depends on arterial blood saturation (SaO_2), the balance between VO_2 and CO, and hemoglobin (Hgb) levels.
  - Normal SvO_2 is greater than or equal to 70% (drawn from a pulmonary artery catheter).
  - Central venous oxygenation ($ScvO_2$) is normally greater than or equal to 65% (drawn from a central venous catheter).

Hemodynamic Values		
	Definition	**Calculations & Normal Range**
Cardiac output (CO)	The volume of blood pumped through the heart per minute (L/min)	Normal range is 4-8 L/minute. <u>Calculation</u> CO = Stroke Volume (SV) X Heart Rate (HR)
Cardiac index (CI)	CO adjusted for body surface area (BSA)	Normal range is 2.8-4.2 $L/min/m^2$. <u>Calculation</u> CI = CO/BSA
Central venous pressure (CVP)	The blood pressure in the vena cava and right atrial diastolic pressure; used to assess preload and volume status	Normal range is 2-6 mm Hg.
Mean arterial blood pressure (MAP)	Systolic blood pressure + (2 x diastolic blood pressure)/3	Normal range is 70-105 mm Hg.
Right atrial pressure (RA)	Reflects venous return to the right atrium and right ventricular end-diastolic pressure	Normal range is 0-7 mm Hg.
Right ventricular pressure (RV)	Measured during catheter insertion	Normal RV systolic pressure is 15-25 mm Hg.
Pulmonary artery pressure (PA)	Used to diagnose pulmonary artery hypertension	Normal PA systolic pressure is 15-25 mm Hg. Normal mean PA pressure is 10-22 mm Hg.
Pulmonary capillary wedge pressure (PCWP)	Reflects left atrial pressure and left ventricular end-diastolic pressure (left ventricular preload)	Normal range is 6-15 mm Hg. Normal mean PCWP is 9 mm Hg.
Systemic vascular resistance (SVR)	The amount of resistance the heart must overcome to open the aortic valve and push the blood	Normal range is 800-1200 $dynes\text{-}sec/cm^{-5}$.

	volume out into the systemic circulation	
Pulmonary vascular resistance (PVR)	Reflects the resistance the blood must overcome to pass into the pulmonary vasculature	Normal is less than 250 dynes-sec/cm^{-5}.

Novel Cardiac Output Monitoring Devices

Assessment of values obtained from a pulmonary artery catheter is currently considered the gold standard for monitoring a patient's hemodynamics and cardiac output). However, there are safety concerns with pulmonary artery catheters (e.g., infection, pneumothorax, pulmonary artery rupture). There's also a lack of evidence to suggest a benefit to mortality.

As an alternative, devices for minimally invasive cardiac output monitoring have been developed. These devices use arterial pressure and pulse contour or chest bioreactance to assess hemodynamics. Another alternative, esophageal doppler monitoring, utilizes a flexible trans-esophageal doppler ultrasound probe to estimate cardiac output and stroke volume. However, these techniques aren't typically accurate enough to provide absolute cardiac output values but are more commonly utilized for trending values.

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