HEMODYNAMIC MONITORING: WHAT’S NEW?

Michael L. Cheatham, MD, FACS, FCCM
Director, Surgical Intensive Care Units
Orlando Regional Medical Center

OBJECTIVES

• To discuss the need for hemodynamic monitoring in the critically ill patient
• To review the various techniques currently available for assessing hemodynamic function in the ICU
• To describe the relative merits and limitations of the various monitoring techniques

DISCLAIMERS

• I have no financial relationship with any company that produces hemodynamic monitoring equipment
• I will not be mentioning companies or products by name, but rather speaking about generic technologies
• Chances are that I will either not speak about your favorite technology or will have negative comments about it
• We are comparing technologies and their application in monitoring the sickest patients in our ICUs

WHY DO WE MONITOR?

• Preload, contractility, afterload, and oxygen transport are commonly abnormal in the critically ill
• Inadequate resuscitation and failure to restore cellular oxygen delivery and organ perfusion results in multiple system organ failure (MSOF) and death
• Optimization of cardiopulmonary function during critical illness reduces organ failure and improves survival
• Accurate assessment of hemodynamic function and goal-directed resuscitation is essential to improving patient outcome

CURRENT MONITORING TECHNOLOGIES

Invasive Monitoring Techniques
• Bolus thermodilution PAC
• Continuous thermodilution PAC
• Central venous oxygen saturation (ScvO₂)
• Arterial Pulse Contour Analysis

Noninvasive Monitoring Techniques
• Ultrasound
• Thoracic Electrical Bioimpedance
• Partial Carbon Dioxide Rebreathing

PULMONARY ARTERY CATHETER (PAC)

• Originally described by Swan & Ganz (1972)
• The “gold standard” for the next two decades
• Allows assessment of
  • Preload
    • Pulmonary artery occlusion pressure (PAOP)
  • Contractility
    • Cardiac output (CO)
  • Afterload
    • Systemic vascular resistance (SVR)
Hemodynamic Monitoring: Today’s Tools in the ICU – M. L. Cheatham, MD, FACS, FCCM

INTERMITTENT THERMODILUTION

- CO is determined by measuring a “thermodilution curve” following injection of iced saline
- Accuracy is dependent upon multiple factors:
  - Respiratory cycle
  - Injection technique
  - Regular heart rate
  - Proper catheter positioning
  - Transducer calibration
  - Accurate waveform interpretation
  - i.e., knowledgeable physician and nurse

THE LIMITATIONS OF THE PAC

- Requires an invasive right heart catheter
  - Risks of pneumothorax, hemothorax, arrhythmia, infection
- Use is based upon several assumptions:
  - Intermittent measurements reflect a patient’s continuously changing hemodynamic state
  - PAOP & CVP accurately reflect end-diastolic volume
  - Ventricular compliance is unchanged

THE PAOP ASSUMPTION

Preload = LVEDV = LVEDP = LAP = PAOP

PAOP is accurate ONLY when these potential sources of error have been minimized

Are intrathoracic or intra-abdominal pressures elevated?

IS THE PAC FLAWED OR ARE WE?

- The PAC has been subjected to greater scrutiny than any other monitoring technique
- Various studies have demonstrated that...
  - 47% of physicians cannot derive basic hemodynamic information from a PAC
  - 33% cannot identify a PAOP tracing
  - 33% cannot describe how to increase a patient’s oxygen delivery
- Does it surprise anyone that prospective trials have failed to demonstrate a survival benefit with the use of this device?

BEFORE WE THROW OUT THE PAC

Conclusions
1. Significant deficits exist regarding fundamental concepts of hemodynamic monitoring and pulmonary artery catheterization
2. A PAC is a diagnostic tool and not a therapeutic intervention
3. The outcome of a patient with a PAC is altered only if management is guided by the data obtained
4. Our current concepts of PAC-related survival in the critically ill may be inaccurate

THE EVOLUTION OF THE PAC

- Mixed venous oximetry (SvO₂) (1980’s)
  - Assessment of oxygen transport balance
- Volumetric technology (1990’s)
  - Assessment of right heart function
    - Right ventricular ejection fraction (RVEF)
    - Right ventricular end-diastolic volume (RVEDV)
      - A volumetric, as opposed to pressure-based, estimate of intravascular volume status
    - Superior to PAOP & CVP in predicting preload recruitable increases in CO
  - Helps answer the important question
    - Volume or catecholamines?
ARE WE MISSING TOO MUCH?

