CRITCARE BITES

CARDIAC OUTPUT MONITORING

Wang Zhemin

SICM
Society of Intensive Care Medicine
SINGAPORE

MAD FOR MEDICINE

OVERVIEW

- Background
- Indication
- Monitoring methods
- Pulse contour analysis
- Transpulmonary thermodilution
- Pulmonary artery catheter
- Others

BACKGROUND

- Cardiac output monitoring devices derive cardiac output (in different ways) and other haemodynamic parameters
- Devices differ: Parameters, invasiveness, limitations
- Basic ICU haemodynamic monitoring: Arterial line, CVC, ultrasound
- Use cases: Cardiogenic/mixed shock, high doses of vasoactive medication, failure to respond to treatment
- Generally, less invasive modalities have not been shown to be accurate in critically ill patients

INDICATION/USES

- Assess fluid responsiveness: Change in stroke volume, stroke volume variation
- Etiology of shock: Cardiac index, systemic vascular resistance, preload indices
- Phenotyping in cardiogenic shock
- Guide/assess response to treatment
- Fluid status/tolerance: EVLWI, PAOP

MONITORING METHODS

Non-Invasive	Minimally Invasive	Invasive
• Bioimpedence/ Bioreactance • Volume clamp/ radial artery applanation tonometry	• **Arterial line pulse contour analysis** • Esophageal doppler	• **Transpulmonary thermodilution** • **Pulmonary artery catheterisation**

MEASUREMENTS

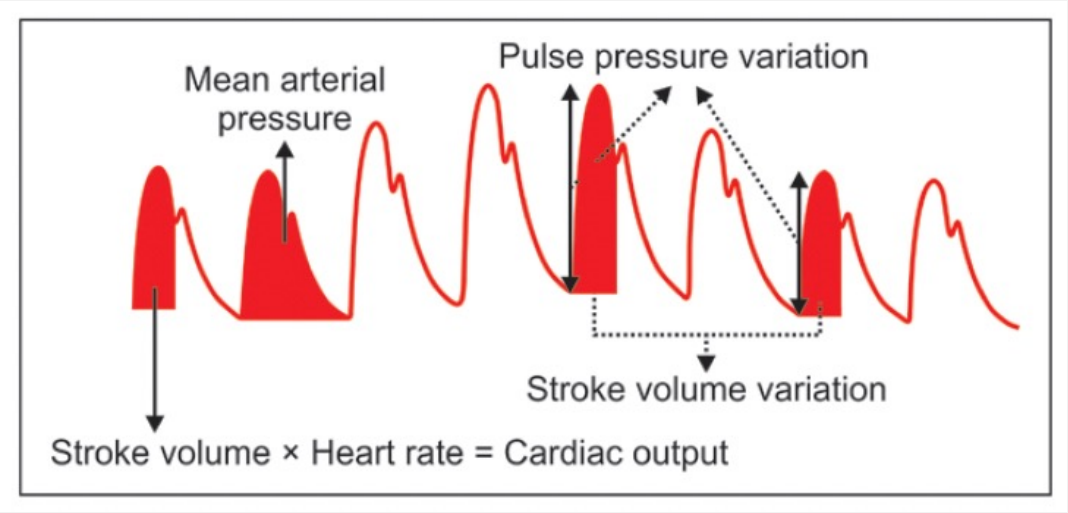
	Pulse Contour Analysis	Transpulmonary Thermodilution	Pulmonary Artery Catheter
Preload	-	Global end-diastolic volume	**CVP** (right), **PCWP** (left)
Contractility	-	Cardiac function index, global ejection fraction	PAPI (RV function) = *((**PAS-PAD**)/**RAP**)*
Afterload	SVR = *[(MAP – CVP)/CO] x 80*	SVR	SVR PVR = *[(mPAP-PCWP)/CO] x 80)*
Cardiac Output/Stroke Volume	**SV** CO (HR x SV)	**CO**	**CO** RVEF
Fluid Responsiveness	**SVV**	**SVV** (when paired with pulse contour analysis)	-
Fluid tolerance	-	Extra vascular lung water Pulmonary vascular permeability	-

