Hemodynamic monitoring in the ICU

Dr. Aditya Jindal

1/4/11

- Introduction
- Pulmonary artery and central venous catheter
- Blood pressure
- Cardiac output determination

‘‘The same old Watson! You never learn that the gravest issues may depend upon the smallest things.’’

– Sherlock Holmes in *The Adventure of the Creeping Man* by Sir Arthur Conan Doyle

- Why monitor?
  - Monitoring may identify disease, even though the link between the monitored parameters and the disease is not clear
  - Pathophysiological basis
  - Monitoring driven treatment protocols

Hemodynamic parameters

Primary hemodynamic variables

- HR, beats/min
- MAP, mm Hg
- Pra, mm Hg
- MPAP, mm Hg
- Ppao, mm Hg
- CO, L/min
- Sa_{O_2}, %
- Sp_{O_2} as an estimate of Sa_{O_2}, %
- $S\bar{v}_{O_2}$, %
- Hb, g/dL
- Height and weight needed to calculate BSA, m^2

Calculated hemodynamic parameters

- CI = CO/BSA, $L/min/m^2$
- Stroke volume = CO/HR $\times$ 1,000, mL/min
- Stroke index = stroke volume/BSA, mL/m^2
- LV stroke work = stroke volume $\times$ (MAP $-$ Ppao), mL · mm Hg
- LV stroke work index = LV stroke work/BSA, mL · mm Hg/m^2
- Total peripheral resistance = (MAP/CO) $\times$ 80, dyne · s/cm^5
- Systemic vascular resistance = ([MAP $-$ Pra])/CO $\times$ 80, dyne · s/cm^5
- RV stroke work = stroke volume $\times$ (MPAP $-$ Pra), mL · mm Hg
- RV stroke work index = RV stroke work/BSA, mL · mm Hg/m^2
- Pulmonary vascular resistance = ([MPAP – Ppao]/CO) $\times$ 80, dyne · s/cm^5
- Global D_{O_2}† = CO $\times$ (Sa_{O_2} $-$ $S\bar{v}_{O_2}$) $\times$ Hb $\times$ 1.36 $\times$ 1,000, mL oxygen/min
- Global D_{O_2} index† = CI $\times$ (Sa_{O_2} $-$ $S\bar{v}_{O_2}$) Hb $\times$ 1.36, mL oxygen/min
- Global $\dot{V}_{O_2}$† = CO $\times$ Sa_{O_2} $\times$ Hb $\times$ 1.36 $\times$ 1,000, mL oxygen/min
- Global $\dot{V}_{O_2}$ index† = CI $\times$ Sa_{O_2} $\times$ Hb $\times$ 1.36 $\times$ 1,000, mL oxygen/min

Pinsky MR. Hemodynamic Evaluation and Monitoring in the ICU; *CHEST 2007; 132:2020–2029*

Right heart catheterization

History

- First heart catherisation performed by Fritz Bleichroder, Ernst Unger, and W. Loeb in early 1900s
- Similar experiments done by Werner Forssmann
- Pioneering studies by Cournand and Richards in the 1940s
  - Cournand A. Cardiac catheterization; development of the technique, its contributions to experimental medicine, and its initial applications in man. *Acta Med Scand Suppl 1975;579:3–32*
  - Nossaman et al. History of Right Heart Catheterization: 100 Years of Experimentation and Methodology Development. *Cardiol Rev. 2010 ; 18(2): 94–101*

- Developed by Swan, Ganz etal in 1970

William Ganz and H.J.C. Swan

Central venous catheter

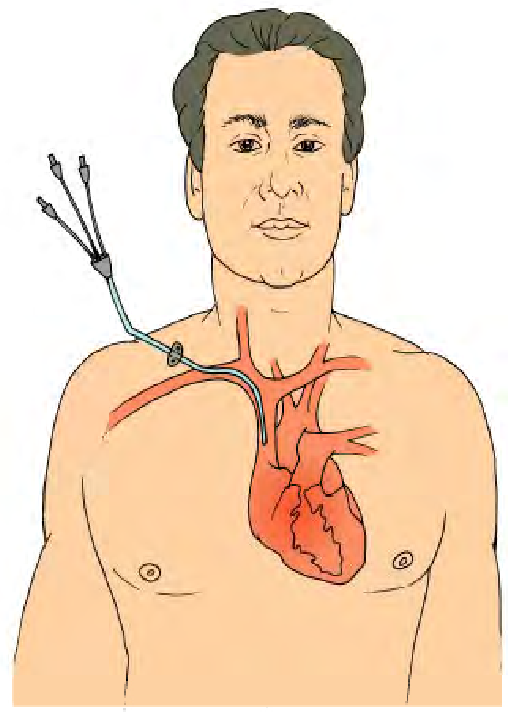
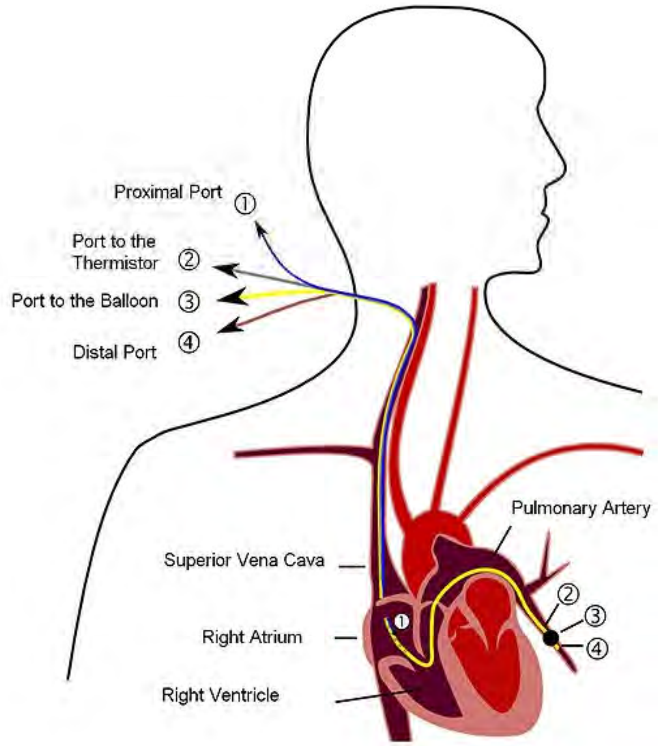


Figure 46-10 Placement of triple-lumen nontunneled percutaneous central venous catheter.

