Functional Hemodynamic Monitoring

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Important Conflicts of Interest
Unimportant Conflicts of Interest

- Michael R. Pinsky, MD is the inventor of a US patent “Use of aortic pulse pressure and flow in bedside hemodynamic management” owned by the University of Pittsburgh, plus two other “complexity” patents.
- Michael R. Pinsky, MD is a co-founder and stockholder of Intelomed.
- Michael R. Pinsky, MD is a medical advisor for:
  - Edwards Lifesciences
  - LiDCO Ltd
- Michael R. Pinsky, MD is receiving research funding from:
  - Edwards LifeSciences
- Michael R. Pinsky, MD is receiving research funding as Principal Investigator from the NHLBI and (co-I) DoD T32 HL07820, R01 NR013912 and W81XWH-11-2-0049
Three Primary Clinical Problems

• How to identify patients who are becoming hemodynamically unstable before they progress too far?
• How to determine the most appropriate therapy to reverse the primary cause for impending circulatory shock?
• How to you implement the most appropriate therapy with when individual responses of patients and skill level of care givers vary?
Three Primary Clinical Problems

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Why Not Give Volume to All Hemodynamically Unstable Patients?

- Signs of cardiovascular insufficiency are impressive but not specific
- Hypotension must decrease blood flow to the heart and brain
- Most forms of circulatory shock have a pathological component of decreased effective circulatory blood volume
Fluid Challenge as a Clinical Trail

If one wishes to know if a patient will increase their cardiac output in response to intravascular volume loading, then a time-honored way to determine if the patient is to give a bolus of fluid (~5-10 ml/kg) over < 30 minutes and note if there is an increase in flow.
<table>
<thead>
<tr>
<th>Responders / Non-Responders</th>
<th>% Responders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calvin (Surgery 81)</td>
<td>20 / 8</td>
</tr>
<tr>
<td>Schneider (Am Heart J 88)</td>
<td>13 / 5</td>
</tr>
<tr>
<td>Reuse (Chest 90)</td>
<td>26 / 15</td>
</tr>
<tr>
<td>Magder (J Crit Care 92)</td>
<td>17 / 16</td>
</tr>
<tr>
<td>Diebel (Arch Surgery 92)</td>
<td>13 / 9</td>
</tr>
<tr>
<td>Diebel (J Trauma 94)</td>
<td>26 / 39</td>
</tr>
<tr>
<td>Wagner (Chest 98)</td>
<td>20 / 16</td>
</tr>
<tr>
<td>Tavernier (Anesthesiology 98)</td>
<td>21 / 14</td>
</tr>
<tr>
<td>Magder (J Crit Care 99)</td>
<td>13 / 16</td>
</tr>
<tr>
<td>Tousignant (A Analg 00)</td>
<td>16 / 24</td>
</tr>
<tr>
<td>Michard (AJRCCM 00)</td>
<td>16 / 24</td>
</tr>
<tr>
<td>Feissel (Chest 01)</td>
<td>10 / 9</td>
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</tbody>
</table>

**Mean** 211 / 195 52 %

Is Cardiac Output Adequate?

- Is blood flow adequate to meet metabolic demands?
- Will increasing intravascular volume increase cardiac output?
- Will decreasing the driving pressure for venous return decrease cardiac output?

Preload Responsiveness
Is cardiac output responsive to intravascular fluid loading?

• Assumes that venous return and LV preload are the primary determinants of cardiac output (Starling’s Law of the Heart)

• Assumes low LV end-diastolic volume (EDV) equals preload-responsiveness

• Attempts to assess EDV through surrogate measures
  – CVP, Ppao, LV end-diastolic area, RV EDV, intrathoracic blood volume
CVP before volume expansion in Responders (R) and Non-Responders (NR)

CVP does not predict volume responsiveness

$r = 0.45$

No Relation Between CVP and Total Blood Volume

Neither $\Delta CVP$ or $\Delta P_{pao}$ Mirror $\Delta SV$
Neither CVP or Ppao reflect Ventricular Volumes or Tract Preload-Responsiveness

Preload ≠ Preload Responsiveness

Kumar et al. Crit Care Med 32:691-9, 2004
Starling’s Law of the Heart Lives!

Kumar et al. Crit Care Med 32:691-9, 2004
Starling versus Anrep
Heterometric v. Homeometric autoregulation of the heart

Sudden increase and decrease in venous return

Rosenblueth et al. Arch Int Physiol 67: 358, 1959
Hemodynamic Effects of Changes in Intrathoracic Pressure
Effect of Positive-Pressure Ventilation on LV Volumes and Pressure

Intact Anesthetized Human

- **ECG** (mv)
- **Pa** (mm Hg)
- **Ppa** (mm Hg)
- **Pra** (mm Hg)
- **LV Area** (cm²)
- **Paw** (cm H₂O)

LV Pressure-Volume Loop

Ejection (stroke volume)

End-systole

Diastolic filling

LV Pressure (mm Hg)

