Assessment of Cardiac Hemodynamics by Echocardiography

M. Vaturi MD

Department of Cardiology
Rabin Medical Center, Beilinson Hospital
Sackler Faculty of Medicine
Tel Aviv University

Caesarea, 2010
Flow Rate, Volume

Not constant (pulsatile flow)

**Flow rate** = CSA x Flow velocity

\( \text{Flow rate} = \text{CSA} \times \text{Flow velocity} \)

\( \text{Flow rate} = \text{cm}^3/\text{s} \quad \text{cm}^2 \quad \text{cm/s} \)

\[ \text{CSA} = \pi r^2 = \pi \left(\frac{D}{2}\right)^2 \]

**Volume** = CSA \( \int \) Velocity (time) \( \text{VTI} \)

\( \text{Volume} = \text{CSA} \times \int \text{Velocity (time)} \)

\( \text{Volume} = \text{cm}^3 \quad \text{cm}^2 \quad \text{cm} \)
**Stroke Volume - LVOT**

- **Assumptions:**
  - Circular orifice
    - Constant orifice size
  - Flat velocity profile
    - Laminar flow
  - Velocity & orifice measurements
    - At the same level

\[
\text{CSA}(\text{cm}^2) = 3.14(D/2)^2
\]

\[
SV = \text{CSA} \times \text{VTI}
\]
Assessment of forward stroke volume

- MR $\rightarrow$ valid measurements of LV forward (systemic) SV

- AR $\rightarrow$ LV SV $\neq$ forward (systemic) SV
**SV – Other Techniques**

- **MR / AR → LV output ≠ forward (systemic) output**
- **LV SV = forward (systemic) SV + regurgitant volume (MR/AR)**

**LV volumes**

4-ch

2-ch

End-diastole  End-systole
Aortic Stenosis
Transvalvular Pressure Gradients

Maximum instantaneous gradient

Peak to peak gradient

Ao

LV

Doppler peak velocity
Doppler does not measure AV pressure gradient directly

\[ \Delta P_{\text{Doppler}} = PLV - P_{\text{vena contracta}} \]
\( \Delta P - \text{Aortic Stenosis} \)

- Constant relationship between peak & mean \( \Delta P \): \( \text{AVMG} \approx \frac{2}{3} \text{AVPG} \)

- Severe AS (AVA <1.0 cm\(^2\))
  - \( V_{\text{max}} > 4.0 \text{ m/s} \) (peak \( \Delta P > 60 \text{ mmHg} \), mean >40)
  - Assumption: normal transaortic flow (SV)
  - Incorrect assumption
    - LV / RV dysfunction / MR / TR ++ \( \rightarrow \Delta P \downarrow \)
      - Low-gradient AS
    - Hyperdynamic LV / AR ++ \( \rightarrow \Delta P \uparrow \)
ΔP AS – Pitfalls

► Inadequate Doppler alignment

► Serial stenoses
  - Subaortic / mid-LV & aortic
When might pressure gradient calculation by the Bernoulli equation fall?

- Underestimation of poststenotic flow velocity $v_2$ (suboptimal angle to flow, calcified valve)

- Tunnel shaped muscular subaortic stenosis (viscous friction not negligible - underestimation)

- Prestenotic flow velocity $v_1$ not negligible (severe AR, high CO) or close to $v_2$ (prostheses) - overestimation

- Pressure recovery (tapered outlet geometry, e.g. bileaflet prostheses) - overestimation
• Conservation of mass
What causes the pressure gradient across a stenotic valve?