Pulmonary artery catheter



Indications for Pulmonary Artery Catheters (PACs)

- Assessment of shock states
- Assessment of pulmonary edema (cardiogenic vs ARDS)
- Guidance of therapy
- Optimization of cardiac index in cardiogenic shock
- Evaluation and drug titration for severe pulmonary hypertension
- Diagnostic evaluation of left-to-right cardiac shunts

Relative Contraindications of PACs

- Severe coagulopathy or thrombocytenia
- Prosthetic right heart valve
- Endocardial pacemaker/ defibrillator
- Caution with LBBB (5% risk of complete heart block)
- Right-sided Endocarditis
- Uncontrolled ventricular or atrial dysrhythmias
- Right ventricular mural thrombus

Complications of PAC

- Complications from cordis catheter placement
  - Pneumothorax
  - Arterial puncture
  - Air embolus
- Knotting of catheter
- Atrial or ventricular dysrhythmias
- RBBB (0.1- 5% of insertions)
- Pulmonary infarction
- Pulmonary artery rupture (0.2% incidence)
- Catheter-related blood stream infection
- Marantic or infectious endocarditis
- Mural thrombus

Clinical Summary of Recent Large Investigations Comparing management with to without a Pulmonary Artery Catheter (PAC)

Author/Group	Type	Patient Group	Number of Patients Enrolled	Significant Outcome Differences
Sandham et al (Canadian Critical Care Clinical Trials Group)[30]	Prospective, multicenter	Perioperative	1994	More adverse events in PAC group related to insertion
Polanczyk et al[31]	Observational cohort, single center	Perioperative	4059 total, 215 matched pairs	Increased heart failure and noncardiac events in PAC group after propensity adjustment
Harvey et al (PAC-Man)[32]	Prospective, multicenter	General ICU	1041	None
Rhodes et al[33]	Prospective, single center	General ICU	201	Increased renal insufficiency and thrombocytopenia in PAC group
Sakr et al[34]	Observational cohort, multicenter	General ICU	3147 total, 453 matched pairs	None
Yu et al[35]	Observational, prospective	Severe sepsis	1010 total, 141 matched pairs	None
Binanay et al (ESCAPE)[36]	Prospective, multicenter	Decompensated heart failure	433	Increased infections in PAC group
Richard et al[37]	Prospective, multicenter	ARDS	676	None
ARDS Net[40,41]	Prospective, multicenter	ARDS	PAC 501, CVC 480	Increased catheter-related complications and blood transfusions in PAC group

Leibowitz et al. The Pulmonary Artery Catheter in Anesthesia Practice in 2007: An Historical Overview With Emphasis on the Past 6 Years; *Semin Cardiothorac Vasc Anesth 2007 11: 162*

FACTT (Fluid and catheter treatment trial)

The NEW ENGLAND JOURNAL of MEDICINE

ESTABLISHED IN 1812 MAY 25, 2006 VOL. 354 NO. 21

Pulmonary-Artery versus Central Venous Catheter to Guide Treatment of Acute Lung Injury

The National Heart, Lung, and Blood Institute Acute Respiratory Distress Syndrome (ARDS) Clinical Trials Network*

ABSTRACT

BACKGROUND

The balance between the benefits and the risks of pulmonary-artery catheters (PACs) has not been established.

METHODS

We evaluated the relationship of benefits and risks of PACs in 1000 patients with established acute lung injury in a randomized trial comparing hemodynamic management guided by a PAC with hemodynamic management guided by a central venous catheter (CVC) using an explicit management protocol. Mortality during the first 60 days before discharge home was the primary outcome.

RESULTS

The groups had similar baseline characteristics. The rates of death during the first 60 days before discharge home were similar in the PAC and CVC groups (27.4 percent and 26.3 percent, respectively; P=0.69; absolute difference, 1.1 percent; 95 percent confidence interval, −4.4 to 6.6 percent), as were the mean (±SE) numbers of both ventilator-free days (13.2±0.5 and 13.5±0.5; P=0.58) and days not spent in the intensive care unit (12.0±0.4 and 12.5±0.5; P=0.40) to day 28. PAC-guided therapy did not improve these measures for patients in shock at the time of enrollment. There were no significant differences between groups in lung or kidney function, rates of hypotension, ventilator settings, or use of dialysis or vasopressors. Approximately 90 percent of protocol instructions were followed in both groups, with a 1 percent rate of crossover from CVC- to PAC-guided therapy. Fluid balance was similar in the two groups, as was the proportion of instructions given for fluid and diuretics. Dobutamine use was uncommon. The PAC group had approximately twice as many catheter-related complications (predominantly arrhythmias).

CONCLUSIONS

PAC-guided therapy did not improve survival or organ function but was associated with more complications than CVC-guided therapy. These results, when considered with those of previous studies, suggest that the PAC should not be routinely used for the management of acute lung injury. (ClinicalTrials.gov number, NCT00281268.)

The members of the Writing Committee (Arthur P. Wheeler, M.D., and Gordon R. Bernard, M.D., Vanderbilt University, Nashville; B. Taylor Thompson, M.D., and David Schoenfeld, Ph.D., Massachusetts General Hospital, Boston; Herbert P. Wiedemann, M.D., Cleveland Clinic, Cleveland; Ben deBoisblanc, M.D., Louisiana State University Health Sciences Center, New Orleans; Alfred F. Connors, Jr., M.D., Case Western Reserve University at MetroHealth Medical Center, Cleveland; R. Duncan Hite, M.D., Wake Forest University Health Sciences, Winston-Salem, N.C.; and Andrea L. Harabin, Ph.D., National Institutes of Health, Heart, Lung, and Blood Institute, Bethesda, Md.) assume responsibility for the integrity of the article. Address reprint requests to Dr. Wheeler at T-1217 MCN, Vanderbilt Medical Center, Nashville, TN 37232-2650, or at art.wheeler@vanderbilt.edu.

*Participants are listed in the Appendix.

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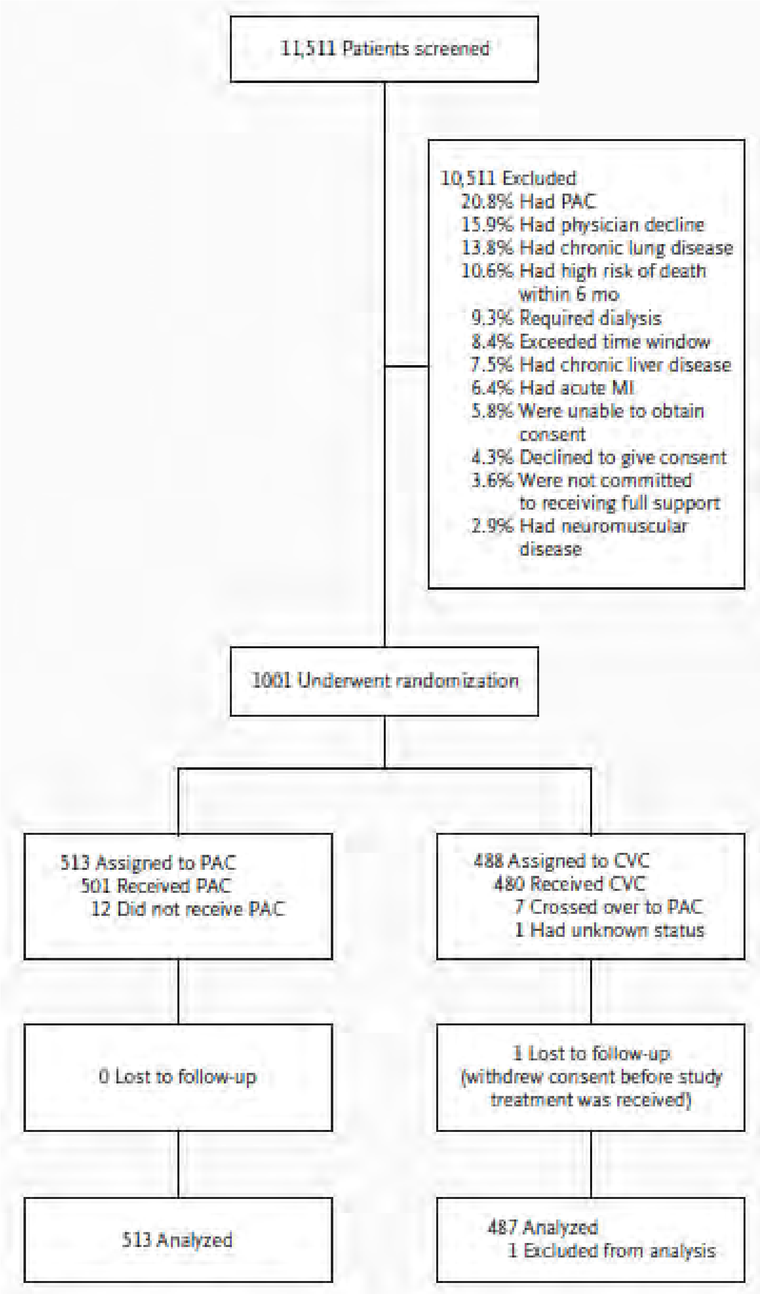
N Engl J Med 2006;354:2213-24.