Isometric Relaxation

Mitral Valve Opening

Aortic Valve Opening

Isometric Contraction

End-diastole

LV Volume (mL)

Pressure-Volume Loops During Positive Pressure Ventilation

End systole

Transmural Pressure

Airway Pressure

Time (sec)

End diastole

Left Ventricular Volume

Effect of IPPV on LV Pressure and Volume

IPPV 20 ml/kg

Increased Preload

Stroke Volume Variation

Decreased Preload

Preload-Responsiveness is Dependent on Initial Volume Status and Cardiac Contractility
Effect of IVC Occlusion on Flow Measures in Man

Arterial Pressure

Cinoflo™ Aortic Flow Probe

Relation Between Stroke Volume and Pulse Pressure During IVC Occlusion in Man

Effect of Mechanical Ventilation on PP and SV

Definitions: $\Delta$ Pulse Pressure & $\Delta$ Systolic Pressure

$\Delta$ Systolic Pressure (SP) = $SP_{\text{max}} - SP_{\text{min}}$

$\Delta$ Pulse Pressure (PP) = $PP_{\text{max}} - PP_{\text{min}}$

PPV = $\Delta$PP/mean PP

Michard et al. Am J Respir Crit Care Med 159:935-9, 1999
Baseline PPV Predicts Volume Responsiveness

Changes in Cardiac Index (%)

Baseline PPV (%)

y = 0.95x - 1.62
r² = 0.87

Receiver Operator Characteristic (ROC) Curve for >15% increase in cardiac output to a 500 ml volume challenge in patients in septic shock

Effect of IVC Occlusion on Flow Measures in Man

Arterial Pressure

Cineflo™ Aortic Flow Probe

Hemosonic™ Esophageal Doppler Calculated Flow

Pulse Oximetry Plethysmograph

PPV and SVV Predict Preload-Responsiveness
Google Scholar search 8/24/12 244 peer-reviewed publications

NO, I CAN'T DUMB IT DOWN ANY FURTHER!

Moses, the Editor...
Monitoring Truth

No monitoring device, no matter how accurate or insightful its data will improve outcome,

Unless coupled to a treatment, which itself improves outcome

Pinsky & Payen. Functional Hemodynamic Monitoring, pp 1-4, 2004
Goal-Directed Therapy Using PPV in High-Risk Surgery Patients

Pulse Pressure Minimization

Goal-Directed Therapy Using PPV in High-Risk Surgery Patients

- Fluid resuscitation to keep PPV or SVV <10%
- 16 pt in Intervention Group v. 17 in Control Group
- Both groups were comparable in terms of demographic data, ASA score, type, and duration of surgery.

<table>
<thead>
<tr>
<th></th>
<th>Intervention Group (n=16)</th>
<th>Control Group (n=17)</th>
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<tbody>
<tr>
<td>Intra-op fluids</td>
<td>4,618 ± 1,557</td>
<td>1,694 ± 705 ml (P &lt; 0.0001)</td>
</tr>
<tr>
<td>ΔPP decrease</td>
<td>22 ± 75 to 9 ± 1% (P &lt; 0.05)</td>
<td>no change</td>
</tr>
<tr>
<td>Median post-op LOS</td>
<td>7</td>
<td>17 days (P &lt; 0.01)</td>
</tr>
<tr>
<td># post-op comp/pt</td>
<td>1.4 ± 2.1</td>
<td>3.9 ± 2.8 (P &lt; 0.05)</td>
</tr>
<tr>
<td>Median mech vent</td>
<td>1</td>
<td>5 days (P &lt; 0.05)</td>
</tr>
<tr>
<td>ICU stay</td>
<td>3</td>
<td>9 days (P &lt; 0.01)</td>
</tr>
</tbody>
</table>

Goal-Directed Therapy Using PPV in High-Risk Surgery Patients

PPV v. GEDV Targets as Guides to Resuscitation

- Porcine hemorrhagic shock model (MAP 40 mmHg x 60 m)
- Resuscitation with HES as needed to targeted minimal PPV or PAC-derived GEDVI
- All static and dynamic markers to tissue oxygenation and hemodynamic stability similar in both groups following resuscitation
- Volume and time to resuscitation higher with GEDV target than PPV minimization (<10%) target
  - 1,305 ± 331 v. 965±245 mL (p<0.05)
  - 24.8±4.7 v. 8.8±1.3 min (p<0.05)

Perioperative goal-directed hemodynamic monitoring based therapy: a multi-center, prospective, randomized study
Perioperative goal-directed hemodynamic monitoring based therapy: a multi-center, prospective, randomized study

Effects of Goal-Directed Therapy based on Dynamic Parameters on post-surgical outcomes
A Meta-analysis of randomized controlled trials

Benes et al. Critical Care 18:584, 2014
Technical Limitations of PPV and SVV for Assessment of Preload-Responsiveness

