Hemodynamics I Basic Calculations: Stroke Volume, Cardiac Output Valve Area and Intracardiac Pressures

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No Disclosures
Hemodynamic Data From Doppler Echocardiography

- **Volumetric Measurements**
  - Stroke volume and CO
  - Pulmonary-systemic flow ratio (Qp/Qs)
  - Regurgitant volume and fraction
- **Valve Area**
  - Stenotic valve area
  - Regurgitant orifice area
- **Intracardiac pressures**
  - Pulmonary artery pressures
  - Left atrial pressures
  - Left ventricular end diastolic pressure
- **Pressure Gradient**
  - Maximal instantaneous gradient
  - Mean gradient
3 Major Concepts

• Modified Bernoulli Equation and Pressure Gradients
• Hydraulic Orifice Formula and Calculating Volume of Blood Flow
• Conservation of Mass Theory and the Continuity Equation
Doppler Hemodynamics Part 1: Determining Intracardiac Pressures OR The Modified Bernoulli Equation (and others)
Bernoulli Equation

- Swiss Mathematician (1700-1782)
- Bernoulli's equation describes the behavior of a fluid moving along a streamline.
  - Compressible fluids
  - Incompressible fluids
Hemodynamics: Pressure Gradients

• Blood flow velocities can be converted to pressure gradients (mmHg) according to the Bernoulli equation

• Fundamental assumptions:
  • No additional loss of pressure from viscous effects (friction)
  • Contribution of flow acceleration \((\frac{dV}{dT})\) is small
  • \(V_1 \ll V_2\)
  • Convert density from dynes cm to mmHg:

\[
\Delta P = 4 \left( \frac{V_2}{2} \right)^2
\]

**Modified Bernoulli Equation**
Modified Bernoulli Equation

- When the proximal velocity \( V_1 \) is > 1 m/s, then it should be included in the equation:

\[
\Delta P = P_2 - P_1 = 4 \left( V_2^2 - V_1^2 \right)
\]

Requarth JA. In vitro verification of Doppler prediction of transvalve pressure gradient and orifice area in stenosis. Am J Cardiol 1984;53(9):1369-73
Intracardiac Pressure Measurements

- Can we measure the following:
  - Right atrium
  - Right ventricle
  - Pulmonary artery
  - Left ventricle
  - Left atrium
### ASE: Inferior Vena Cava

<table>
<thead>
<tr>
<th></th>
<th>Size</th>
<th>Resp</th>
<th>RAp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>≤ 2.1 cm</td>
<td>&gt; 50%</td>
<td>3 (0-5) mmHg</td>
</tr>
<tr>
<td></td>
<td>&gt; 2.1 cm</td>
<td>&gt; 50%</td>
<td>8 (5-10) mmHg</td>
</tr>
<tr>
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<td>&lt; 50%</td>
<td>8 (5-10) mmHg</td>
</tr>
<tr>
<td></td>
<td>&gt; 2.1 cm</td>
<td>&lt; 50%</td>
<td>15 (10-20) mmHg</td>
</tr>
<tr>
<td>High</td>
<td>&gt; 2.1 cm</td>
<td>&lt; 50%</td>
<td></td>
</tr>
</tbody>
</table>

Athletes mean IVC = 2.31 ± 0.46 cm  
Highest diameters in highly trained swimmers  
Mechanical Ventilation: dilated IVC did not always indicated high RAP however small IVC (<1.2 cm) 100% specificity for RAP <10 mmHg

Rudski LG et al, J Am Soc Echocardiogr 2010;23:685-713
Estimating RA Pressure

Diameter = 2.0 cm, Decrease by < 50%
RAP = 8 (range 5-10) mmHg

Diameter = 2.8 cm, Decrease by < 35%
RAP = 15 (range 10-20) mmHg

Diameter = 0.8 cm, Decrease by > 55%
RAP = 3 mmHg (<5 mmHg)

IVC Diameter: just proximal to the junction of the hepatic veins that lie approximately 0.5 to 3.0 cm proximal to the ostium of the right atrium
Right Ventricular Systolic Pressure (in absence of pulmonic stenosis)

- Tricuspid Regurgitation
  - $RVSP = [\text{Velocity}_{TR}^2 \times 4] + \text{RA pressure}$

- TR Vel = 4.1 m/s
- Gradient = 68 mmHg

On-Axis Imaging is KEY

- TR = 2.4 m/s
- TR = 3.1 m/s

Measure PEAK, well-defined spectral border
In setting of pulmonic stenosis:

\[
PASP = RVSP - PS \text{ gradient}
\]

\[
PASP = [(\text{Velocity}_{TR})^2 \times 4] + RAP - [(\text{Velocity}_{PS})^2 \times 4]
\]