- Low-tidal volume strategy

- PAC or CVC inserted within 4 hours of randomization
- Protocol management started within the next 2 hours and continued for 7 days or 12 hours of unassisted breathing

- Primary end point → mortality at 60 days
- Secondary end points → length of hospital stay, length of ICU stay and complication rates

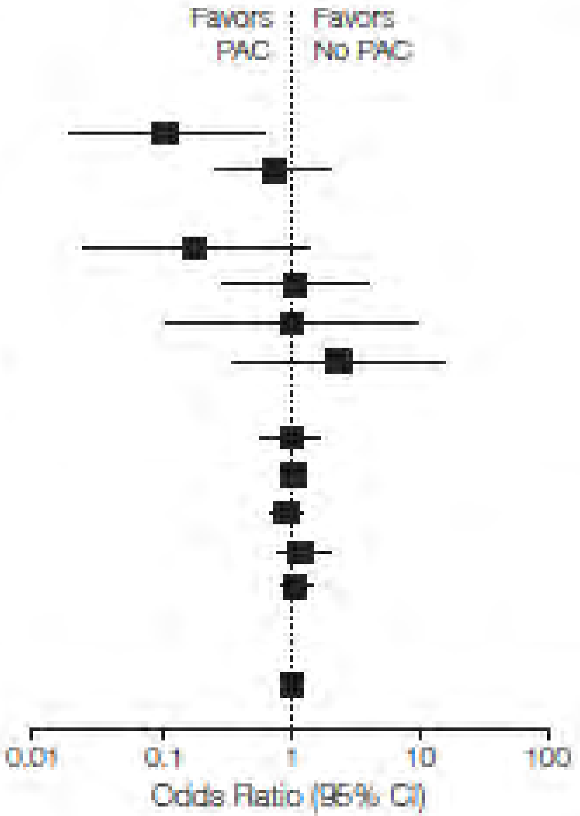
- Primary end point → 27.4 % and 26.3 %; P = 0.69; absolute difference, 1.1 %; 95 % CI, 4.4 to 6.6 %

- Number of ventilator-free days in the first 28 days (13.2±0.5 and 13.5±0.5 respectively; P = 0.58)

- CVC recipients
  - More ICU-free days during the first week of the study (0.88 day, vs. 0.66 day in the PAC group; P = 0.02)
  - Differences were small and not significant at day 28 (12.5±0.5 vs. 12.0±0.4, P = 0.40)

Odds Ratio (PAC vs No PAC) for Mortality of RCTs Evaluating the Safety and Efficacy of the PAC

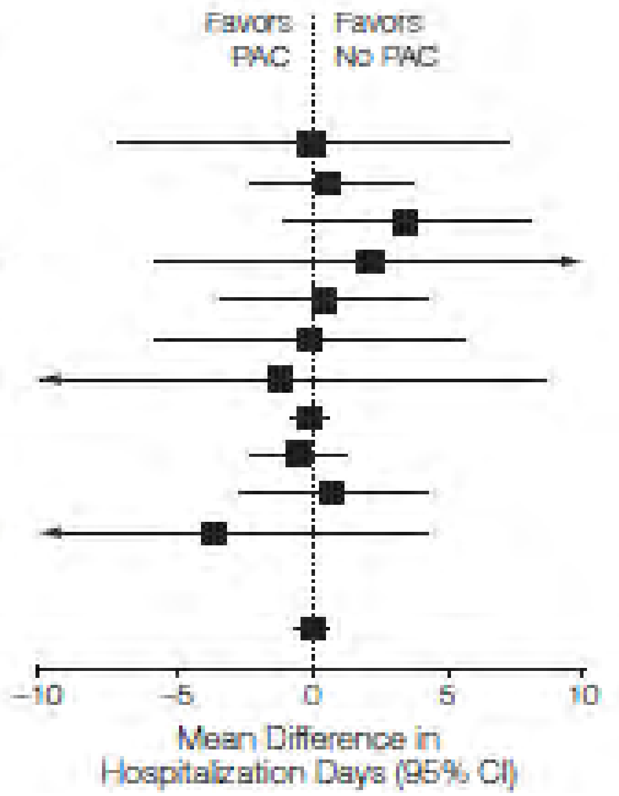
Source	No. of Deaths/Total No. of Patients: PAC	No. of Deaths/Total No. of Patients: No PAC	Odds Ratio (95% CI)
Schultz et al,[15] 1985	1/35	10/35	0.11 (0.02-0.63)
Shoemaker et al,[16] 1988	11/58	7/30	0.76 (0.27-2.15)
Isaacson et al,[17] 1990	1/49	0/53	NA
Berlauk et al,[18] 1991	1/66	2/21	0.18 (0.02-1.42)
Guyatt,[19] 1991	10/16	9/17	1.10 (0.29-4.22)
Bender et al,[20] 1997	1/51	1/53	1.04 (0.11-9.95)
Valentine et al,[21] 1998	3/60	1/60	2.38 (0.35-16.29)
Bonazzi et al,[22] 2002	0/50	0/50	NA
Rhodes et al,[23] 2002	46/95	50/106	1.01 (0.58-1.76)
Sandham et al,[24] 2003	163/997	155/997	1.06 (0.83-1.35)
Richard et al,[25] 2003	199/335	208/343	0.93 (0.68-1.26)
ESCAPE,[10] 2005	45/215	38/218	1.25 (0.78-2.02)
Harvey et al,[14] 2005 (PAC-Man)	346/506	333/507	1.13 (0.87-1.47)
Combined			1.04 (0.90-1.20)



Shah et al. Impact of the Pulmonary Artery Catheter in Critically Ill Patients. Meta-analysis of Randomized Clinical Trials; *JAMA. 2005;294:1664-1670*

Mean Difference in the Average Number of Days Hospitalized in PAC Randomized Controlled Trials (Mean for PAC – Mean for No PAC)