‘NORMAL’ VALUES

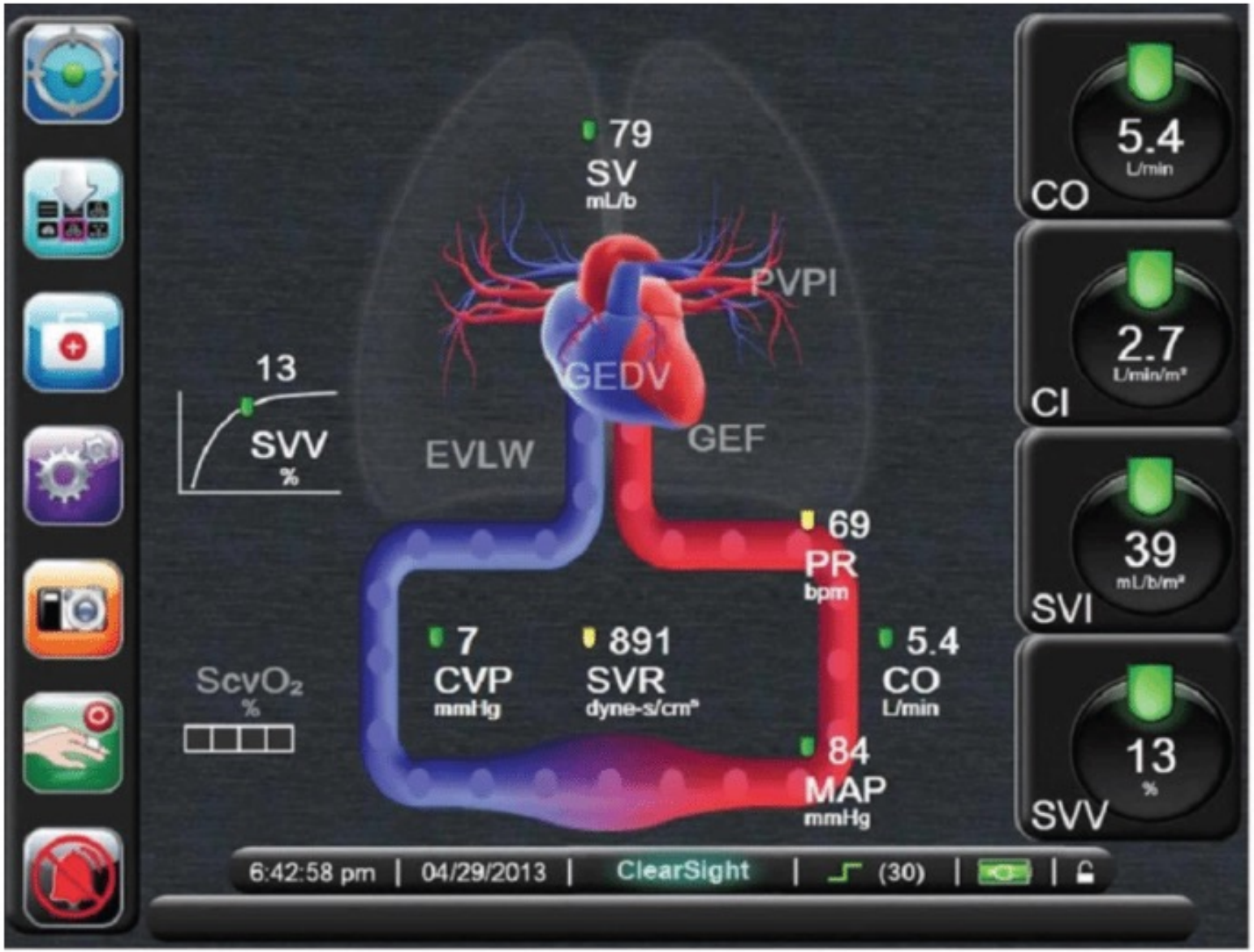
General	Transpulmonary Thermodilution	Pulmonary Artery Catheterisation
• CO: >5L/min • **CI: >2.2 L/min/m2** • SV: 50-100ml • SVI: > 35 ml/m2 • SVR ((MAP – CVP) / CO) x 80): 800-1200 dynes s/cm5 • **SVRI: 1700-2400 dynes s m2/cm5**	• GEDVI: >700 • EVLWI: <10 • PVPI: <3 • CFI: >5	• CVP < 14, PCWP <18 • mPAP < 25 • PAPI ((PAS-PAD)/RA) >1.5 • CPO (MAP x CO / 451): 0.5-0.7W/m2 • RVEF: >35% • PVR ((mPAP-PCWP)/CO) x 80): 100-200 dynes/cm5 • PVRI: 250-300 dynes s m2/cm4

PULSE CONTOUR ANALYSIS

- **Arterial pulse pressure and its contour are analysed** and a **stroke volume is determined** from the **area under the systolic part** of the arterial curve, based on the principle of **ventriculo-arterial coupling**
- Pulse contour analysis can be externally calibrated (e.g. based on values derived from echocardiography or thermodilution) or internally calibrated (based on patient-specific anthropometric and demographic data to adjust for arterial compliance and tone)
- Application
  - Non-invasive: Volume clamp, radial artery applanation tonometry
  - Non-calibrated via IA line: E.g. Flotrac
  - Calibrated: Calibration with transpulmonary thermodilution (e.g. PiCCO, VolumeView)



Karim Kouz, Thomas W. L. Scheeren, Daniel de Backer, Bernd Saugel; Pulse Wave Analysis to Estimate Cardiac Output. *Anesthesiology* 2021; 134:119–126 doi: https://doi.org/10.1097/ALN.0000000000003553



	Pulse Contour Analysis
Preload	-
Contractility	-
Afterload	SVR = *[(MAP – CVP)/CO] x 80*
Cardiac Output/Stroke Volume	**SV** CO (HR x SV)
Fluid Responsiveness	**SVV**
Fluid tolerance	-

IVC Size	IVC Collapsibility	Interpretation (CVP)
< 1.5cm	>50% collapsibility	0-5 mm Hg (Low CVP)
< 1.5-2.5cm	>50% collapsibility	6-10 mm Hg
1.5-2.5cm	<50% collapsibility	11-15 mm Hg
>2.5cm	<50% collapsibility	16-20 mm Hg (High CVP)

Aldawoodi, Nasrin & Escher Jr, Allan & Ninan, David & Patel, Sephalie. (2019). Transesophageal Echocardiography During Cytoreductive Surgery with Hyperthermic Intraperitoneal Chemotherapy: A Novel Approach. Cureus. 11. 10.7759/cureus.5062.