- Significant physiologic changes may go undetected by conventional intermittent monitoring techniques
  - A “snapshot” in time when a “moving picture” is what is needed

CONTINUOUS THERMODILUTION

- Utilizes pulsed thermal energy technology
- Provides an updated hemodynamic assessment every 60 seconds
- Reduces measurement variability
  - Automates CO measurement
  - Averages respiratory cycle variation
  - Standardizes injection technique
- Provides a constantly updated assessment of patient response to resuscitation leading to more efficient, goal-directed resuscitation

LIMITATIONS OF CONTINUOUS THERMODILUTION

- Accuracy may be decreased by
  - Irregular heart rate and/or rhythm
  - Mitral valve disease
  - Incorrect catheter placement
  - Hyperthermia (> 41° Celsius)
- Data obtained must guide interventions to justify the risk – benefit ratio of the PAC
- The patient outcome benefits are achieved at the cost of increased data complexity and intensivist time

CONTINUOUS THERMODILUTION

- Most invasive and labor-intensive of the monitoring technologies demanding a thorough understanding of PAC monitoring principles
- Provides a continuous assessment of
  - preload (RVEDV, PAOP, CVP)
  - contractility (CO)
  - afterload (SVR, RVEF)
  - oxygen transport balance (SvO₂)
- Improves patient resuscitation and outcome
- Appropriate for the most critically ill patients
Two of these technologies require initial indicator dilution calibration with subsequent measurements obtained using pulse contour analysis. An initial CO is determined using iced saline thermodilution for calibration with subsequent measurements obtained using pulse contour analysis.

Three different technologies are currently available:
- Iced saline indicator calibration
- Lithium indicator dilution calibration
- Computer algorithm

Two of these technologies require initial indicator dilution calibration.

All three technologies provide varying degrees of hemodynamic information.

- Estimation of stroke volume from the arterial pressure waveform was first described almost 100 years ago.
- CO is proportional to the area under the arterial pressure waveform.
- Proposed as a less invasive alternative to the PAC.

- Requires an invasive indwelling catheter.
- Does not provide an accurate estimate of preload or a measurement of contractility.
- SvO₂ and ScvO₂ are not equivalent.

- Restoration of oxygen transport balance is essential.
- Central venous oxygen saturation (ScvO₂) monitoring allows continuous assessment of oxygen transport balance without a PAC.

- ScvO₂ has gained widespread interest as a primary tool of EGDT and is advocated by the Surviving Sepsis Campaign.

- Provides a continuous assessment of:
  - preload (CVP)
  - oxygen transport balance (ScvO₂)
- ScvO₂ as simple as inserting a CVC, requires minimal interpretation, and may be initiated prior to ICU admission.
- Allows earlier assessment and resuscitation.
- Expensive, but a useful early tool for identifying critical illness and beginning EGDT.

- Provides continuous assessment of:
  - Stroke volume (SV) and CO
  - Stroke volume variation (SVV)
- Variation in beat-to-beat SV during a single respiratory cycle.

- Provides intermittent assessment of:
  - Global end-diastolic volume (GEDV)
  - Intrathoracic blood volume (ITBV)
  - Extravascular lung water (EVLW).
LIMITATIONS OF COLD SALINE CALIBRATION TECHNIQUE

- Recalibration is necessary at least every 8 hours
- Not all measurements are continuous
- Accuracy is dependent upon
  - Arterial catheter location
    - Axillary / femoral more accurate than radial
  - Absence of aortic regurgitation, arrhythmias, intracardiac shunts, aortic aneurysms
  - Fully ventilated patient with stable heart rhythm