Source	Mean Hospitalization Days (Sample Size): PAC	Mean Hospitalization Days (Sample Size): No PAC	Mean Difference (95% CI)
Shoemaker et al,[15] 1988	22.4 (58)	22.2 (30)	0.15 (−6.98 to 7.28)
Isaacson et al,[17] 1990	10.2 (49)	9.4 (53)	0.80 (−2.20 to 3.80)
Berlauk et al,[18] 1991	18.9 (68)	15.4 (21)	3.51 (−1.05 to 8.07)
Guyatt,[19] 1991	10.3 (16)	8.1 (17)	2.20 (−5.80 to 10.20)
Bender et al,[20] 1997	12.5 (51)	12.0 (53)	0.50 (−3.33 to 4.33)
Valentine et al,[21] 1998	13.0 (60)	13.0 (60)	0.00 (−5.65 to 5.65)
Rhodes et al,[23] 2002	13.0 (95)	14.0 (106)	−1.20 (−11.10 to 8.70)
Sandham et al,[24] 2003	10.0 (997)	10.0 (997)	0.00 (−0.62 to 0.62)
Richard et al,[25] 2003	14.0 (335)	14.4 (341)	−0.40 (−2.13 to 1.33)
ESCAPE,[10] 2005	17.0 (215)	16.1 (218)	0.90 (−2.54 to 4.34)
Harvey et al,[14] 2005 (PAC-Man)	48.9 (304)	52.4 (291)	−3.50 (−11.21 to 4.21)
Combined			0.11 (−0.51 to 0.74)

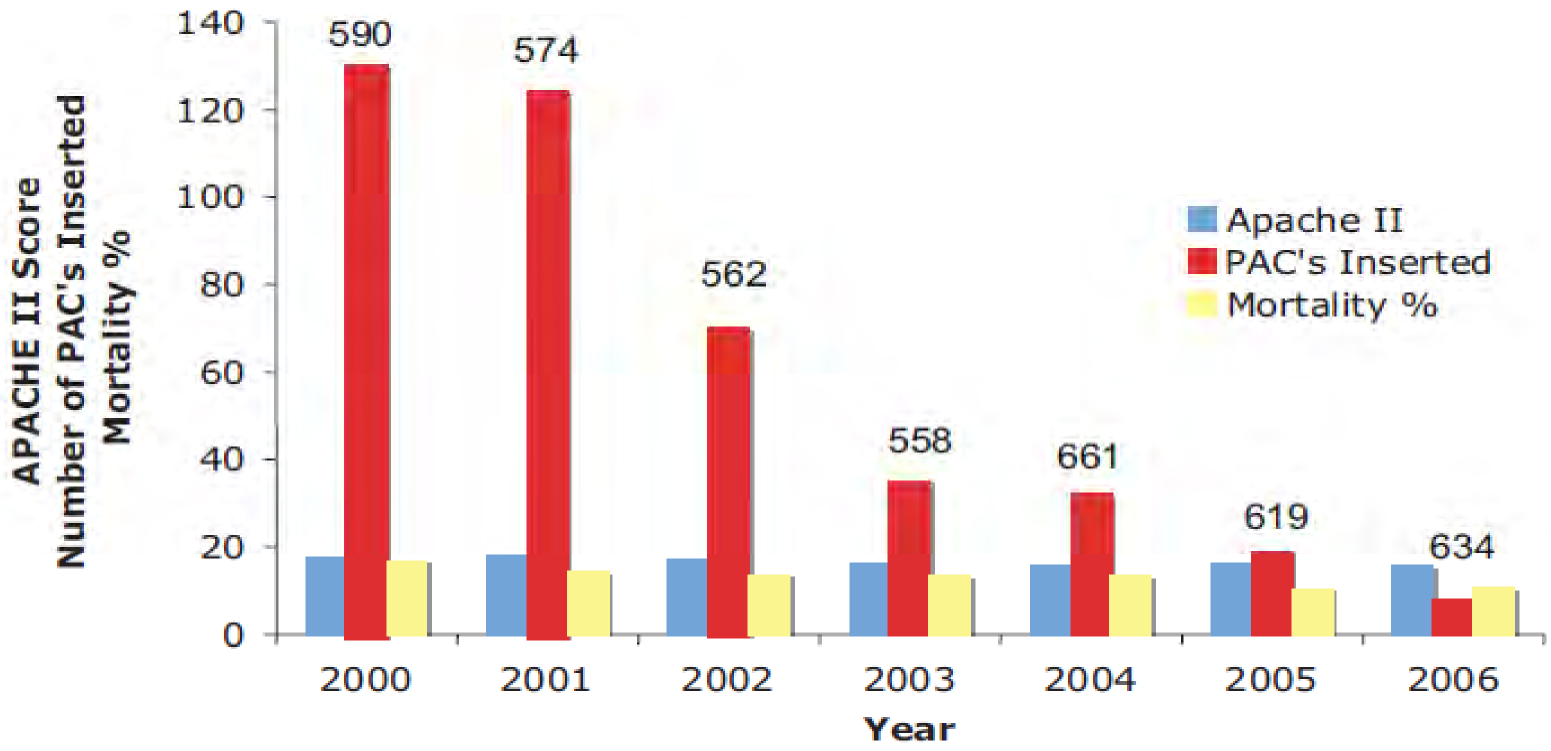


Shah et al. Impact of the Pulmonary Artery Catheter in Critically Ill Patients. Meta-analysis of Randomized Clinical Trials; *JAMA. 2005;294:1664-1670*

- A Cochrane review concluded that “PACs do not appear to confer the survival advantage expected of them, nor do they reduce hospital length of stay or costs of care”

    – Harvey et al. Pulmonary artery catheters for adult patients in intensive care. *Cochrane Database of Systematic Reviews 2006, Issue 3*

Mount Sinai surgical intensive care unit data



Leibowitz et al. The Pulmonary Artery Catheter in Anesthesia Practice in 2007: An Historical Overview With Emphasis on the Past 6 Years; *Semin Cardiothorac Vasc Anesth 2007 11: 162*

Comments

1. Some patient groups are either to sick or too well to benefit

2. Utility of data
   - Pulmonary artery occlusion pressure
   - Thermodilution cardiac output
   - Mixed venous oxygen saturation

3. Difficulty in interpretation
   - Respiratory variation
   - Inter observer variability

4. It is a tool and not a therapy

Current Indications for Use

Not indicated as routine pulmonary artery catheterization in high-risk cardiac and noncardiac patients
Indicated in patients with cardiogenic shock during supportive therapy
Indicated in patients with discordant right and left ventricular failure
Indicated in patients with severe chronic heart failure requiring inotropic, vasopressor, and vasodilator therapy
Indicated in patients with suspected "pseudosepsis" (high cardiac output, low systemic vascular resistance, elevated right atrial and pulmonary capillary wedge pressures)
Indicated in some patients with potentially reversible systolic heart failure such as fulminant myocarditis and peripartum cardiomyopathy
Indicated for the hemodynamic differential diagnosis of pulmonary hypertension
Indicated to assess response to therapy in patients with precapillary and mixed types of pulmonary hypertension
Indicated for the transplantation workup

Chatterjee K. The Swan-Ganz Catheters: Past, Present, and Future: A Viewpoint. *Circulation 2009;119;147-152*

Blood pressure

Noninvasive

1. Mercury sphygmomanometer
2. Oscillatory method
3. Infra sound / Ultrasonic technology
4. Impedance plethysmography
5. Arterial tonometry

Invasive blood pressure

Indications

1. Inability to obtain noninvasive blood-pressure measurements

2. Disease that necessitates close hemodynamic observation

3. Anticipated large hemodynamic changes from operative procedure (eg, cardiac or major vascular surgery)

4. Pharmacologic or mechanical manipulation of the cardiovascular system (eg. deliberate hypotension or intraaortic balloon counterpulsation)