Fluids are incompressible. By continuity (conservation of mass) flow rate $Q$ must therefore be the same through any cross section $A$ of the flow path: $Q_1 = Q_2$. Since $Q = A \times v$, it follows that if $A$ decreases, $v$ must increase.
AVA – Continuity Equation

AVA = CSA_{(LVOT)} \times \frac{VTI_{(LVOT)}}{VTI_{(AV)}}
Continuity Equation – Pitfalls

Inadequate PW sample location in LVOT

Too close (to AoV) → AVA ↑
Too far (within LV) → AVA ↓

\[ {AVA} = \frac{\text{CSA}_{(LVOT)} \times VTI_{(LVOT)}}{VTI_{(AS)}} \]

Usually underestimated

\( \text{AVA} \downarrow \)

Inadequate alignment

with max flow velocity

\( \text{Mistake}^2 \)
Assessing aortic valve area in aortic stenosis by continuity equation: a novel approach using real-time three-dimensional echocardiography

Kian Keong Poh¹,², Robert A. Levine¹, Jorge Solis¹, Liang Shen³, Mary Flaherty¹, Yue-Jian Kang¹, J. Luis Guerrero, and Judy Hung¹

A=1.2cm; AVA=0.44cm²
B=1.5cm; AVA=0.69cm²
C=2.1cm; AVA=1.35cm²
D=1.8cm; AVA=0.99cm²
AVA derived from 2D continuity equation correlates only modestly with that derived from 3D color Doppler.

Significant discrepancies between both methods are predicted by presence of **upper septal hypertrophy**, representing distorted LVOT geometry.

RT3DE measurement of LVOT SV agrees better with the gold standard of aortic flow probe measurement in an animal model of varying LVOT geometry than 2DE.

A better agreement of AVA derived from RT3DE color Doppler and AVA planimetry guided by RT3DE.
**Dimensionless Index**

AVA = \( \text{CSA}_{(LVOT)} \times \frac{\text{VTI}_{(LVOT)}}{\text{VTI}_{(AS)}} \)

- **Index**
  - \( > 1/2.5 \) Mild
  - \( 1/2.5-1/4 \) Moderate
  - \( < 1/4 \) Severe
  - \( < 1/5 \) Critical

**AS severity**

**Shortcut**

Calculate with peak velocities

VTI ratio \( \approx \) Peak V ratio
Discrepancies Between Catheter and Doppler Estimates of Valve Effective Orifice Area Can Be Predicted From the Pressure Recovery Phenomenon

Practical Implications With Regard to Quantification of Aortic Stenosis Severity

Damien Garcia, ENG,* Jean G. Dumesnil, MD, FACC,† Louis-Gilles Durand, ENG, PhD,* Lyes Kadem, ENG,† Philippe Piparo, DVM, PhD, FACC†

Sainte-Foy and Montreal, Quebec, Canada
Coefficient of contraction

plate

funnel

tube

Inlet-הша פונגוצ'ה של צורת ה-ERO-

0.6

0.8

1.0
Pressure Recovery
Pressure gradient across a stenotic valve - energy dissipation

Most of the kinetic energy is dissipated in turbulence and is therefore not reconverted into static pressure
Three Types of Pipe Flowrate Meters
(obstruction type flowmeters)

Orifice Meter

Nozzle Meter

Venturi Meter

In a **nozzle meter** (e.g. valve prosthesis) there is a head loss of 65%.

In a well-designed **Venturi meter** the head loss is only 15%.

85% of the pressure drop is recovered!

*Prandtl L, Tietjens O: Applied Hydro- and Aeromechanics, New York, Dover 1957*
Pressure recovery in bileaflet prosthesis (SJM type)

Max. PG (Doppler)

PG after recovery (cath)

Pressure

Distance

upstream
downstream
The lowest pressure (the greatest pressure drop) after the stenotic valve is at the vena contracta. From there forward the pressure rises (E kinetic drops, E potential rises. This is the pressure recovery.