• Requires fixed HR
  – Atrial fibrillation, frequent PVCs
• Requires positive-pressure ventilation
• Requires no spontaneous ventilatory efforts
  – Can not use during CPAP, PSV, A/C
• Cor Pulmonale and ventricular interdependence
• Magnitude of PPV or SVV will change if tidal volume changes
• Changes in vasomotor tone will alter the PPV/SVV relation
Dynamic shifts in Intrathoracic Blood Volume during IPPV

Effect of Tidal Volume on LV Pressure and Volume

Spontaneous Ventilation Alters LV Filling by Ventricular Interdependence

Effect of ventilation on RV and LV Output

Spontaneous inspiration

Positive-pressure Inspiration

Ventricular Interdependence

Minimal Ventricular Interdependence

The PLR effects occur over a epoch of time encompassing several cardiac and respiratory cycles.

Change in Mean Aortic Flow during PLR

How to assess preload-responsiveness in spontaneously breathing patients?

- Volume challenge
- Passive leg raising

Is arterial tone normal?

- Normal baroreceptor reflex mechanisms vary vasomotor tone to maintain arterial pressure constant despite changes in cardiac output, thus….

Hypotension is always pathological

Normotension does not mean hemodynamic stability
Comparing PPV to SVV as Dynamic Arterial Elastance

Arterial Pulse Pressure

Dynamic Ea

Increased Dynamic Arterial Elastance

Decreased dynamic Arterial Elastance

Stroke Volume

0 0 50

100
Ventriculo-Arterial Coupling

- Vasopressor Therapy
- Volume Loading
  - Exercise
  - Increase catecholamines
- Hemorrhage
- Acute Heart Failure
- Tamponade
- Sepsis
- Vasodilator Therapy

+ Stroke Volume
- Pulse Pressure
Changes in Vasomotor Tone alter LiDCCO-derived PPV/SVV

Vasodilator therapy increased PPV 13% to 17% and SVV from 9% to 15% (P<0.001).

Pre: PPV/SVV .13/.09 = 1.44  
Post: PPV/SVV .17/.15 = 1.13

Comparing PPV to SVV as Dynamic Arterial Elastance

Limits of Preload-Responsiveness Approaches in Practice

• Preload ≠ Preload-responsiveness
• Preload-responsiveness ≠ Need for fluids
• The means of altering preload matters
  – Size of Vt, passive leg raising, spontaneous breaths
• The PPV/SVV will vary with vasomotor tone
  • Pinsky Intensive Care Med 30: 1008-10, 2004
  • Hadian et al. J Crit Care 2010 (doi:10/10-1016/j.jcrc.2010.08.018)
Flow and Pulse Pressure Variation

- $\Delta SV$, $\Delta PP$, & PLR $\Delta CO > 10-15\%$ accurately identify subjects whose cardiac output will increase during a fluid challenge and by how much.

- $\Delta SV$, $\Delta PP$, & PLR $\Delta CO$ can be used to monitoring the change in cardiac output in response to therapy.

- If $\Delta SV$, $\Delta PP$, or PLR $\Delta CO$ are not present, then fluid loading will not increase cardiac output.
Continuous Monitoring of Preload Responsiveness

- **Arterial Pressure**
  - Non-invasive
    - ccNexfin®, Fenapres®
  - Invasive
    - Arterial catheterization

- **Arterial flow**
  - Esophageal Doppler
    - Deltex CardiaQ®
  - Echocardiogram, hTEE®

- **Combined Pressure and Flow**
  - Pulse Contour Technology
    - PiCCO®, LiDCO®, FloTrac®

PPV > 13%
SVV > 10%
ΔCO > 10%
Clinical Implications

• We can identify critically ill patients by their changing arterial pressures and flow
• We can identify the presence or absence of volume responsiveness and assess easily arterial tone at the bedside
• Using these dynamic measures and defined resuscitation algorithms, we can effectively resuscitate high risk surgery patients reducing post-operative complications and length of stay
• The short term benefits of Pre-optimization protocols appear to be sustained over time
Hemodynamic Monitoring Protocol

Is the patient hemodynamically stable?
- Yes: Do Nothing
- No:
  - Yes: Is the patient preload-responsive?
    - Yes: Does the patient hypotensive and have reduced vasomotor tone?
      - Yes: Volume bolus, Add Vasopressor
      - No: Volume bolus
    - No: Add Inotrope
  - No: Add Vasopressor

Reassess the patient

Applications of Functional Hemodynamic Monitoring

- Define resuscitation options in circulatory shock
  - UPMC Pre-optimization trial in high risk surgery (Whitehurst & Pinsky)
  - ESICM Multi-center Trail Resuscitation from Shock: ReFIT
  - Closed loops control during in-flight resuscitation (Guyette)

- Define fluid requirements in ARDS
  - Better rationale than Pra or Ppao used in the ARDSNet Fluids and catheters treatment trial (FACTT)

- Monitoring fluid removal during hemodialysis (Pinsky)

- Cadaveric support prior to organ harvesting (Kellum)
Thank You