Aortic Stenosis
Different Variants

Amr E Abbas, MD, FACC, FSCAI, FASE, FSVM
Director, Interventional Cardiology Research
Beaumont Health
Associate Professor of Medicine,
OU/WB School of Medicine
ASCeXAM/ReASCeXAM 2018
Boston, MA

DISCLOSURE
Relevant Financial Relationship(s)
None
Off Label Usage
None
**Severity of Aortic Stenosis**

**Severe Aortic Stenosis**

<table>
<thead>
<tr>
<th>Area Gradient Match</th>
<th>Mean Gradient (mmHg)</th>
<th>Valve Area (cm²)</th>
<th>Valve Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>&lt;25</td>
<td>&gt;1.5</td>
<td>2-2.9</td>
</tr>
<tr>
<td>Moderate</td>
<td>25-40</td>
<td>1.0-1.5</td>
<td>3-3.9</td>
</tr>
<tr>
<td>Severe</td>
<td>&gt;40</td>
<td>&lt;1.0</td>
<td>&gt;4.0</td>
</tr>
</tbody>
</table>

\[iAVA < 0.6 \text{ cm/m²}\]

**Severity of Aortic Stenosis**

**Severe Aortic Stenosis**

**Area Gradient Mismatch**

<table>
<thead>
<tr>
<th></th>
<th>Mean Gradient (mmHg)</th>
<th>Valve Area (cm²)</th>
<th>Valve Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>&lt;20</td>
<td>&gt;1.5</td>
<td>2 - 2.9</td>
</tr>
<tr>
<td>Moderate</td>
<td>20-39</td>
<td>1.0-1.5</td>
<td>3 - 3.9</td>
</tr>
<tr>
<td>Severe</td>
<td>&gt;40</td>
<td>&lt;1.0</td>
<td>&gt;4.0</td>
</tr>
</tbody>
</table>

Nishimura, et al., Circulation, 2014

**Reverse Area Gradient Mismatch**

<table>
<thead>
<tr>
<th></th>
<th>Mean Gradient (mmHg)</th>
<th>Valve Area (cm²)</th>
<th>Valve Velocity (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild</td>
<td>&lt;20</td>
<td>&gt;1.5</td>
<td>2 – 2.9</td>
</tr>
<tr>
<td>Moderate</td>
<td>20-39</td>
<td>1.0-1.5</td>
<td>3 – 3.9</td>
</tr>
<tr>
<td>Severe</td>
<td>&gt;40</td>
<td>&lt; 1.0</td>
<td>&gt; 4.0</td>
</tr>
</tbody>
</table>

Nishimura, et al., Circulation 2014

Aortic Stenosis
Determining the “True” Severity

Measurement Errors Must be Excluded

Topics of Discussions

• GOA Vs. EOA
• Doppler Vs. Catheter
• Factors affecting Gradient
• Area/Gradient Mismatch
• Reverse Area Gradient Mismatch
GOA Versus EOA

GOA: Planimetry
EOA: Continuity Equation/Gorlin
Coefficient of Contraction: EOA/GOA
Evangelista Torricelli 1608-1647

Georg Simon Ohm 1789-1854

Aortic Stenosis

Catheterization: Flow $Q = \Delta \text{Pressure}$

Doppler: Flow $Q = \text{Area} \times \text{Velocity}$
Daniel Bernoulli
1700-1782

Bernoulli Equation

P1-P2 = \frac{1}{2} \rho (V_2^2 - V_1^2) + \rho \int \max \frac{dv}{dt} * ds + R(\mu)

Convective acceleration
Flow acceleration
Viscous Friction

Short Tube
Non-Laminar
Acceleration

P1 & V1 = proximal to obstruction
P2 & V2 = distal to obstruction
\rho = mass density of blood
R = viscous resistance
\mu = viscosity
Pressure Recovery

Pressure Energy In Ventricle

Doppler Gradient: $\Delta P_{\text{max}}$

Pressure Recovery

Catheter Gradient: $\Delta P_{\text{net}}$

Doppler versus Catheter Area and Gradient Assessment
Upcoming Concepts

• For a given AV GOA
  The Gradient can be variable
  The EOA can be variable
  (Derived from gradient)
  The Area and Gradient may not match
  The Doppler and Catheter measures may not match

Doppler Aortic Valve Area Assessment

[Table]

Noninvasive estimation of valve area in patients with aortic stenosis by Doppler ultrasound and two-dimensional echocardiography

Terje Skjærpe, M.D., Lars Hegrenaes, M.D., and Liv Hatle, M.D.

• Described in 30 subjects; 14 had significant AR
• Compared only to Fick and single plane CO angiography
Doppler Gradient Assessment

Described in 10 subjects
Extrapolated to aortic valve

Doppler Aortic Valve Gradient Assessment

- Doppler
  - $MIG = 4V_2^2 - 4V_1^2$
  - $MIG = 4V_2^2$
  - Use $MIG = 4V_2^2 - 4V_1^2$
    - $V_1 > 1.5\text{ m/second}$
    - $V_2 < 3\text{ m/second}$
Doppler versus Catheter Gradient Assessment

- Catheterization
  - Peak to Peak
  - $P_{mean \text{ Catheter}}$
- Doppler
  - $MIG (4V_2^2 - 4V_1^2)$
  - $P_{mean \text{ Doppler}}$
  - $MIG \text{ always } > \text{ PPG}$
  - $P_{mean \text{ Doppler}} - P_{mean \text{ Catheter}} = P_{rec}$