If aorta is small, P recovers more steeply (than in wider aorta). Hence, in small aorta (big pressure recovery) the delta P (P LV-P asc Ao) is smaller (in pull back) compared to delta P in Doppler => greater discrepancy in measurement of pressure gradient.
EL index = ELCo/BSA

EOA cath or EL index ≤0.55-0.6 cm²/m² is indicative of severe AS

<table>
<thead>
<tr>
<th>Catheter-Derived EOA (cm²)†</th>
<th>Doppler-Derived EOA (cm²)</th>
<th>Aortic Diameter = 2.0 cm (Aₐ = 3.14 cm²)</th>
<th>Aortic Diameter = 3.0 cm (Aₐ = 7.07 cm²)</th>
<th>Aortic Diameter = 4.0 cm (Aₐ = 12.0 cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50 (1.69)</td>
<td>1.02</td>
<td>1.24</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>1.00 (1.13)</td>
<td>0.76</td>
<td>0.88</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>0.75 (0.85)</td>
<td>0.61</td>
<td>0.68</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>0.50 (0.56)</td>
<td>0.43</td>
<td>0.47</td>
<td>0.48</td>
<td></td>
</tr>
</tbody>
</table>
Other factors (beside pressure recovery) can be associated with AVG – AVA dissociation (low gradients but severe valve area stenosis)

- Low cardiac output (LV dysfunction)
- Small stroke volume in LV with nEF
- Valvulo-arterial impedance (the impact of SBP)
Mitral Stenosis
Mitral stenosis
Transvalvular Pressure Gradients

\[ \Delta P_{\text{max}} \]

\[ \Delta P_{\frac{1}{2}} \]

\[ \text{MVA (cm}^2\text{)} = \frac{220}{T_{\frac{1}{2}}} \]

\[ = 0.9 \text{ cm}^2 \]

\[ V_{\text{max}} \]

\[ V_{\text{max}} / \sqrt{2} \]

\[ T_{\frac{1}{2}} \]

\[ 250 \text{ ms} \]

\[ 0 \text{ to } 0.5 \text{ s} \]
$\Delta P$ – Mitral Stenosis

- Heart rate dependence +++
- Non-constant (HR-dependent) relationship

Peak ↔ mean $\Delta P$
MVA – Pressure Halftime

\[ MVA = \frac{220}{P \cdot t_{1/2}} \]

- \( P \propto V^2 \)
- \( V \propto \sqrt{P} \)
- \( P_{\text{max}} \rightarrow \frac{1}{2} P_{\text{max}} \)
- \( V_{\text{max}} \rightarrow \sqrt{\frac{1}{2}} V_{\text{max}} \)
MVA By $P_{t_{1/2}}$

Rule of Thumb

- $P_{t_{1/2}}$ may be shorter than expected for specific MVA
  - Presence of confounding LA / LV variables
  - Overestimation of MVA (less severe MS)
- $P_{t_{1/2}}$ “never” underestimates MVA*
  - Calculated MVA $\downarrow$ = severe MS
  - Calculated MVA $> \text{expected}$ (morphology, $\Delta P$)
    - May still be severe MS!

*Exception – Mild MS & LV relaxation $\downarrow \downarrow$ (HHD)
1. The larger the MVA, the more rapidly LAP drops, and diastolic LVP increases (equilibrium is reached quickly) - $t_1/2$ will be shortened. However,
2. LAP may also drop rapidly if LA has a second outlet (ASD) - $t_1/2$ will be shortened.
3. Or LVP may rise rapidly if LV fills from a second source (AR) - $t_1/2$ will be shortened.
4. Or LVP may rise rapidly if LV is stiff (low ventricular compliance) - $t_1/2$ will be shortened.
5. Or LAP may drop rapidly if LA is stiff (low atrial compliance) - $t_1/2$ will be shortened.
The decay of the pressure gradient across a stenotic mitral valve is not only determined by the size of the orifice but also by net AV compliance (Cn).
T1/2 never underestimates MVA.

Therefore, if t1/2 is > 200-220 ms, MS is always severe.

