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
  – Pathophysiologival basis
  – Monitoring driven treatment protocols
Hemodynamic parameters

Pinsky MR. Hemodynamic Evaluation and Monitoring in the ICU; CHEST 2007; 132:2020–2029
Right heart catheterization
History

• First heart catheterisation 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

• Developed by Swan, Ganz et al. in 1970
Central venous catheter

Pulmonary artery catheter

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

<table>
<thead>
<tr>
<th>Author/Group</th>
<th>Type</th>
<th>Patient Group</th>
<th>Number of Patients Enrolled</th>
<th>Significant Outcome Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandham et al (Canadian Critical Care Clinical Trials Group)(^{30})</td>
<td>Prospective, multicenter</td>
<td>Perioperative</td>
<td>1994</td>
<td>More adverse events in PAC group related to insertion</td>
</tr>
<tr>
<td>Polanczyk et al(^{11})</td>
<td>Observational cohort, single center</td>
<td>Perioperative</td>
<td>4059 total, 215 matched pairs</td>
<td>Increased heart failure and noncardiac events in PAC group after propensity adjustment</td>
</tr>
<tr>
<td>Harvey et al (PAC-Man)(^{32})</td>
<td>Prospective, multicenter</td>
<td>General ICU</td>
<td>1041</td>
<td>None</td>
</tr>
<tr>
<td>Rhodes et al(^{33})</td>
<td>Prospective, single center</td>
<td>General ICU</td>
<td>201</td>
<td>Increased renal insufficiency and thrombocytopenia in PAC group</td>
</tr>
<tr>
<td>Sakr et al(^{34})</td>
<td>Observational cohort, multicenter</td>
<td>General ICU</td>
<td>3147 total, 453 matched pairs</td>
<td>None</td>
</tr>
<tr>
<td>Yu et al(^{35})</td>
<td>Observational, prospective</td>
<td>Severe sepsis</td>
<td>1010 total, 141 matched pairs</td>
<td>None</td>
</tr>
<tr>
<td>Binanay et al (ESCAPE)(^{36})</td>
<td>Prospective, multicenter</td>
<td>Decompensated heart failure</td>
<td>433</td>
<td>Increased infections in PAC group</td>
</tr>
<tr>
<td>Richard et al(^{37})</td>
<td>Prospective, multicenter</td>
<td>ARDS</td>
<td>676</td>
<td>None</td>
</tr>
<tr>
<td>ARDS Net(^{40,41})</td>
<td>Prospective, multicenter</td>
<td>ARDS</td>
<td>PAC 501, CVC 480</td>
<td>Increased catheter-related complications and blood transfusions in PAC group</td>
</tr>
</tbody>
</table>

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

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 (±SD) numbers of both ventilator-free days (13.2±6.5 and 13.5±6.5; P=0.58) and days not spent in the intensive care unit (12.0±6.4 and 12.5±6.5; 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.
- 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

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Lancet PAC (Sample Size)</th>
<th>Lancet No PAC (Sample Size)</th>
<th>Mean Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoemaker et al, 1988</td>
<td>22.4 (58)</td>
<td>22.2 (30)</td>
<td>0.15 (-6.96 to 7.28)</td>
</tr>
<tr>
<td>Isaacson et al, 1980</td>
<td>10.2 (49)</td>
<td>9.4 (53)</td>
<td>0.80 (-2.20 to 3.80)</td>
</tr>
<tr>
<td>Bertaug et al, 1991</td>
<td>18.9 (66)</td>
<td>15.4 (21)</td>
<td>3.51 (-1.05 to 8.07)</td>
</tr>
<tr>
<td>Guyatt, 1991</td>
<td>10.3 (18)</td>
<td>8.1 (17)</td>
<td>2.20 (-6.80 to 10.20)</td>
</tr>
<tr>
<td>Bender et al, 1997</td>
<td>12.5 (66)</td>
<td>12.0 (53)</td>
<td>0.50 (-3.33 to 4.33)</td>
</tr>
<tr>
<td>Valentine et al, 1988</td>
<td>13.0 (60)</td>
<td>13.0 (60)</td>
<td>0.00 (-5.65 to 5.65)</td>
</tr>
<tr>
<td>Rhodes et al, 2002</td>
<td>13.0 (95)</td>
<td>14.0 (105)</td>
<td>-1.20 (-11.10 to 8.70)</td>
</tr>
<tr>
<td>Sandham et al, 2003</td>
<td>10.0 (997)</td>
<td>10.0 (997)</td>
<td>0.00 (-0.62 to 0.62)</td>
</tr>
<tr>
<td>Richard et al, 2003</td>
<td>14.0 (335)</td>
<td>14.4 (341)</td>
<td>-0.40 (-2.13 to 1.33)</td>
</tr>
<tr>
<td>ESCAPE, 2005</td>
<td>17.0 (215)</td>
<td>18.1 (218)</td>
<td>-3.50 (-11.21 to 4.21)</td>
</tr>
<tr>
<td>Harvey et al, 2005</td>
<td>48.9 (304)</td>
<td>52.4 (291)</td>
<td>0.11 (-0.51 to 0.74)</td>
</tr>
</tbody>
</table>

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 too 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