TR Vel = 4.1 m/s

Gradient = 68 mmHg

RAP = 10 mmHg

\[
PASP = (78 - 46) = 32 \text{ mmHg}
\]
Tricuspid Regurgitant Profile

- Loss of late systolic regurgitant flow secondary to early equalization of RV and RA pressures:
  - Rapid rise in right atrial pressure
    - Severe tricuspid regurgitation
    - Atrial septal defect
  - Rapid fall in right ventricular pressure
    - Poor RV function

PASP \neq RV-RA gradient + RAP
Mean Pulmonary Artery Pressures

- In absence of tricuspid regurgitation, mean PAp estimated by:
  - Acceleration time (msec) of transpulmonary flow used in regression equation:
    79 - (0.45 x AT)
  - 50 consecutive pts for cath:
    - Prediction of mean pulmonary artery pressure was unsatisfactory (r = 0.65) but improved (r = 0.85) when only patients with a heart rate between 60 and 100 beats/min were considered
  - If AT ≤ 120 msec
    90 - (0.62 x AT)

CAVEATS:
1. Measure from ONSET OF FLOW to ONSET OF PEAK pulmonary flow velocity
2. HR in normal range (60-100 bpm)

Dabestani A et al. Am J Cardiol 1987;59:622-8
Mean PAP Estimate

- MPAP by TR mean correlated well with Cath (with or without saline)
  - The median absolute percentage difference of the MPAP calculations relative to RHC was significantly less with this method than with the pulmonary regurgitation method (18% vs 71%; P < .001)

<table>
<thead>
<tr>
<th>RHC (mm Hg)</th>
<th></th>
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<tbody>
<tr>
<td>MPAP</td>
<td>34.3 ±14.5</td>
</tr>
<tr>
<td>SPAP</td>
<td>53.0 ±23.7</td>
</tr>
<tr>
<td>RA pressure</td>
<td>9.3 ± 5.3</td>
</tr>
</tbody>
</table>

**Echocardiography (mm Hg)**

<table>
<thead>
<tr>
<th>Echocardiography</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>MPAP by RV-RA mean systolic gradient (w/o saline)</td>
<td>33.6 ±14.9</td>
</tr>
<tr>
<td>MPAP by PR velocity w/o saline</td>
<td>21.7 ± 13.0</td>
</tr>
<tr>
<td>SPAP w/o saline</td>
<td>48.3 ±24.4</td>
</tr>
<tr>
<td>MPAP by RV-RA mean systolic gradient (with saline)</td>
<td>40.9 ±18.2</td>
</tr>
<tr>
<td>MPAP by PR velocity with saline</td>
<td>29.2 ±13.5</td>
</tr>
<tr>
<td>SPAP with saline</td>
<td>55.4 ±25.6</td>
</tr>
<tr>
<td>RA pressure</td>
<td>6.0 ± 3.7</td>
</tr>
</tbody>
</table>

Pulmonary Artery Diastolic Pressure

- **Pulmonic Regurgitation**
  - \( PAEDP = \left(\frac{\text{Velocity}_{\text{PR}_{\text{end}}}}{\text{Velocity}_{\text{PR}_{\text{peak}}}}\right)^2 \times 4 \) + RAP
  - \( \text{Mean PAP} = \left(\frac{\text{Velocity}_{\text{PR}_{\text{peak}}}}{\text{Velocity}_{\text{PR}_{\text{peak}}}}\right)^2 \times 4 \)
  - \( \text{Mean PAP} = PAEDP + \frac{1}{3} (\text{PASP} - \text{PAEDP}) \)

Reporting PAP

Recommendations:
1. SPAP should be estimated and reported in all subjects with reliable tricuspid regurgitant jets. The recommended method is by TR velocity, using the simplified Bernoulli equation, adding an estimate of RA pressure as detailed above.
2. In patients with PA hypertension or heart failure, an estimate of mean PAP from either the mean gradient of the TR jet or from the pulmonary regurgitant jet should be reported.
3. If the estimated SPAP is >35 to 40 mm Hg, stronger scrutiny may be warranted to determine if PH is present, factoring in other clinical information.

Rudski LG et al, J Am Soc Echocardiogr 2010;23:685-713
Pulmonary Vascular Resistance

- Resistance \(\approx\) Pressure/Flow

  \[
  \text{PVR} \approx \frac{\text{Mean PA Pressure} - \text{PCWP}}{\text{Cardiac Output}}
  \]

  \[
  \text{PVR} \approx \frac{\text{Tricuspid Regurgitant Velocity}}{\text{RVOT VTI}}
  \]

  \[
  \text{PVR} = 10 \left( \frac{\text{TRV}}{\text{RVOT VTI}} \right) + 0.16
  \]

  Ratio > 0.175 is consistent with a PVR > 2 WU

Recommendation: The estimation of PVR is not adequately established to be recommended for routine use but may be considered in subjects in whom pulmonary systolic pressure may be exaggerated by high stroke volume or misleadingly low (despite increased PVR) by reduced stroke volume.