However, if t1/2 is < 200 ms, look at the mean gradient, and pulmonary artery pressure, try mitral valve planimetry, and consider exercise echo.
MVA – Continuity Equation

Assumptions

- No MR (MR ≤ mild)
- No AR (AR ≤ mild)
Mitral Regurgitation
Qualitative Assessment
Color Flow Imaging

Anatomical orifice

Proximal flow convergence

Entrainment of fluid

Vena contracta
Regurgitation jet depends on:

- ERO
- Driving pressure
If the same amount of fluid is injected with the same speed through a thinner needle (i.e. at a higher driving pressure) a larger jet results

This explains why regurgitant jets (of the same flow rate) are larger in patients with hypertension, aortic stenosis, HOCM
PISA – Formulas

Flow @ PISA = flow @ regurgitant orifice

Flow (t) = surface area x velocity (t)

\[ 2\pi r^2 \times V_{aliasing} = ERO \times V_{regurg} \]

Hemispheric surface area

Similar timing (mid-systole)

ERO (cm\(^2\)) = 6.28r\(^2\) \times \frac{V_{aliasing}}{V_{regurg}}

Reg Vol (ml/beat) = ERO \times VTI
**MR PISA – Shortcut I**

- \( V_{\text{aliasing}} \rightarrow \text{set @ 30 cm/s} \)
  
  Assume \( V_{\text{MR}} \sim 5 \text{ m/s (500 cm/s; 100 mmHg)} \)
  
  If \( r \geq 1 \text{ cm} \rightarrow \text{ERO} \geq 0.4 \text{ cm}^2 \) (severe MR)

\[
\text{ERO} = 6.28r^2 \times \frac{V_{\text{aliasing}}}{V_{\text{regurg}}} 
\]
MR PISA – Shortcut II

- $V_{\text{aliasing}} \rightarrow \text{set @ 40 cm/s}$
- Assume $V_{\text{MR}} \sim 5 \text{ m/s}$
- $\rightarrow \text{ERO} = r^2 / 2$

\[
\text{ERO} = 6.28r^2 \times \frac{V_{\text{aliasing}}}{V_{\text{regurg}}}
\]
PISA – Caveats

- Multiple technical caveats
- Dynamic MR
  - Timing of measurement
    - e.g. – MVP, ischemic MR
- Multiple MR jets
- Angle correction
  - Eccentric jets +++
## MR Severity

<table>
<thead>
<tr>
<th></th>
<th>ERO (cm²)</th>
<th>RV (ml)</th>
<th>RF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mild (I)</strong></td>
<td>&lt;0.2</td>
<td>&lt;30</td>
<td>&lt;30</td>
</tr>
<tr>
<td><strong>Moderate (II)</strong></td>
<td>0.2-0.3</td>
<td>30-45</td>
<td>30-40</td>
</tr>
<tr>
<td><strong>Mod-severe (III)</strong></td>
<td>0.3-0.4</td>
<td>45-60</td>
<td>40-50</td>
</tr>
<tr>
<td><strong>Severe (IV)</strong></td>
<td>&gt;0.4</td>
<td>&gt;60</td>
<td>&gt;50</td>
</tr>
</tbody>
</table>

**Grades III & IV = surgical MR**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;0.3</td>
<td>&gt;45</td>
<td>&gt;40</td>
</tr>
</tbody>
</table>
Aortic Regurgitation
## AR Severity (PISA / QD)

<table>
<thead>
<tr>
<th>Grade</th>
<th>ERO (cm²)</th>
<th>RV (ml)</th>
<th>RF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild (I)</td>
<td>&lt; 0.1</td>
<td>&lt; 30</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Moderate (II)</td>
<td>0.1-0.2</td>
<td>30-45</td>
<td>30-40</td>
</tr>
<tr>
<td>Mod-severe (III)</td>
<td>0.2-0.3</td>
<td>45-60</td>
<td>40-50</td>
</tr>
<tr>
<td>Severe (IV)</td>
<td>&gt; 0.3</td>
<td>&gt; 60</td>
<td>&gt;50</td>
</tr>
</tbody>
</table>

**Grades III & IV = surgical AR**

<table>
<thead>
<tr>
<th></th>
<th>&gt; 0.2</th>
<th>&gt; 45</th>
<th>&gt;40</th>
</tr>
</thead>
</table>
Additional Doppler Findings - AR