PULSE CONTOUR ANALYSIS

- Advantages:
  - Automated
  - Continuous, beat-by-beat
  - User-independent measurement technique
- Disadvantages (uncalibrated devices):
  - Bias of proprietary algorithms (based off healthy population, hence unclear reliability in haemodynamically unstable patients with changing arterial resistance)
  - Subject to drift over time (without calibration)
  - Limited hemodynamic variables provided (CO, PPV, SVV)

TRANSPULMONARY THERMODILUTION

- Transpulmonary thermodilution technologies (e.g. PiCCO, VolumeView) offer haemodynamic insights through **thermodilution, pulse contour analysis and intrathoracic volumes**
- Cardiac output is determined by administration of a cold injectate via an internal jugular central line and detection of temperature change through a femoral arterial catheter. A **thermodilution curve allows for calculation of cardiac output using the Stewart-Hamilton equation** (cardiac output is inversely related to area under thermodilution curve)
- While thermodilution is intermittent, incorporation of calibrated **pulse contour analysis** allows for real-time monitoring of cardiac output

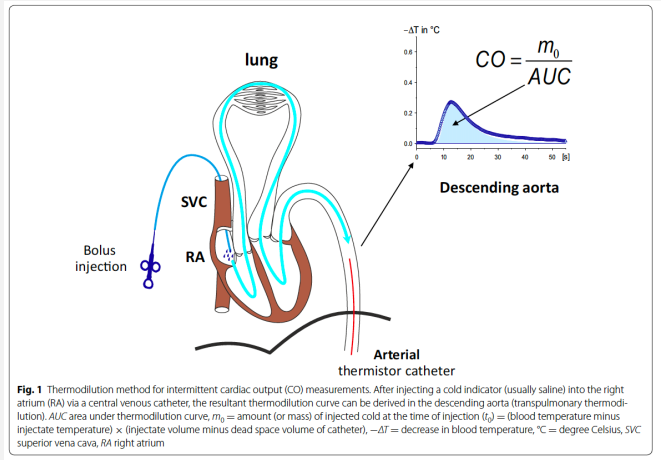
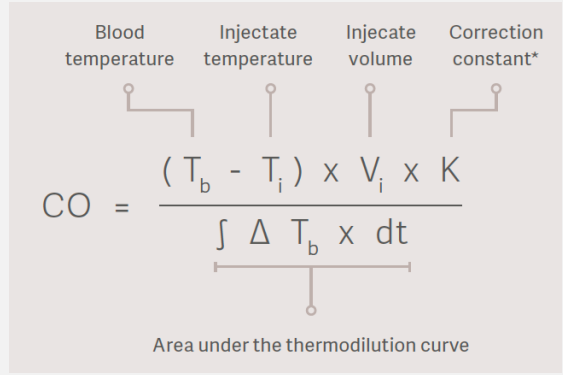
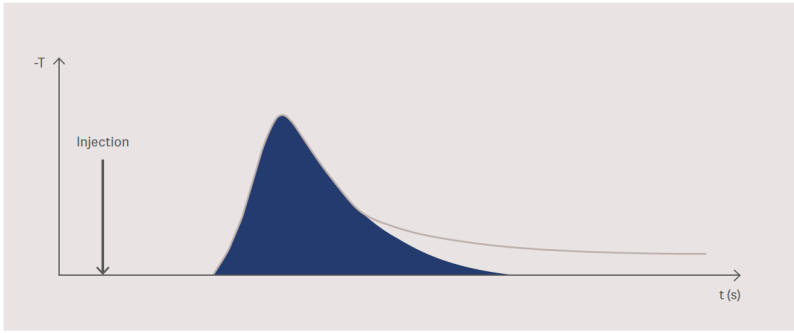


Fig. 1 Thermodilution method for intermittent cardiac output (CO) measurements. After injecting a cold indicator (usually saline) into the right atrium (RA) via a central venous catheter, the resultant thermodilution curve can be derived in the descending aorta (transpulmonary thermodilution). *AUC* area under thermodilution curve, m_0 = amount (or mass) of injected cold at the time of injection (t_0) = (blood temperature minus injectate temperature) × (injectate volume minus dead space volume of catheter), $-\Delta T$ = decrease in blood temperature, °C = degree Celsius, *SVC* superior vena cava, *RA* right atrium