Rudski LG et al, J Am Soc Echocardiogr 2010;23:685-713
Intracardiac Pressure Measurements

- Pressure Assessment:
  - Right atrium
  - Right ventricle
  - Pulmonary artery
  - Left ventricle
  - Left atrium
Left Ventricular Systolic Pressure

In absence of aortic stenosis:

LV Systolic Pressure = Systolic BP

In presence of aortic stenosis:

LV Systolic Pressure = Systolic BP + [(Velocity_{AS})^2 \times 4]

Caveat in Significant AS: SBP audible at aortic valve closure (just after peak Ao pressure)

LVSP = SBP + Peak to Peak gradient
Left Ventricular Systolic Pressure

In the setting of significant Aortic Stenosis:

• Peak to Peak Gradient approximates MEAN transaortic gradient

• Mean Ao gradient = 0.66 x maximum instantaneous gradient (MIG)

In presence of aortic stenosis:

LV Systolic Pressure = Systolic BP + (0.7 x AS MIG)
Left Ventricular Diastolic Pressure

- **Aortic Regurgitation**

\[ \text{LVEDP} = \text{DBP} - \left(\text{Velocity}_{\text{AR}}^2 \times 4\right) \]

AR End-diastolic gradient = \(4(2.6)^2 = 27 \text{ mmHg}\)

BP = 110/64 mmHg

\[ \text{LVEDP} = 64 - 27 = 36 \text{ mmHg} \]
Left Atrial Pressure

- Mitral Regurgitation

\[ \text{LA pressure} = \text{SBP} - [(\text{Velocity}_{MR})^2 \times 4] \]

\[ \text{SBP} = 122 \text{ mmHg} \]
\[ \text{LAP} = 122 - 100 = 22 \text{ mmHg} \]
Tissue Doppler and Pre-A (PCWP)

- E:E’ (septal) measured in 200 patients in the cath lab
- Relation with Pre-A independent of EF
- E:E’ ratio ≥ 9 discriminated Pre-A >12 mmHg (Sn 81%, Sp = 80%)
- PCWP (mmHg) = E/E’ + 4
  
  Kim and Sohn, JASE 2000; 13:980-5

- E:E’ (lateral) measured in 120 patients (60 with simultaneous cath)
- Relation with Pre-A independent of EF
- E:E’ ratio > 10 discriminated Pre-A >12 mmHg (Sn 91%, Sp = 81%)
- PCWP = 1.9 + 1.24(E/E’)
  
  Nagueh et al, JACC 1997;301527-33
E-Wave/Propagation Velocity

Linear Relation to Left Atrial Pressure

Garcia et al., J Am Coll Cardiol 1997; 29:448-454

E-wave Velocity

Color M-Mode
Propagation Velocity

\[r = 0.80\]
\[p < 0.001\]
\[y = 5.27x + 4.66\]
SEE = 3.1

\[\frac{E}{v_p} = 84/28 = 3.0\]
\[p_w = 20 \text{ mmHg}\]
Intracardiac Pressure Measurements

- Pressure Assessment:
  - Right atrium
  - Right ventricle
  - Pulmonary artery
  - Left ventricle
  - Left atrium
Doppler Echocardiography 2: Hydraulic Orifice Formula and Calculating Volume of Blood Flow
Stroke Volume and Cardiac Output

- **Hydraulic Orifice Formula:**
  \[ \text{Flow} = \text{Area} \times \text{Velocity} \]
  - Flow varies over time

- **Stroke Volume:**
  \[ \text{CSA (cm}^2\text{)} = 3.14 (r)^2 \]

- **Velocities integrated over time = TVI**
  Represents the distance the blood travels in a single beat = stroke distance
Stroke Volume and Cardiac Output

- **Stroke Volume** = CSA \( (\text{cm}^2) \times \text{TVI} \ (\text{cm}) \)
  - CSA = \( (D/2)^2 \times \pi = D^2 \times 0.785 \)

- **Cardiac Output** = Stroke Volume \times HR

- **Cardiac Index** = C.O. / BSA
Ultrasound Cardiac Output Correlation With Thermodilution

• Ultrasound CO correlated with thermodilution CO
  - $R = 0.96$

Stroke Volume and Cardiac Output

• **Systemic Arterial Stroke Volume:**
  - **Aortic:** typically measured at the aortic anulus (or LVOT)
    - VTI measured by tracing the peak velocity envelope of pulsed flow profile in **systole**
  - **Mitral:** measure mitral anulus in 4 chamber view
    - VTI measured by tracing the peak velocity envelope in **diastole**