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 (e.g., cardiac or major vascular surgery)
4. Pharmacologic or mechanical manipulation of the cardiovascular system (e.g. deliberate hypotension or intraaortic balloon counterpulsation)

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

6. Refractory shock
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 be measured

• Site: Radial>femoral>axillary
Normal arterial pressure waveform

Use

- MAP better than SBP/DBP/PP

- Represents organ perfusion pressure

- No single ‘magic value’ for therapeutic MAP

- MAP $\geq$ 65mm Hg (Grade 1C)
  
Influence of natural frequency and damping coefficient on the dynamic response of pressure monitoring systems

- Natural frequency
- Pressure overshoot/resonance
- Damping

Using the fast flush test to measure natural frequency

Using the fast flush to calculate damping co-efficient

Respiratory variations

• In positive pressure mechanical ventilation

• Mechanism
  – Onset of inspiration
    • Decreased right ventricular (RV) preload and increased RV afterload $\rightarrow$ decreased RV stroke volume (SV)
    • Increased left ventricular (LV) preload and decreased LV afterload $\rightarrow$ increased LV stroke volume
    • Increased systolic BP
  – Late inspiration or early expiration
    • Reduced RV stroke volume $\rightarrow$ reduced LV preload $\rightarrow$ decreased LV stroke volume and systolic BP
  – Known as systolic pressure variation (SPV) or $\Delta$SBP
• 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

• 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

• 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

Kapelakis et al
Puri et al
Gronbeck et al
Frezza et al
Frezza at al

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

<table>
<thead>
<tr>
<th>Method of analysis</th>
<th>PICCO</th>
<th>LiDCO</th>
<th>FloTrac/Vigileo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>Transpulmonary thermodilution</td>
<td>Transpulmonary lithium dilution</td>
<td>Internal</td>
</tr>
<tr>
<td>(Re)calibration</td>
<td>Manual</td>
<td>Manual</td>
<td>Automatically</td>
</tr>
<tr>
<td>Indicator</td>
<td>Saline/glucose</td>
<td>Lithium solution</td>
<td>None</td>
</tr>
<tr>
<td>Central venous access necessary</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Recalibration intervals</td>
<td>24 h/1 h</td>
<td>8 h/hemodynamic changes</td>
<td>60 s</td>
</tr>
<tr>
<td>Hemodynamically stable/unstable</td>
<td>Major artery</td>
<td>Peripheral/major artery</td>
<td>Peripheral/major artery</td>
</tr>
<tr>
<td>Arterial access</td>
<td>Major artery</td>
<td>Peripheral/major artery</td>
<td>Peripheral/major artery</td>
</tr>
</tbody>
</table>

- Calibrations provide additional parameters
- Maximum daily dose of lithium limits calibrations; Interacts with muscle relaxants
- Easy to set up; Quickly established
Mixed Venous Oxygen Saturation

• The oxygen saturation of hemoglobin 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

• 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

• 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
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

<table>
<thead>
<tr>
<th>CO determination</th>
<th>Intermittent</th>
<th>‘Continuous’</th>
<th>Invasiveness</th>
<th>Major limitations</th>
<th>Situations of limited accuracy</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAC</td>
<td>+</td>
<td>+ (reaction time 5–12 min; TrUCCOMs 10 s)</td>
<td>+++</td>
<td>well described complications</td>
<td>large temperature shifts</td>
<td>PAP, PCWP, SvO₂</td>
</tr>
<tr>
<td>Pulse wave analysis &amp; PiCCO</td>
<td>+</td>
<td>+ (every 3 s)</td>
<td>+ (</td>
<td>specific arterial (femoral) catheter lithium injection</td>
<td>intra- and extracardiac shunt valve pathologies low arterial signal quality</td>
<td>GEDV, EVLW, SVV, SV Sw</td>
</tr>
<tr>
<td>PulseCO</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>rapid changes of vascular tone</td>
<td>Sw</td>
</tr>
<tr>
<td>FloTrac/Vigileo</td>
<td>+ (every 20 s)</td>
<td>+ (</td>
<td>(+)</td>
<td></td>
<td>arrhythmias³ use of IABP²</td>
<td>Sw</td>
</tr>
<tr>
<td>TEE</td>
<td>(</td>
<td>–</td>
<td>+</td>
<td>operator dependency</td>
<td></td>
<td>diagnostic assessment flow measurement</td>
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<tr>
<td>TE Doppler</td>
<td>+</td>
<td>(</td>
<td>+</td>
<td>used preferably in intubated patients blood volume of descending aorta measured</td>
<td>pulmonary pathologies</td>
<td>operator dependency</td>
</tr>
<tr>
<td>Partial CO₂ rebreathing</td>
<td>–</td>
<td>+ (cycle of 3 min)</td>
<td>–</td>
<td>used in intubated patients only fixed ventilatory settings needed peripheral transcatheter signal detection allergy to indocyanin green</td>
<td>pulmonary pathologies</td>
<td>ventilatory data shunt calculation</td>
</tr>
<tr>
<td>Pulsed dye dilution</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>peripheral transcatheter signal detection allergy to indocyanin green</td>
<td>large fluid shifts intra- and extracardiac shunt aortic dilatation</td>
<td>liver function assessment</td>
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<tr>
<td>Bioimpedance</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>movement artifacts electrical interference</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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