15ml of cold saline < 8 degC injected quickly, average across 3 readings

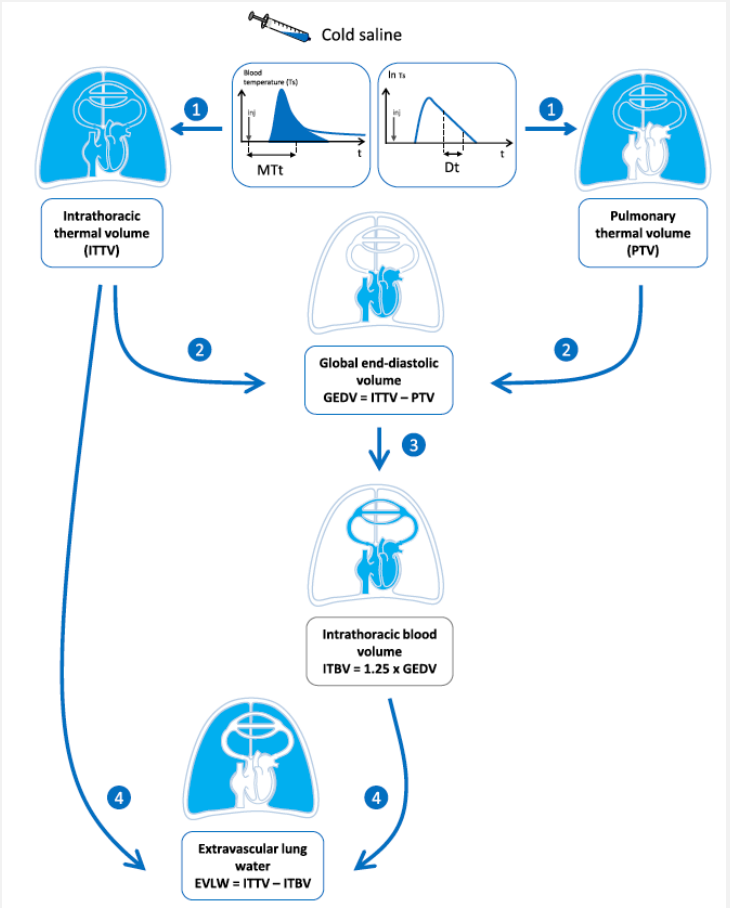




The CO is calculated from the area under the thermodilution curve [19, 20]

TRANSPULMONARY THERMODILUTION

- TPTD also estimates some **intrathoracic volumes** base on analysis of the thermodilution curve and its logarithmic transformation
- According to Stewart Hamilton principle, total distribution volume of cold indicator between injection and detection sites represents the intrathoracic thermal volume
- Specific volumes
  - Intrathoracic thermal volume: CO x mean transit time of cold indicator
  - Pulmonary thermal volume: CO x downslope time of curve
  - Global end-diastolic volume: Intrathoracic thermal volume – total pulmonary volume; corresponds to volume of all 4 chambers at end of diastole (marker of preload)
  - Extravascular lung water: Intrathoracic thermal volume – intrathoracic blood volume (ITBV = GEDV x 1.25)
  - Pulmonary vascular permeability index: EVLW/Pulmonary blood volume (i.e. ratio of volume out of vessels to in vessels)



TRANSPULMONARY THERMODILUTION

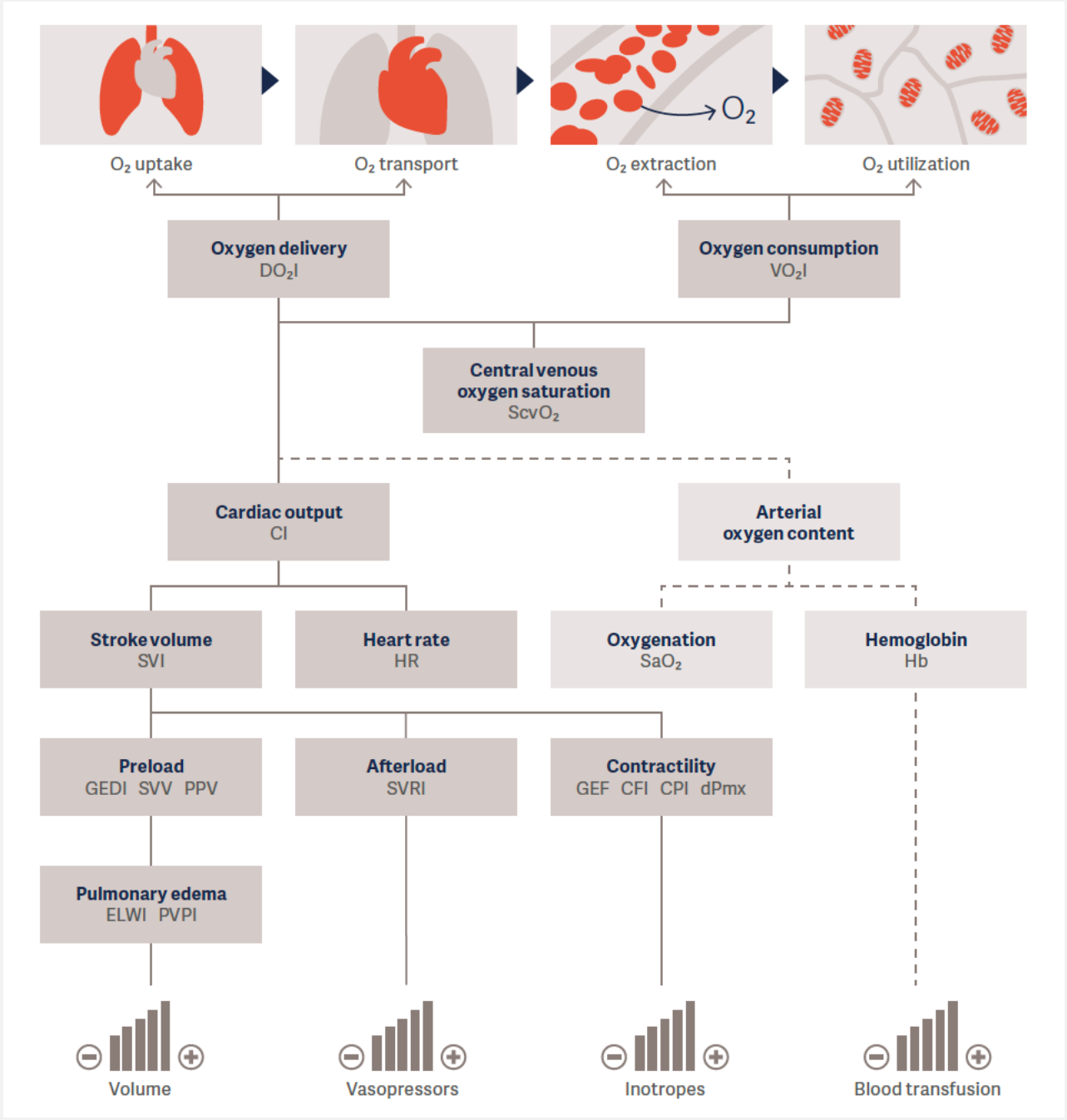
Variable	Clinical Significance	Normal Values	Limitations
Global end-diastolic volume	Preload	680-800ml/m^2	Does not distinguish between right and left ventricles, hence less directly reflects risk of pulmonary edema than PAOP
Cardiac function index, global ejection fraction	Cardiac contractility	CFI aim > 5, <2.3 suggests LVEF < 30% GEF 25-35%	Overestimates LV systolic function in case of RV dilation
Cardiac index	Affected by preload and contractility	Generally aim >2.2-2.5, but must contextualise to patient	
Extravascular lung water index	Marker of lung edema	3-7ml/kg (<10)	Unreliable in pulmonary embolism, lung resection, large pleural effusion
Pulmonary vascular permeability index	Discriminate between hydrostatic vs permeability	<3 cardiogenic edema, >3 permeability edema	Unreliable in pulmonary embolism, lung resection, large pleural effusion
Systemic vascular resistance index ((MAP-CVP)/CI) x 80	Afterload	1700-2400 dynes s m^2 /cm^5	