COLD SALINE CALIBRATION TECHNIQUE

- A less invasive alternative to a PAC
- Provides continuous assessment of
  - Preload (SVV)
  - Contractility (CO)
- Provides intermittent assessment of
  - Preload (GEDV, ITBV, EVLW)
  - Contractility (CO)
  - Afterload (SVR) (requires CVC for CVP)
- Can answer the “volume or catecholamine” question
- A viable option for minimally invasive continuous hemodynamic monitoring

LIMITATIONS OF LITHIUM INDICATOR DILUTION

- Cannot be used in patients on lithium therapy
- Lithium indicator is contraindicated in patients < 40 kg and during the first trimester of pregnancy
- Neuromuscular blocking agents can interfere with the lithium electrode
- Accuracy is dependent upon
  - Frequent recalibration
  - Arterial catheter location
  - Absence of aortic regurgitation, arrhythmias, intracardiac shunts, aortic aneurysms

LITHIUM INDICATOR DILUTION

- Utilizes pulse contour analysis via the patient’s arterial catheter to measure CO, SV, and SVV
- Initial calibration is via indicator dilution using a lithium bolus and lithium-selective electrode
- Accuracy is dependent upon arterial resistance, compliance, and impedance
  - Initial calibration via indicator dilution is required
  - Recalibration is necessary every 8 hours
- The bedside monitor contains a variety of monitoring screens and assessment tools

- Another less invasive alternative to a PAC
- Provides continuous assessment of
  - preload (SV, SVV)
  - contractility (CO)
  - afterload (SVR) (requires CVC for CVP)
- Bedside monitor is very user-friendly
- A viable option for minimally invasive continuous hemodynamic monitoring
**COMPUTER ALGORITHM**

- Utilizes pulse contour analysis via the patient’s arterial catheter to measure CO, SV, and SVV
- Can also measure SvO₂ or ScvO₂ if appropriate catheters are in place
- Does not require indicator dilution for initial calibration
  - Utilizes a computer algorithm based upon pulse pressure and a mathematical model for vascular tone based upon patient gender, height, weight, and BSA

**COMPUTER ALGORITHM**

- Accuracy is dependent upon arterial resistance, compliance, and impedance
- Provides a continuously updated CO, SV, and SVV every 20 seconds
- Currently requires that the patient is mechanically ventilated and without significant arrhythmias

**COMPUTER ALGORITHM**

- Another less invasive alternative to a PAC
- Provides continuous assessment of
  - preload (SV, SVV)
  - contractility (CO)
  - oxygen transport (SvO₂, ScvO₂)
- A viable option for minimally invasive continuous hemodynamic monitoring

**ULTRASOUND**

- Several different methods exist for applying ultrasound to hemodynamic monitoring
  - 2-D echocardiography
    - Transthoracic
    - Transesophageal (TEE)
  - Esophageal Doppler
  - Transcutaneous ultrasound

**LIMITATIONS OF 2-D ECHOCARDIOGRAPHY**

- Both
  - Not a continuous monitoring technology
- Transthoracic (TTE)
  - 10-40% failure rate in ICU due to patient anatomy
- Transesophageal (TEE)
  - Requires a sedated patient; may require neuromuscular blockade
  - Contraindicated in patients with esophageal disease or difficult airway

---

**2-D ECHOCARDIOGRAPHY**

- Provides information of cardiac structure and mechanical function
- Useful for assessing valvular anatomy and function as well as for aortic injury
- Can identify the presence of pericardial fluid
- Useful for assessing preload and contractility
2-D ECHOCARDIOGRAPHY

- An alternative to a PAC
  - Arguably invasive
- Provides information not available with other techniques
- Provides assessment of
  - preload (LVED, LVEDA)
  - contractility (CO, LVEF)
  - valve function
  - pericardial fluid
- An essential technology for intermittently assessing the critically ill patient

ESOPHAGEAL DOPPLER

- First described as a method for measuring CO in 1971
- Based upon measurement of blood flow velocity in the descending aorta
  - Requires either measurement or estimation of cross-sectional aortic diameter