5. Need for multiple arterial blood gas or other laboratory analyses

6. Refractory shock

– Barbeito et al. Arterial and Central Venous Pressure Monitoring. *Anesthesiology Clin 24 (2006) 717–735*
– Antonelli et al. Hemodynamic monitoring in shock and implications for management, International Consensus Conference. *Intensive Care Med (2007) 33:575–590*
– Dellinger et al. Surviving Sepsis Campaign: International guidelines for management of severe sepsis and septic shock: 2008*; Intensive Care Med (2008) 34:17–60*

Materials required

Intravascular catheter

↓

Low-compliance, saline-filled tubing

↓

Electronic transducer

↓

Signals are amplified, displayed, or recorded

- System must be zeroed
- Expose the pressure transducer to the atmosphere through a stopcock
- Set zero on monitor
- Position of transducer → should correspond to fluid level in chamber or vessel in which pressure is to measured
- Site: Radial>femoral>axillary

Normal arterial pressure waveform

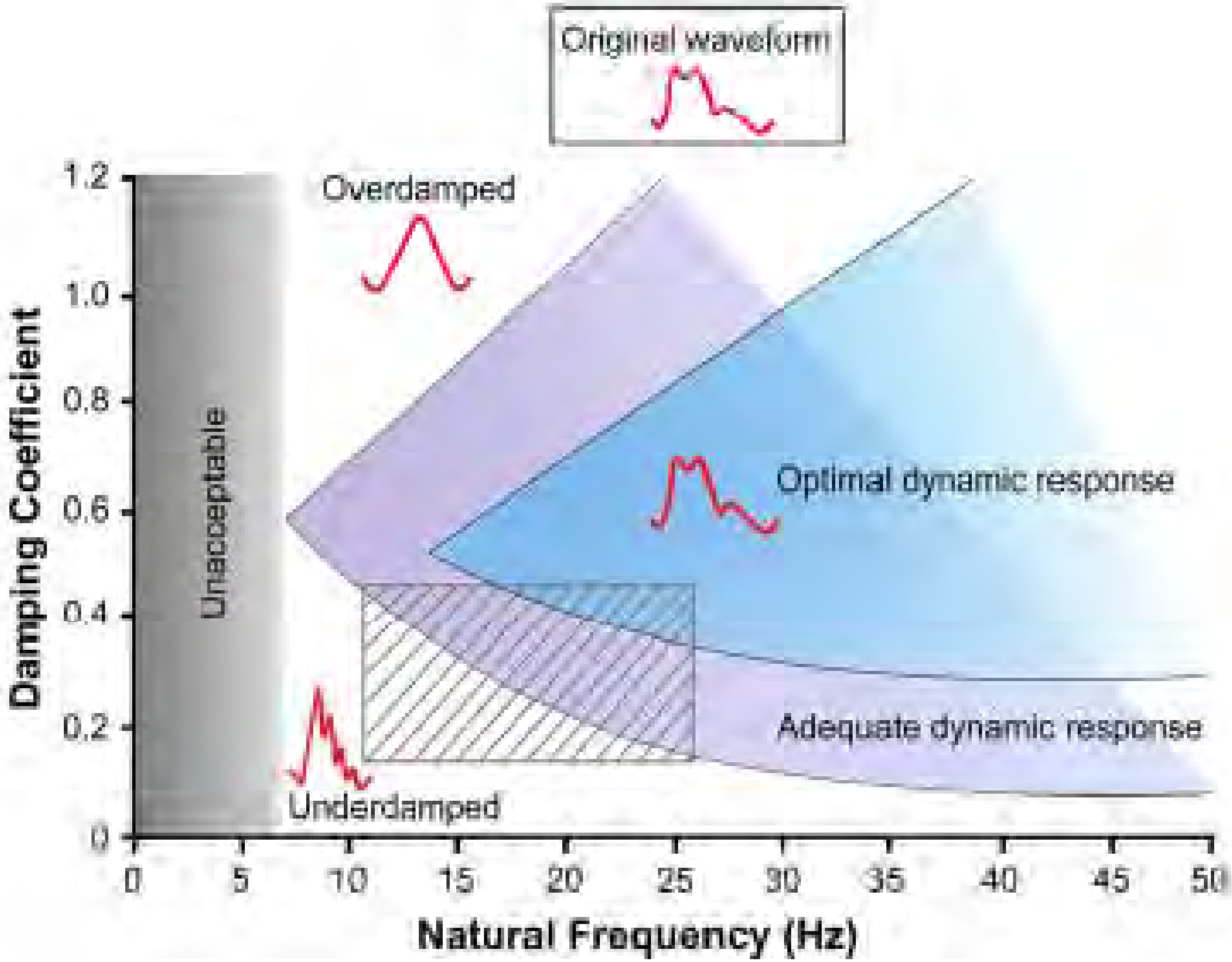
Barbeito et al. Arterial and Central Venous Pressure Monitoring.
Anesthesiology Clin 24 (2006) 717–735

Use

- MAP better than SBP/DBP/PP
- Represents organ perfusion pressure
- No single ‘magic value’ for therapeutic MAP
- MAP ≥ 65mm Hg (Grade 1C)
    - Dellinger et al. Surviving Sepsis Campaign: International guidelines for management of severe sepsis and septic shock: 2008*; Intensive Care Med (2008) 34:17–60*

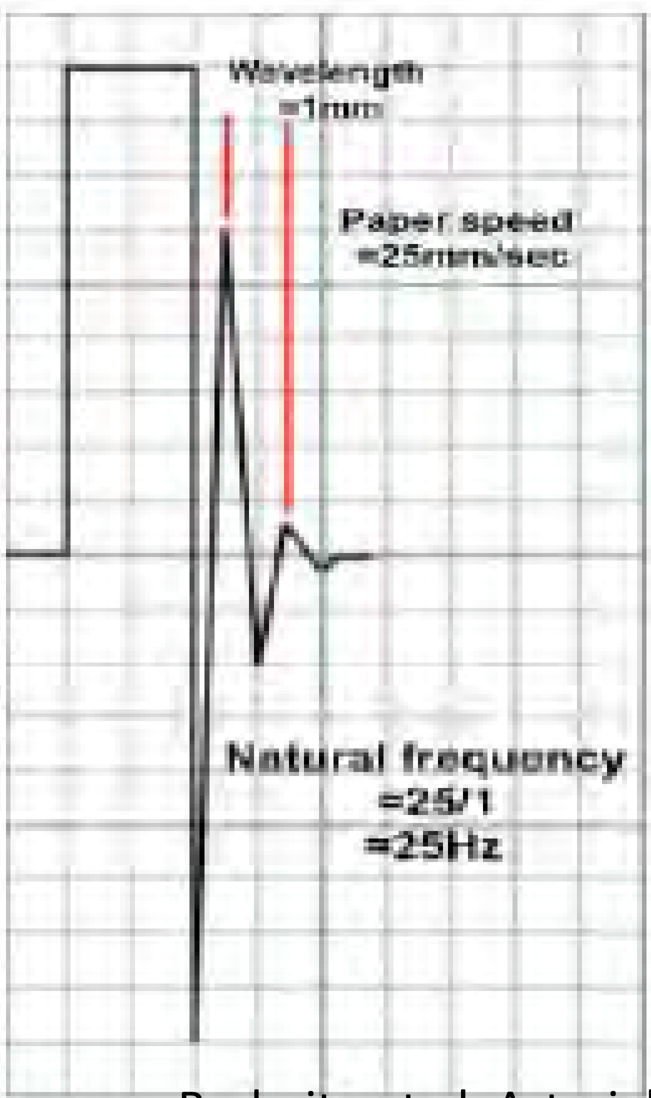
Influence of natural frequency and damping coefficient on the dynamic response of pressure monitoring systems