Some caveats

- Femoral vein CVC: **Cannot be on same side as arterial catheter**. If on different side, cardiac output measurements still valid but **thoracic volumes invalid**
- Can be used in CRRT but not ECMO
- Can be used in therapeutic hypothermia
- Contraindicated in case of femoral vascular prosthesis (or other vascular related concerns)
- Unreliability in low CO states

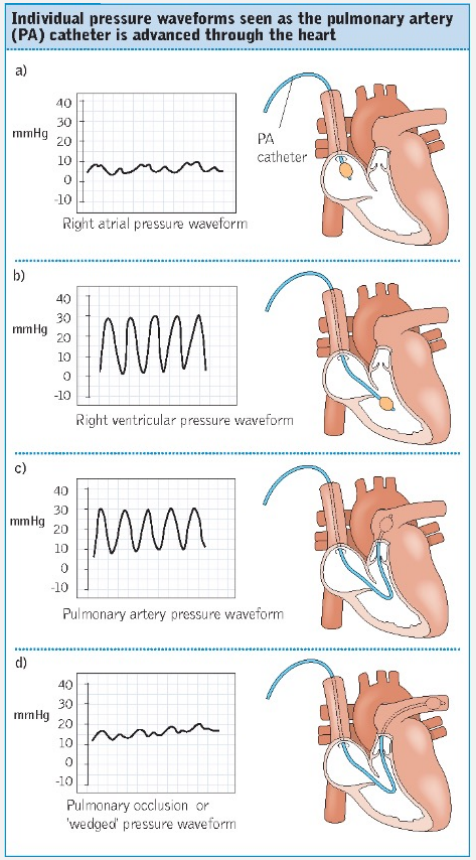
Clinical use

- May be particularly useful in ARDS with shock
- Thoracic volume indices may help with fluid management and de-resuscitation
- Measurement of cardiac output more robust than less invasive methods
- Incorporation of pulse contour analysis allows for real time and precise monitoring
- Unable to differentiate between right and left heart pathologies



PULMONARY ARTERY CATHETER

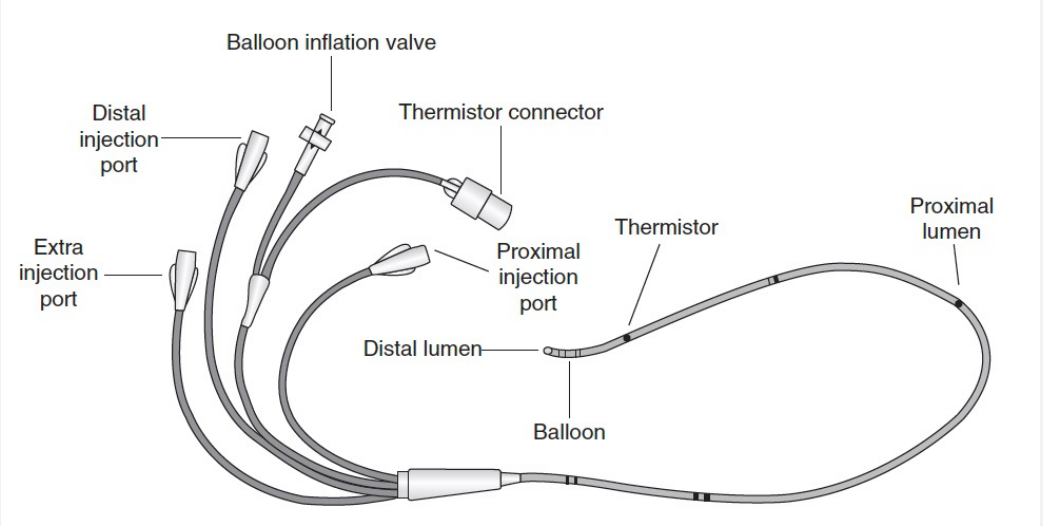
- Pulmonary artery catheters (PACs) are largely considered the gold standard for cardiac output monitoring because of accurate measurement method (thermodilution) and provision of right and left heart indices
- The catheter is inserted via a large vein into the RA > RV > PA. Catheter tip is intermittently wedged with an occlusion balloon in a tapering branch of the PA and a wedge pressure is obtained. Thermodilution is performed for cardiac output measurement.
- Main drawback is relative invasiveness and requirement for technical and interpretational expertise
- PACs are most useful in the context of right heart/biventricular cardiac dysfunction or pulmonary hypertension