• **Systemic Venous Stroke Volume:**
  - **Pulmonary Artery:** measured at the anulus
    - VTI measured by tracing the peak velocity envelope in **systole**
Stroke Volume

LVOT Stroke Volume

RVOT Stroke Volume
Shunt Calculation: Correlation with Cath

In patients with ASD:

- Correlation of pulmonary and systemic flows = 0.93 and 0.92
- Derived Qp/Qs
  - R = 0.82
  - SEE ± 0.21
# AR Quantitative Doppler

<table>
<thead>
<tr>
<th>Doppler Parameter</th>
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<th>Moderate</th>
<th>Severe</th>
</tr>
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<tbody>
<tr>
<td>Regurgitant Volume</td>
<td>&lt; 30 cc</td>
<td>30-59 cc</td>
<td>≥ 60 cc</td>
</tr>
<tr>
<td>Regurgitant Fraction</td>
<td>&lt; 30%</td>
<td>30-39 %</td>
<td>≥ 50 %</td>
</tr>
<tr>
<td>Regurgitant Orifice Area</td>
<td>&lt; 10 mm²</td>
<td>10-19 mm²</td>
<td>≥ 30 mm²</td>
</tr>
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Volumetric Measurements

Systole

Diastole

LVOT VTI = 0.368 m
Vmax = 1.51 m/sec
Pk Grad = 9.1 mmHg
Mn Grad = 5.0 mmHg

MV VTI, Annulus = 0.246 m
Technical Pitfalls: Misplacement of sample volume

Tips MV
1.85 m/s

MV Annulus
1.6 m/s

LA
1.4 m/s
## MR Quantitative Doppler

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<tr>
<td><strong>Regurgitant Orifice Area</strong></td>
<td>&lt; 20 mm²</td>
<td>20-29 mm²</td>
<td>≥ 40 mm²</td>
</tr>
</tbody>
</table>

Mitral Regurgitant Volume: Correlation with Invasive Measures

- Other methods of estimating SVt
  - Teichholz volume
  - Simpson’s method
- Using any method in patients, $r = 0.82$

Ascah KG et al. Circulation 1985;72:381
Doppler Echocardiography
Part 3: Conservation of Mass and the Continuity Equation
Continuity Equation

- Continuity Equation utilizes the conservation of mass theory
  - Stroke Volume$_1$ = Stroke Volume$_2$
  - (Area x TVI)$_1$ = (Area x TVI)$_2$
  - Area$_2$ = (Area x VTI)$_1$ / (VTI$_2$)
- \[ \text{Area}_{AV} = \frac{\text{Area}_{LVOT} \times \text{VTI}_{LVOT}}{\text{VTI}_{AV}} \]
Continuity Equation: Aortic Valve Area

- Stroke Volume across the LVOT
  - LVOT diameter: Measure just beneath the anular plane and parallel to the aortic valve plane
  - VTI measured by tracing the peak velocity envelop of pulsed flow profile within 0.5 cm above the annular plane
Transaortic Velocity or VTI

1. Image peak velocity from at least two different windows

2. Use the highest velocity profile.
Continuity Equation: Aortic Valve Area

- \((\text{Area} \times \text{TVI})_{\text{LVOT}} = (\text{Area} \times \text{TVI})_{\text{Aortic Valve}}\)
  - \(\text{Area}_{\text{Aortic Valve}} = (\text{Area} \times \text{VTI})_{\text{LVOT}} / (\text{VTI}_{\text{Aortic Valve}})\)
- \(\text{Area}_{\text{AV}} = \frac{\text{Area}_{\text{LVOT}} \times \text{VTI}_{\text{LVOT}}}{\text{VTI}_{\text{AV}}}\)

\[D^2 \times 0.785 \times x\]

\[= [3.141 \times (1.0)^2] \times 37 \text{ cm} = 0.98 \text{ cm}^2\]

\[119 \text{ cm}\]

Note: using the VTI results in the mean AVA, using the peak velocities results in the largest AVA
Using Aortic Stroke Volume

Continuity Equation: Mitral Valve Area

- Stroke Volume$_1$ = Stroke Volume$_2$
- Mitral Valve Area x Mitral VTI = LVOT Area x LVOT VTI
- Mitral Valve Area = LVOT Area x LVOT VTI

Mitral VTI

\[ D^2 \times 0.785 \]

= 1.2 cm$^2$
Continuity Equation: Mitral Valve Area

- Stroke Volume$_1$ = Stroke Volume$_2$
- Mitral Valve Area \times Mitral VTI = PV Area \times PV VTI
- Mitral Valve Area = \text{PV Area} \times \text{PV VTI}

Mitral VTI

\[ D^2 \times 0.785 \]

\[ = 1.3 \text{ cm}^2 \]

Using Pulmonic Stroke Volume
Hemodynamic Data From Doppler Echocardiography

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