- –Natural frequency
- –Pressure overshoot/ resonance
- –Damping

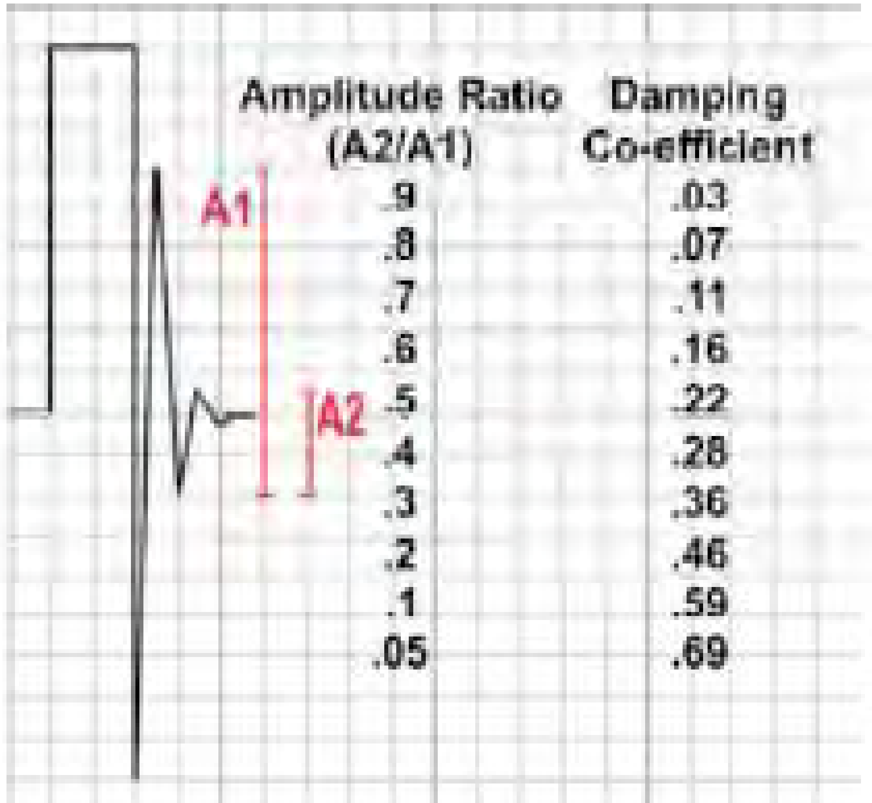


Barbeito et al. Arterial and Central Venous Pressure Monitoring. *Anesthesiology Clin 24 (2006) 717–735*

Using the fast flush test to measure natural frequency



Using the fast flush to calculate damping co-efficient



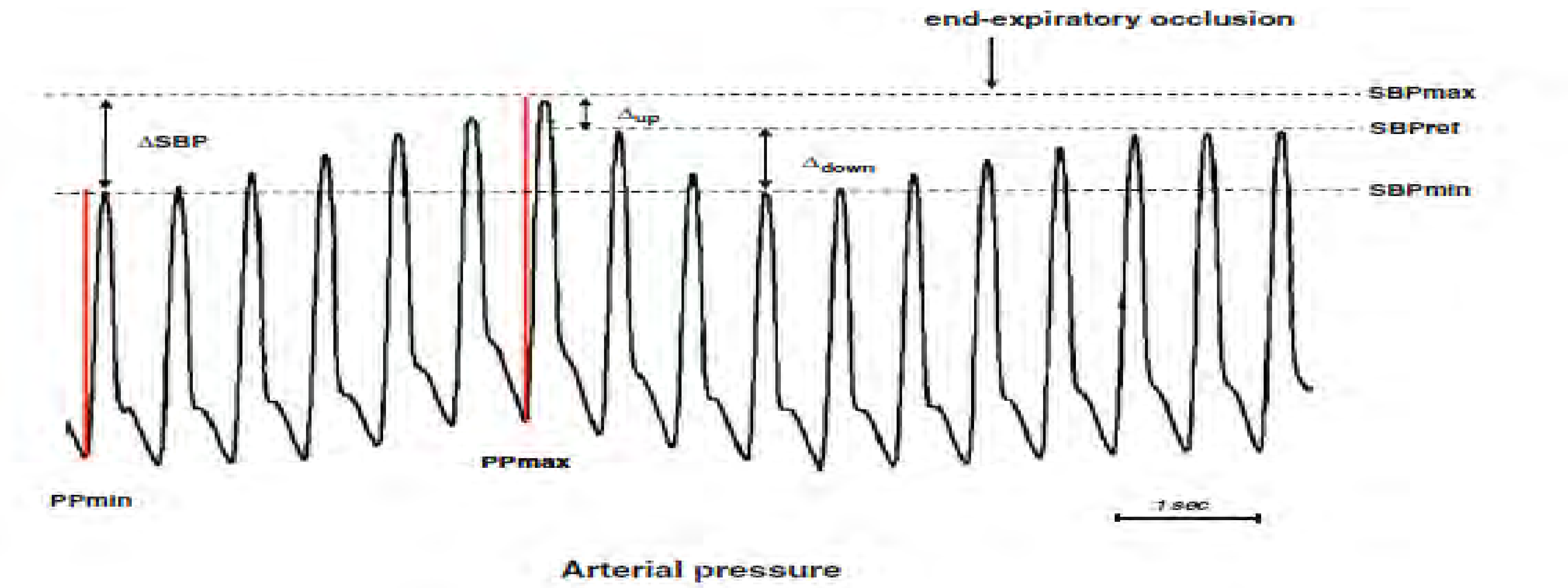
Barbeito et al. Arterial and Central Venous Pressure Monitoring.
Anesthesiology Clin 24 (2006) 717–735

Respiratory variations

- In positive pressure mechanical ventilation
- Mechanism
  - Onset of inspiration
    - Decreased right ventricular (RV) preload and increased RV afterload → decreased RV stroke volume (SV)
    - Increased left ventricluar (LV) preload and decreased LV afterload → increased LV stroke volume
    - Increased systolic BP
  - Late inspiration or early expiration
    - Reduced RV stroke volume → reduced LV preload → decreased LV stroke volume and systolic BP
  - Known as systolic pressure variation (SPV) or ΔSBP

- ΔSBP ≥ 10 mmHg and Δdown ≥ 5 mmHg → predictors of an SV increase of 15% in response to fluid administration

- Influenced by ventilatory parameters, arrhythmias, changes in chest wall and lung compliance, PEEP



Augusto et al. Interpretation of blood pressure signal: physiological bases, clinical relevance, and objectives during shock states; *Intensive Care Med (2011) 37:411–419*