Scales, Katie. "A practical guide to using pulmonary artery catheters." *Nursing standard (Royal College of Nursing (Great Britain) : 1987)* 21 43 (2007): 42-48.

PULMONARY ARTERY CATHETER

- Measurements
  - During insertion: RAP (1-6mmHg), RVP (15-30/1-6mmHg), PAP (15-30/6-12mmHg), PAWP (6-12mmHg)
  - When in-situ: CO (thermodilution), PCWP (balloon occlusion), RAP, SvO2 (available on some catheters)
  - Calculated variables: PVR, SVR, SV, CPO, PAPi
- Clinical significance
  - Preload: Right side (RAP), left side (PAWP)
  - Contractility: CO, SV; these indices also affected by preload
  - Afterload: Right side (PVRI 120-200), left side (SVRI 1700-2400)
  - Oxygen supply-demand balance: SvO2

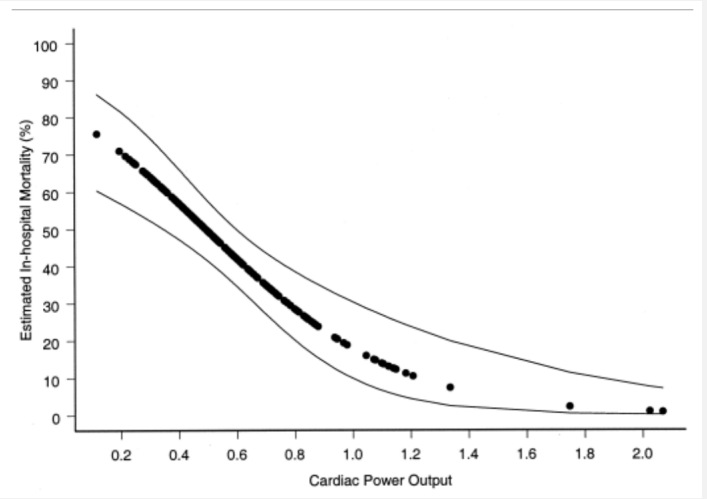


PULMONARY ARTERY CATHETER

	PCWP	CVP	CI	SVR	PVR
Hypovolemic	↓	↓	↓	↑	
Distributive	↓	↓	↑	↓	
Cardiogenic (RV)	-	↑	↓		↑
Cardiogenic (LV)	↑		↓	↑	
Cardiogenic (bivent)	↑	↑	↓	↑	
Tamponade	↑	CVP=PCWP		↑	

PULMONARY ARTERY CATHETER

- Cardiac power output
  - [(MAP – RAP) x CO] / 451
  - Prognostic marker in cardiogenic shock - <0.53W associated with 58% mortality
- Pulmonary artery pulsatility index (PAPi)
  - (PASP - PADP) / RAP
  - <1.5 associated with RV failure, <0.9 associated with severe RV failure