ESOPHAGEAL DOPPLER

- Provides “continuous” assessment of
  - SV and CO
  - Corrected flow time (FTc)
    - A preload estimate superior to PAOP and CVP in predicting preload recruitable increases in CO
    - Peak flow velocity
    - An estimate of ventricular contractility
    - Total SVR
      - Estimated SVR based on aortic blood flow
- Generally feasible only for short-term, intermittent monitoring

LIMITATIONS OF ESOPHAGEAL DOPPLER

- Proper positioning of the Doppler probe is essential
- There is a learning curve
  - Operator technique and experience directly impact upon measurement accuracy
- Requires a sedated or intubated patient
- May not be appropriate for patients with
  - Severe agitation
  - Bleeding diatheses
  - Esophageal varices
  - Aortic dissection

ESOPHAGEAL DOPPLER

- An alternative to a PAC
  - Arguably invasive
- Provides continuous assessment of
  - preload (SV, FTC)
  - contractility (CO, peak flow velocity)
  - afterload (estimated) (TSVR)
- A viable option for intermittent hemodynamic assessment or screening patients for hemodynamic abnormalities

TRANSCUTANEOUS ULTRASOUND

- Utilizes continuous wave Doppler ultrasound coupled with specialized algorithms and signal processing to non-invasively assess hemodynamic function
- A portable monitor allows measurements in a variety of clinical settings
Transcutaneous Ultrasound

- Provides "continuous" assessment of
  - SV
  - CO
  - SVV
  - Corrected flow time (FTc)
  - Peak flow velocity
  - SVR
- Feasible for short-term, intermittent monitoring

Limitations of Ultrasound

- Proper positioning of the transducer is essential
- There is a learning curve
  - Operator technique and experience directly impact upon measurement accuracy
- Accuracy may be limited in the presence of:
  - Subcutaneous air or bone
  - Obesity
  - Valvular abnormalities
  - Significant respiratory disease

Transcutaneous Ultrasound

- A noninvasive alternative to a PAC
- Provides continuous assessment of
  - preload (SV, SVV, FTc)
  - contractility (CO, peak flow velocity)
  - afterload (SVR) (requires CVC)
- A viable option for intermittent hemodynamic assessment or screening patients for hemodynamic abnormalities

Technology Comparison:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Preload</th>
<th>Contractility</th>
<th>Afterload</th>
<th>O₂ Trans</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous TD</td>
<td>PAOP, CVP, RVEDV</td>
<td>CO, RVEF</td>
<td>SVR</td>
<td>SvO₂</td>
<td>$$$</td>
</tr>
<tr>
<td>Bolus TD</td>
<td>PAOP, CVP</td>
<td>CO</td>
<td>SVR</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>ScvO₂</td>
<td>GEDV, SVV</td>
<td>CO</td>
<td>SVR</td>
<td>ScvO₂</td>
<td>$</td>
</tr>
<tr>
<td>Cold Saline</td>
<td>SVV</td>
<td>CO</td>
<td>SVR</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Lithium Dilution</td>
<td>SVV</td>
<td>CO</td>
<td>SVR</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Computer Alg</td>
<td>SVV</td>
<td>CO</td>
<td>SVR</td>
<td>ScvO₂</td>
<td>$</td>
</tr>
<tr>
<td>TEE / TEE</td>
<td>LVESDv, CO</td>
<td></td>
<td></td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Esoph Doppler</td>
<td>FTc</td>
<td>CO</td>
<td></td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Transcut Ultrasound</td>
<td>FTc, SVV</td>
<td>CO</td>
<td>SVR</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Bioimpedance</td>
<td>SV</td>
<td>CO</td>
<td>SVR</td>
<td></td>
<td>$$$</td>
</tr>
<tr>
<td>Partial Rebreathing</td>
<td></td>
<td>CO</td>
<td></td>
<td></td>
<td>$</td>
</tr>
</tbody>
</table>

Invasiveness

Conclusions

- The currently available monitoring technologies vary in the cost and diversity of information provided
- The more invasive techniques generally provide the most accurate and comprehensive data
- Critically ill patients may benefit from the more invasive techniques as a result of the greater breadth of information gained
- Physicians must thoroughly understand the hemodynamic data obtained and utilize it in a goal-directed fashion if the monitoring technology is to improve patient outcome