- ΔPP ≥ 13% → predictor of volume responsiveness
- Higher the ΔPP was at baseline, the greater the increase in CO in response to fluid infusion
- Decrease in ΔPP associated with fluid infusion was correlated with the increase in CO
    - Michard et al: Relation between respiratory changes in arterial pulse pressure and fluid responsiveness in septic patients with acute circulatory failure. *Am J Respir Crit Care Med 2000, 162:134-138*

- Stroke volume variation (SVV)
    - maximal to minimal stroke volume values over three breaths or a defined time interval (eg. 20 – 30s)
    - ≥10% predicts a 15% increase in cardiac output
    - Measured by either esophageal or transthoracic Doppler echocardiography or by pulse contour analysis

Complications

	Cases	Air embolism (%)	Permanent occlusion (%)	Temporary occlusion (%)	Haematoma (%)	Bleeding (%)	Sepsis (%)	Abscess (%)
Kapelakis et al	450	0	0	18.4	–	8.7	0	–
Puri et al	59	0	1.7	6.8	5.1	1.7	0	–
Gronbeck et al	506	0.2	0	–	–	0	0	–
Frezza et al	1556	0	0	3.4	0.2	1.5	0.06	0.3
Frezza at al	565	0	0	4.6	0.3	2.3	0	0.5

Scheer et al. *Critical Care June 2002 Vol 6 No 3*

- Most frequent complication → equipment misuse and misinterpretation
- Major complications → 0.1 – 1%

- Incidence of blood stream infections from arterial lines was 1.7/1,000 device days compared with 0.5 for peripheral venous catheters and 2.7 (for untunnelled CVC)

- Current position of arterial monitoring
  - Analogous to that of PAC in 1990s
  - No randomized trial available for impact on mortality
  - Need for well designed trials

Cardiac output

Means of measuring cardiac output include

Invasive

1. Pulmonary artery catheter (PAC)
2. Transpulmonary thermodilution (TD)
   1. PiCCO monitor
   2. Lithium dilution—LiDCO
3. Pulse contour analysis
   - calibrated
     - PiCCO
     - PulseCO system [LiDCO Ltd]
   - noncalibrated (Flo-trac Vigleo system)
4. Mixed and central venous saturation

Pulmonary artery catheter

1. *Fick method*

$$CO = \frac{VO_2}{C_a - C_v}$$

2. *Thermodilution method*
   - modified Stewart-Hamilton equation

$$Q = \frac{VI \times (TB - TI) \times SI \times CI \times 60 \times CT}{SB \times CB \times \int_0^\infty \Delta TB(t)dt}$$

- Serial measurements
- Average of three if they differ by <10%
- Change in cardiac output >10% is considered significant

3. *Continuous cardiac output measurement*
   - Thermal filament produces signals in a binary mode
   - Resulting changes in blood temprature measured
   - Thermodilution curve calculated

4. *Fast response CCO catheter*
   - truCCOMS; Omega Critical Care,UK
   - Continuously calculates the energy used by a heating filament to maintain a specified blood temperature gradient between two thermistors →instantaneous CCO monitoring

Transpulmonary thermodilution

- PiCCO monitor
- Requires central venous access and a specialized femoral or axillary arterial catheter with a thermistor at its tip
- Pulsion Medical Systems, Germany

- Method:
  - Injection of known volume of thermal indicator (ice cold saline) into central line
  - Fluid sensed by thermistor in arterial line after passing through the heart
  - Calculation of thermodilution curve
  - Calculation of CO using modified Stewart – Hamilton equation

- Less invasive
- More consistent and are not influenced by respiratory cycle
- The validity of the technique has been demonstrated in patients undergoing cardiac surgery and critically ill patients
- Can measure extravascular lung water in patients with pulmonary oedema
- Requires 8 hourly recalibration

- Inaccurate measurements in patients with intracardiac shunt, aortic stenosis, aortic aneurysm, and extra corporeal circulation

- Complications
  - Catheter-related → infection (<0.3%) thrombosis, bleeding, and vascular injury resulting in limb ischemia or pseudoaneurysm
  - All combined approximately 3%

Lithium dilution (LiDCO) [LiDCO Ltd, UK]

- Small amounts of intravenous lithium

- Can be injected through central or peripheral venous line

- Picked up by a lithium ion sensitive electrode attached to a standard radial arterial catheter

- Dye dissipation curve

- Modified Stewart-Hamilton

equation

- Dose is 0.15 to 0.30 mmol for an average adult

- Accuracy affected
  - High doses of neuromuscular blocking agents
  - Severe peripheral vascular disease
  - Aortic valve disease
  - Intra aortic balloon counter pulsation therapy
  - Severe hyponatremia

- Contraindicated in patients on Lithium therapy

Flo-trac Vigleo System (Edwards Lifesciences, USA)

- Works on the principle that the pulse pressure is proportional to SV and inversely proportional to aortic compliance

- Calculates CO by using arterial pressure waveform characteristics in conjunction with patient demographic data

- Does not require external calibration

	PiCCO	LiDCO	FloTrac/Vigileo
Method of analysis	Area under the curve	Pulse power	Arterial waveform
Calibration	Transpulmonary thermodilution	Transpulmonary lithium dilution	Internal
(Re)calibration	Manual	Manual	Automatically
Indicator	Saline/glucose	Lithium solution	None
Central venous access necessary	Yes	No	No
Recalibration intervals Hemodynamically stable/unstable	24 h/1 h	8 h/hemodynamic changes	60 s
Arterial access	Major artery	Peripheral/major artery	Peripheral/major artery
	• Calibrations provide additional parameters	• Maximum daily dose of lithium limits calibrations; • Interacts with muscle relaxants	• Easy to set up; • Quickly established

Mayer et al. Cardiac output derived from arterial pressure waveform;
Current Opinion in Anaesthesiology 2009, 22:804–808

Mixed Venous Oxygen Saturation

- The oxygen saturation of hemoglogin in mixed venous blood
- Normal = 70%
- Depends upon the oxygen extraction in the tissues
- Can be used as a surrogate marker for cardiac output
- Central venous blood saturation

Noninvasive

1. Thoracic bioimpedence
2. Electrical bioreactance cardiography
3. Esophageal Doppler
4. Transgastric Doppler
5. Ultrasonic cardiac output monitor
6. Echocardiography and carbon dioxide rebreathing method (non-invasive continuous cardiac output)

Thoracic bioimpedence (TEB)

- First described by Kubicek to measure cardiac output in astronauts
  - Kubicek et al. Development and evaluation of an impedence cardiac output system. *Aerosp Med 1966;37(12):1208–12*
- Parameters measured
  - CO
  - SV
  - Contractility
  - Systemic vascular resistance
  - Thoracic fluid content and filling index

Current is transmitted through the chest

↓

Seeks path of least resistance (Aorta)