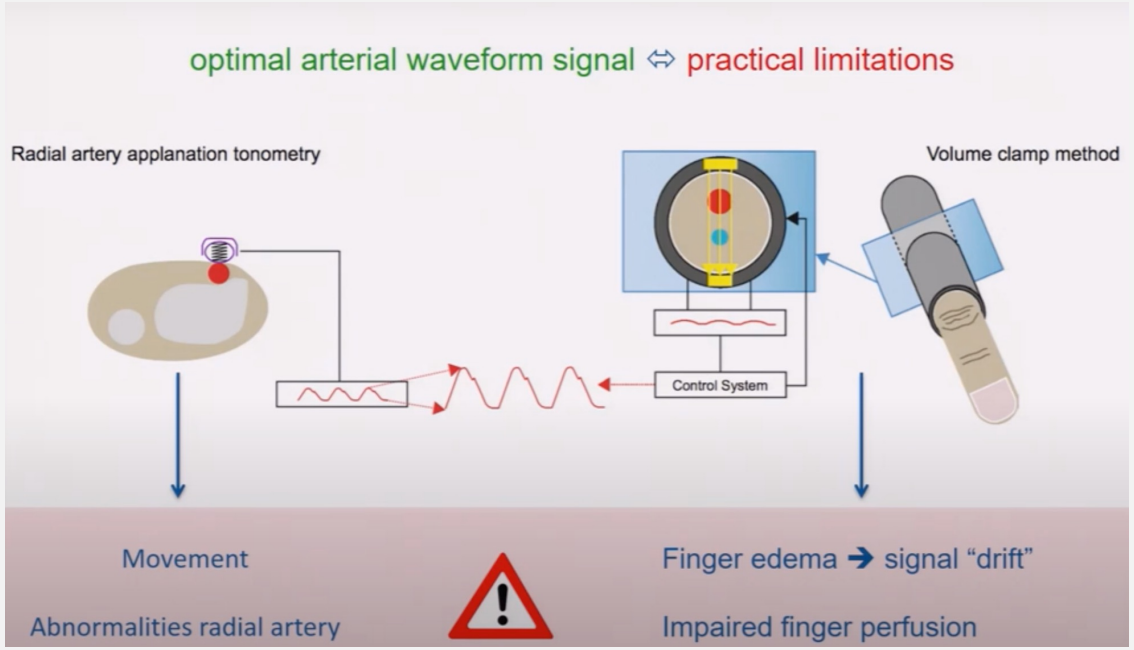
NON-INVASIVE PULSE CONTOUR ANALYSIS

Radial Artery Applanation Tonometry

- Electrico-mechanical sensor records arterial waveform over the radial artery – pulse contour analysis performed
- Limitations: Affected by sensor placement and movement

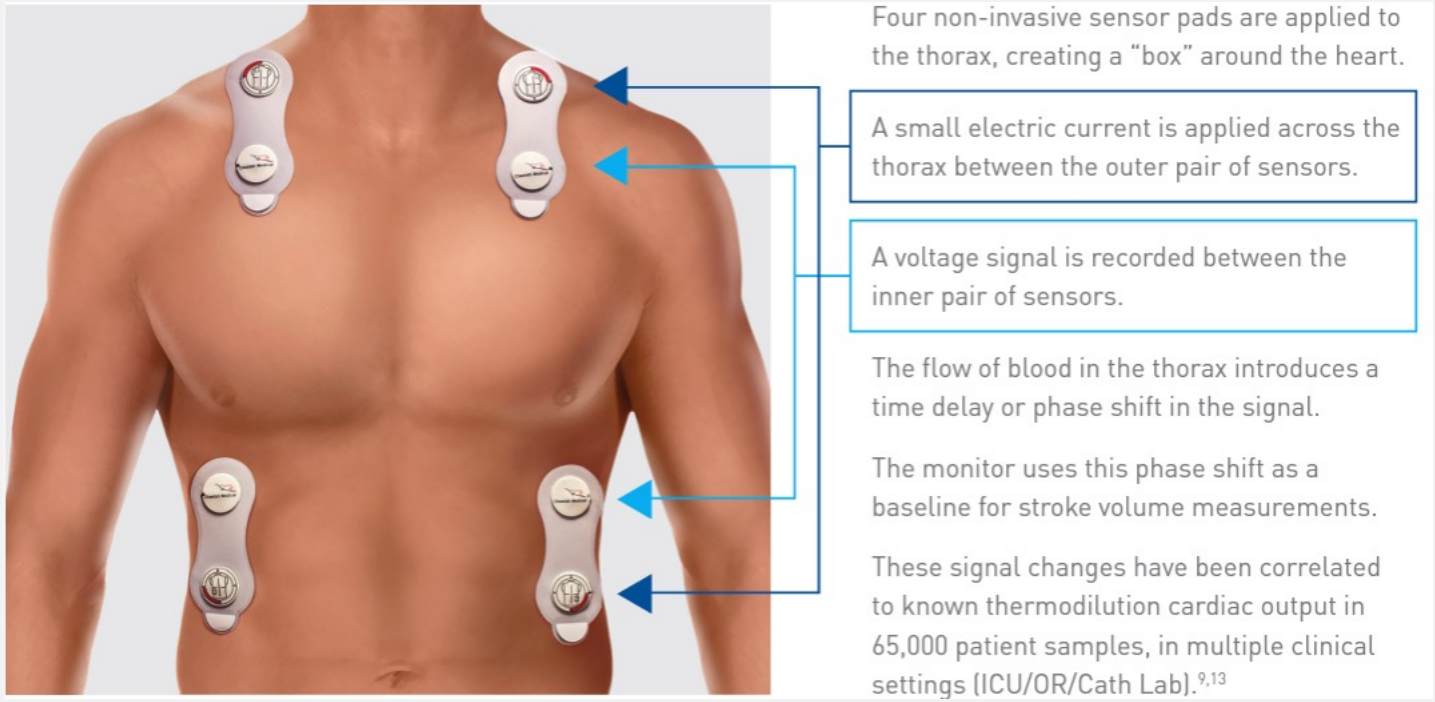
Volume Clamp Method

- Finger arterial pressure waveform derived from pressure needed to keep blood volume in finger artery constant – pulse contour analysis performed
- Limitations: May cause edema and vasoconstriction



BIOREACTANCE

- Stroke volume derived from phase shifts in voltage over the cardiac cycle because of pulsatile changes in intrathoracic blood volume
- Example: Baxter Starling device
- Stroke volume allows derivation of cardiac output and peripheral vascular resistance
- Can be used to monitor change in SV and CO following passive leg raise or fluid bolus
- Caution in pleural effusions, pulmonary edema, pacemaker, electrical interference, movement