- Flow reversal – descending aorta
- P t1/2 – Multiple determinants
  - AR severity $\uparrow \rightarrow$ P t1/2 $\downarrow$
  - LV compliance $\downarrow \rightarrow$ P t1/2 $\downarrow$
  - SVR $\downarrow \rightarrow$ P t1/2 $\downarrow$
- Do not confuse chronic with acute AR
- Cutoffs: >400 ms / 250-400 / <250 ms
Prosthetic Valves
Doppler Velocity Index = \frac{\text{Velocity}_{LVO}}{\text{Velocity}_{jet}}
Effective Orifice Area = \frac{CSA_{LVO} \times VTI_{LVO}}{VTI_{JET}}
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
<th>Possible stenosis</th>
<th>Suggests significant stenosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak velocity (m/s)†</td>
<td>&lt;3</td>
<td>3-4</td>
<td>&gt;4</td>
</tr>
<tr>
<td>Mean gradient (mm Hg)†</td>
<td>&lt;20</td>
<td>20-35</td>
<td>&gt;35</td>
</tr>
<tr>
<td>DVI</td>
<td>≥0.30</td>
<td>0.29-0.25</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>EOA (cm²)</td>
<td>&gt;1.2</td>
<td>1.2-0.8</td>
<td>&lt;0.8</td>
</tr>
<tr>
<td>Contour of the jet velocity through the PrAV</td>
<td>Triangular, early peaking</td>
<td>Triangular to intermediate</td>
<td>Rounded, symmetrical contour</td>
</tr>
<tr>
<td>AT (ms)</td>
<td>&lt;80</td>
<td>80-100</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

PrAV, Prosthetic aortic valve.

*In conditions of normal or near normal stroke volume (50-70 mL) through the aortic valve.
†These parameters are more affected by flow, including concomitant AR.
<table>
<thead>
<tr>
<th>Finding</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak mitral velocity $\geq 1.9$ m/s$^*$</td>
<td>90%</td>
<td>89%</td>
<td>Also consider high flow, PPM</td>
</tr>
<tr>
<td>$\text{VT}<em>{\text{MMV}}/\text{VT}</em>{\text{LVO}} \geq 2.5^*$</td>
<td>89%</td>
<td>91%</td>
<td>Measurement errors increase in atrial fibrillation due to difficulty in matching cardiac cycles; also consider PPM</td>
</tr>
<tr>
<td>Mean gradient $\geq 5$ mmHg$^*$</td>
<td>90%</td>
<td>70%</td>
<td>At physiologic heart rate; also consider high flow, PPM</td>
</tr>
<tr>
<td>Maximal TR jet velocity $&gt; 3$ m/s$^*$</td>
<td>80%</td>
<td>71%</td>
<td>Consider residual postoperative pulmonary hypertension or other causes</td>
</tr>
<tr>
<td>LV stroke volume derived by 2D or 3D imaging is $&gt;30%$ higher than systemic stroke volume by Doppler</td>
<td>Moderate sensitivity</td>
<td>Specific</td>
<td>Validation lacking; significant MR is suspected when LV function is normal or hyperdynamic and $\text{VT}_{\text{LVO}}$ is $&lt;16$ cm</td>
</tr>
<tr>
<td>Systolic flow convergence seen in the left ventricle toward the prosthesis</td>
<td>Low sensitivity</td>
<td>Specific</td>
<td>Validation lacking; technically challenging to detect readily</td>
</tr>
</tbody>
</table>

PRMV, Prosthetic mitral valve.
*Data from Olmos et al.\textsuperscript{146} When both peak velocity and VTI ratio are elevated with a normal pressure half-time, specificity is close to 100%.
Normal

Obstructed

Pulsed Doppler
LVO

1.1 m/s

CW Doppler
Prosthetic AV

2.8 m/s

MG = 22 mmHg
DVI = 0.4
AT = 75 ms

MG = 80 mmHg
DVI = 0.18
AT = 180 ms
Sample Questions
Case #1

76 yo woman; Hx of CHF; syst murmur

- Hyperdynamic LV contraction
  - Small LV cavity
  - Mild concentric LVH
  - No sub-aortic obstruction
- Calcified aortic valve (difficult to image valve)
- Peak velocities
  - Aortic valve (CW): 4.8 m/s
  - LVOT (PW): 1.9 m/s
Question #1
What is the Peak Transaortic PG?