↓

Baseline impedance measured

↓

Blood volume and velocity change with each heartbeat

↓

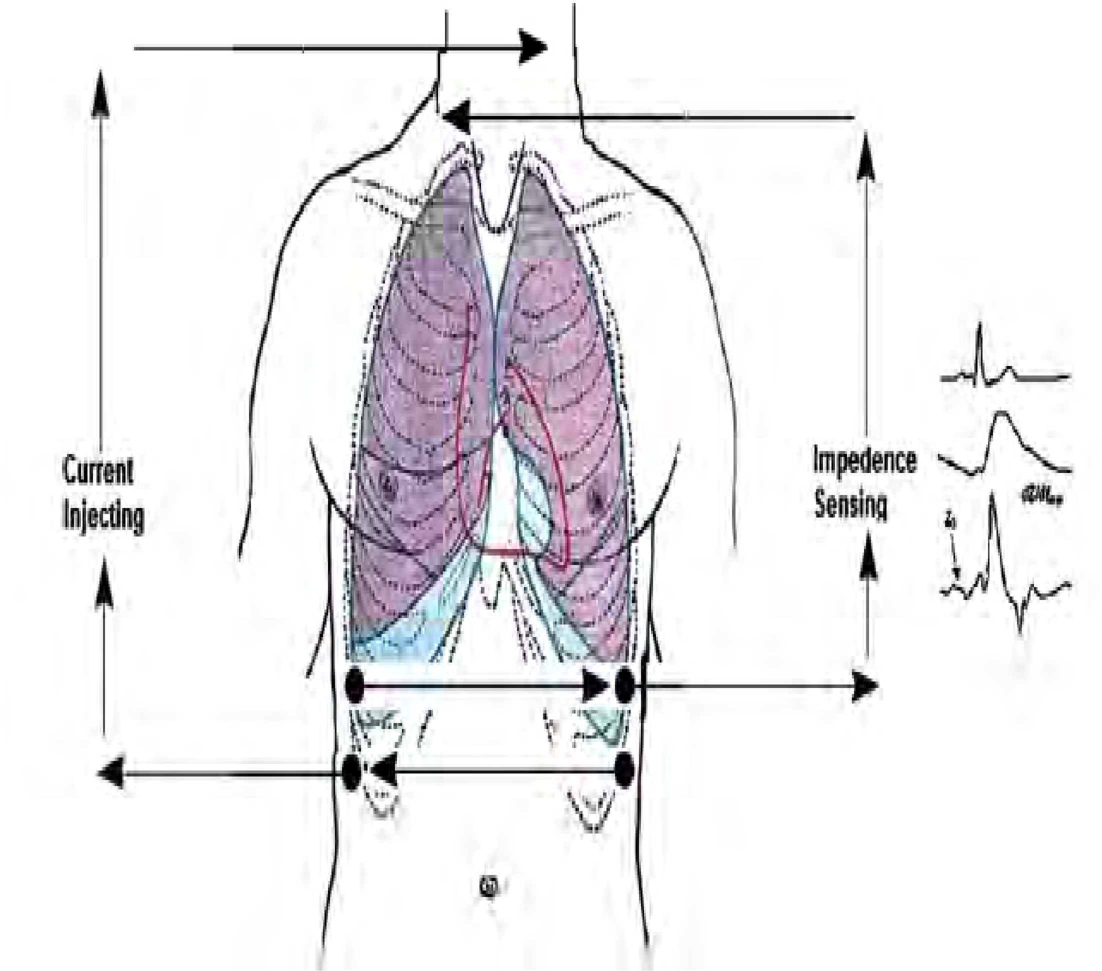
Corresponding change in impedance measured

↓

Change in impedance due to the volumetric expansion

↓

Hemodynamic parameters calculated accordingly



Mohammed et al. Techniques for Determining Cardiac Output in the Intensive Care Unit; *Crit Care Clin 26 (2010) 355–364*

- Factors affecting measurement
  - Height
  - Weight
  - Sex
  - Circumference Of Chest
  - Hemoglobin

- Confounders
  - PEEP
  - Chest wall edema
  - Obesity
  - Pleural fluid
  - Severe pulmonary edema

- Not recommended for routine use because of conflicting results
    - Hofer et al. What technique should I use to measure cardiac output?; *Current Opinion in Critical Care 2007, 13:308–317*

Electrical Bioreactance Cardiography

- Similar to impedance cardiography except that it is based on changes in frequency
- Less susceptible to interference from chest wall movement, chest wall and lung edema, and pleural fluid
- Not as affected by the distance of electrode placement, so the electrodes can be placed anywhere on the chest
- Good correlation with TD in several studies in critically ill patients
    - Mohammed et al. Techniques for Determining Cardiac Output in the Intensive Care Unit*; Crit Care Clin 26 (2010) 355–364*

Partial carbon dioxide rebreathing

- NICO system (Novametrix Medical Systems, USA)

- Uses Fick’s principle applied to carbon dioxide

- Good CO determination in intubated mechanically ventilated patients with minor lung abnormalities and fixed ventilatory settings

- Variations in ventilatory modalities, mechanically assisted spontaneous breathing or presence of significant pulmonary pathology → inaccurate readings

Pulsed dye densitometry

- Transpulmonary thermodilution technique
- Intravenous injection of dye (indocyanin green)
- Concentration estimation in the arterial blood flow by optical absorbance measurements
- CO calculated by Stewart-Hamilton equation

Esophageal Doppler Technique

- Measures blood flow velocity in descending aorta by a Doppler placed on the tip of an esophageal probe
- Operator-dependent and requires specialized training
- Good correlation to thermodilution

Gastric Doppler technique

- Similar technique to esophageal Doppler
- Probe is positioned in the stomach instead of esophagus
- A thinner silicone probe (6 mm) is used
  - Can be more difficult to position
  - requires frequent repositioning
- Acceptable correlation to thermodilution

USCOM

- Ultrasonic cardiac output monitor
- A noninvasive device that determines cardiac output by continuous-wave Doppler ultrasound

- Flow profile is obtained using a transducer (2.0 or 3.3 MHz) placed on the chest
  - either the left parasternal position to measure transpulmonary blood flow
  - or the suprasternal position to measure transaortic blood flow

- This flow profile is presented as a time–velocity spectral display showing variations of blood flow velocity with time

- Not validated at present

Specific features of different cardiac output (CO) monitoring techniques

	CO determination		Invasive-ness	Major limitations	Situations of limited accuracy	Additional information
	Intermittent	'Continuous'				
PAC	+	+ (reaction time 5 – 12 min; TrUCCOMs 10 s)	+++	well described complications	large temperature shifts intra- and extra-cardiac shunt valve pathologies	PAP, PCWP, SvO_2 SVR, PVR
Pulse wave analysis						
PiCCO	+	+ (every 3 s)	+(+)	specific arterial (femoral) catheter	low arterial signal quality[a]	GEDV, EVLW, SVV
PulseCO	+	+	+	lithium injection	rapid changes of vascular tone[a]	SVV
FloTrac/Vigileo		+ (every 20 s)	(+)		arrhythmias[a] use of IABP[a]	SVV
TEE	(+)	–	+	operator dependency		diagnostic assessment
TE Doppler	+	(+)	+	used preferably in intubated patients blood volume of descending aorta measured		flow measurement operator dependency
Partial CO_2 rebreathing	–	+ (cycle of 3 min)	–	used in intubated patients only fixed ventilatory settings needed	pulmonary pathologies	ventilatory data shunt calculation
Pulsed dye dilution	+	–	+	peripheral transcutaneous signal detection allergy to indocyanin green		liver function assessment
Bioimpedance	–	+	–	movement artifacts electrical interference	large fluid shifts intra- and extra-cardiac shunt aortic dilatation	

Hofer et al. What technique should I use to measure cardiac output?;
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