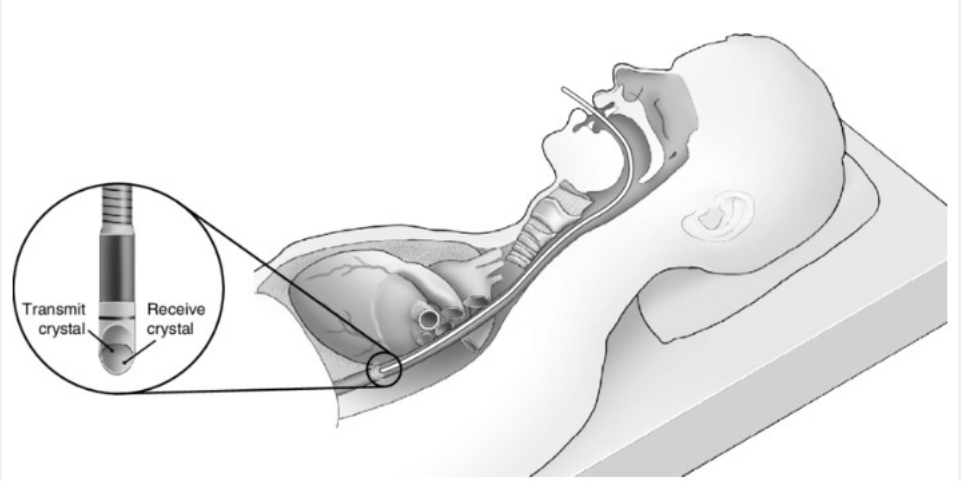


Baxter Starling brochure


CI
2.9
CO
5.3
HR
57
TPRI
1760
TPR
964
SVI
51
SV
92.8
CP
1.2
DO2I
615
--/-- (82)
HR
SV
PLR Protocol
End Time: 01/26/15 10:31:18 AM
SVI
30.2%
Preload
Session Controls
View
Switch Display

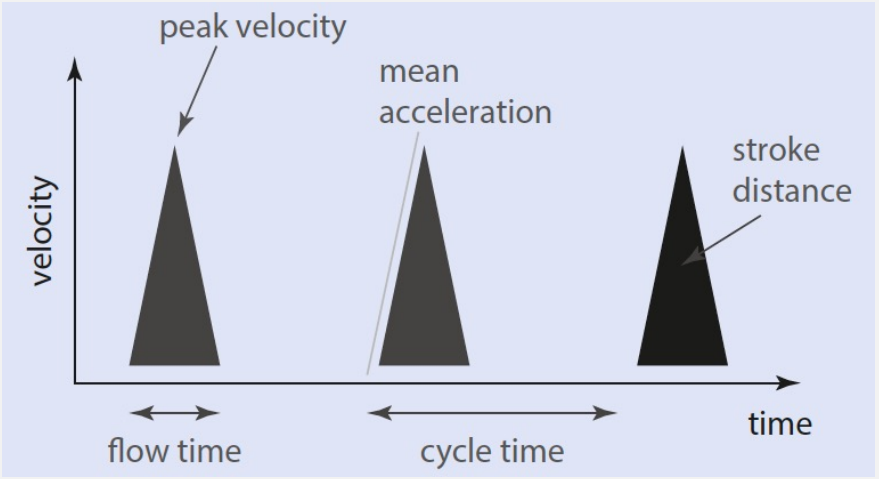
ESOPHAGEAL DOPPLER

- Doppler probe inserted into the midthoracic esophagus and is oriented posteriorly towards the descending aorta
- Continuous wave doppler is transmitted from the probe and a velocity time waveform is plotted based on reflected waves from red blood cells in aorta
- Limitations: SV derived base on nomogram, aortic cross-sectional area not measured, assumption of fixed distribution of cardiac output to descending aorta, positional dependence, assumption of lamina blood flow



ESOPHAGEAL DOPPLER

- **Stroke distance (SD)** is the area under the velocity-time waveform and represents distance moved by the column of blood within the aorta following left ventricular contraction. It is used to generate a nomogram-derived stroke volume, from which cardiac output (HR x SV) can be derived.
- **Flow time (FT)** is the width of the base of the waveform and represents duration of systolic blood flow. The corrected flow time (FTc) which is adjusted for heart rate has a normal range of 330-360ms and is inversely related to vascular resistance. FTc is low in vasoconstricted states (e.g. hypovolemia) while FTc is high in vasoplegic states (e.g. sepsis)
- **Peak velocity (PV)** and mean acceleration (MA) are markers of left ventricular contractility – Normal range in 20yo (90-120cm/s), 70yo (50-70cm/s)



SUMMARY

- Simple shock: Monitoring with invasive blood pressure, ultrasound, biochemical markers (lactate, urine output)
- Mixed shock (mild): Consider monitoring ScvO2, CO2 gap, possible role for arterial line pulse contour analysis (but be aware of limitations)
- Severe/complex mixed shock or cardiogenic shock
  - Concomitant respiratory failure: Transpulmonary thermodilution
  - Cardiogenic shock: Consider PA catheter especially when component of RV dysfunction present, planning for MCS