Hint: $4.8^2 = 23$

1. 92 mmHg
2. 76 mmHg
3. 106 mmHg
4. Can’t tell
Answer #1

1. 92 mmHg
2. 76 mmHg
3. 106 mmHg
4. Can’t tell

Correction for high proximal velocity (1.9 m/s)

**Bernoulli:** \[ PG = 4 \times \left( V_{\text{dist}}^2 - V_{\text{prox}}^2 \right) \]

\[ PG = 4 \times (23 - 4) = 76 \text{ mmHg} \]
Case #2

78 man; CHF; systolic murmur

► Severe LV systolic dysfunction (LVEF ~ 20%)

► Calcified aortic valve

► Aortic valve
  ▪ Peak PG: 41 mmHg; mean PG: 28 mmHg
  ▪ VTI: 72 cm; peak velocity: 3.2

► LVOT
  ▪ Diameter: 2.2 cm
  ▪ VTI: 25 cm; peak velocity: 1.1 m/s
Question #3

AS Severity?

1. Mild
2. Moderate
3. Severe (low-gradient AS)
4. I need more time to calculate
5. Not enough data to answer the question
Answer #3

1. Mild
2. Moderate
3. Severe (low-gradient AS)
4. I need more time to calculate
5. Not enough data to answer the question
Answer #3

► Low-gradient AS – suspected (LVEF ↓↓)

► But

- Normal LV output
  - LVOT VTI: 25 cm, LVOT diameter: 2.2 cm
  - SV: 95 ml (CO = 5.7 L/min)
- VTI ratio (or peak vel ratio) ~ 1:3
  - VTI ratio: 25 / 72
  - Peak vel ratio: 1.1 / 3.2
- AVA = 1.3 cm²
Case #3
40 yo woman; MS; NYHA III

► MVA
  ▪ Planimetry MVA: 1.3 cm²
  ▪ P_{\frac{1}{2}} MVA: 1.3 cm² (P_{\frac{1}{2}}: 170 ms)

► MR: mild

► Mean PG: 12 mmHg (@ HR 70)

► SPAP: 50 mmHg

Discrepancy
Question #4
Possible causes of discrepancy

All of the possibilities EXCEPT

1. Significant sub-valvular disease
2. Severe MR
3. Heart rate
4. LA compliance ↓
5. LV compliance ↓
All of the possibilities **EXCEPT**

1. **Significant sub-valvular disease**
   - Planimetry overestimates physiologic MVA

2. **More severe MR**
   - MV PG ↑ → severe combined MV disease

3. **Heart rate**
   - HR ↑ → MV PG / symptoms ↑ for given MVA

4. **LA compliance ↓** → MVA ↑ (P t1/2 ↓)

5. **LV compliance ↓**
Case #5

60 woman; carcinoid heart disease

- Severe TR (severe leaflet malcoaptation)
- RV systolic dysfunction
- Peak TR PG: 20 mmHg
- Estimated RA pressure: 25 mmHg
Question #5
PA systolic pressure?

1. 45 mmHg
2. Can’t calculate – TR malcoaptation may cause overestimation of peak TR PG
3. Can’t calculate – associated pulmonary valve disease likely
4. Can’t calculate – calculation invalid due to RV dysfunction
Answer #5

PA systolic pressure?

1. 45 mmHg
2. Can’t calculate – TR malcoaptation may cause overestimation of peak TR PG
3. Can’t calculate – associated pulmonary valve disease likely
4. Can’t calculate – calculation invalid due to RV dysfunction
Good Luck with the test

…but just in case it doesn’t go so well, the next slide is not an option!
Thank You

Acknowledgment: Dr. Yoram Agmon