Not Pressure Recovery

- LV Pressure: Peak 200 mmHg
- Aortic Pressure: Peak 150 mmHg
- Cath Peak to Peak: 50 mmHg
- Doppler Velocity: 4.5 m/second
- Doppler Maximum Instantaneous Gradient: Peak: 81
Pressure Recovery

- Catheterization Gradient = Mean 40 mmHg
- Doppler Mean Gradient = 50 mmHg
- Pressure Recovery = 10 mmHg

Gradient Determinants

- Area
- Flow
- Jet Eccentricity
- Aortic root diameter
- Global LV afterload
Gradient Determinants

Area

• There is an inverse quadratic relationship: Area & MG
• \( \Delta P = \frac{Q^2}{(K \times EOA^2)} \)

Gradient Determinants

Flow

• Direct quadratic relationship: Flow & MG
• Low Flow: SVI < 35ml/m²
• Low Flow rate < 200-250 ml/s
Left Ventricle

Gradient: 40 mmHg

Aorta

Vena Contracta

Aortic Valve

GOA

EOA

LVOT

Left Ventricle

Gradient: 24 mmHg

Aorta

Vena Contracta

Aortic Valve

GOA

EOA

LVOT
A: EDV = 115, ESV = 45,
SV = 115 - 45 = 70 ml
BSA = 1.79
EF = 70/115 = 60%
SVI = 39 ml/m²

B: EDV = 85, ESV = 35,
SV = 85 - 35 = 50 ml
BSA = 1.79
EF = 50/85 = 60%
SVI = 28 ml/m²

Moderate AS will have a lower SEP and a higher flow rate than a patient with severe AS despite similar stroke volume.
Gradient Determinants
Eccentric Jet

• Eccentric Jet Up to 30° → Higher Gradient.
• Jet squeezed against aorta. More pressure loss & less pressure recovery, Bicuspid valves/radiation

10 Vel 0.7 m/s, MG 23 mmHg, EOA 0.2

Gradient Determinants
Aortic Root Diameter

• The smaller the aortic root, the less energy loss, the more the pressure recovery, the lower the catheter gradient.
• This effect plateaus at a diameter of STJ 30 mm (area 7 cm²)
Moderate AS and low compliance = Severe AS and normal compliance

\[ Z_{VA} = 150 \text{ mmHg} + 26 \text{ mmHg} = 5.5 \text{ mmHg/ml\cdot m}^2 \]

\[ 32 \text{ ml/m}^2 \]
Severe Aortic Stenosis with Normal Function

Area Gradient Match

Normal Ejection Fraction
Normal SV & Flow Rate
AVA < 1 cm$^2$
$\Delta P_{\text{mean}} > 40$ mmHg

Aortic Stenosis
Area/Gradient Mismatch
Area Gradient Mismatch

- Measurement Error
- Assumption Error
- Low Flow/Low Gradient/Low EF area/gradient mismatch
- Low Flow/Low Gradient/Normal EF area/gradient mismatch

Measurement Errors: LVOT D Error Proportional to AVA
**Measurement Errors: LVOT D**

**Error Proportional to AVA**

\[
\text{LVOT diam} = 2.0 \text{ cm} \\
\text{LVOT TVI} = 25 \text{ cm}
\]

\[
\text{Area 1} \times \text{TVI}_1 = \text{Area 2} \times \text{TVI}_2
\]

\[
.785 \times \left( \frac{\text{LVOT diam}}{2.0} \right)^2 \times \text{AV TVI} = \text{AVA} \times 98
\]

AVA = \frac{78.8}{98} = 0.8 \text{ cm}^2

If LVOT diameter 1.8 cm²

AVA = \frac{78.8}{98} = 0.8 \text{ cm}^2

\downarrow 19\%
Measurement Errors: LVOT TVI
Error Proportional to AVA

Measurement Errors: AV VTI
Error Inversely Proportional to AVA
Measurement Errors
Catheterization and Doppler

84 Y/O NYHA III, 3/6 SEM, no S2

MG 25 mmHg

MG 31 mmHg

Measurement Errors
Catheterization and Doppler
Measurement Errors
Catheterization and Doppler

Assumption Errors
MG when AVA = 1.0cm²

<table>
<thead>
<tr>
<th>Aortic Valve Area (cm²)</th>
<th>Mean Gradient (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>2.0</td>
<td>6.6</td>
</tr>
<tr>
<td>1.0</td>
<td>26</td>
</tr>
<tr>
<td>0.9</td>
<td>32</td>
</tr>
<tr>
<td>0.8</td>
<td>41</td>
</tr>
<tr>
<td>0.7</td>
<td>53</td>
</tr>
<tr>
<td>0.6</td>
<td>73</td>
</tr>
</tbody>
</table>

Carabello BA. NEJM 2002;346:677-682
Aortic Stenosis
Area Gradient Mismatch

Low flow (normal or reduced LVEF)
Mean Gradient <30-40mmHg
AVA <1.0cm²

True, Severe AS
Mild-Mod AS
Low Flow (pseudo AS)

Severe Aortic Stenosis with Normal Function
MIG: 100 mmHg
LVOT AV = 0.2
5 m/s
1 m/s
Area/Gradient Match
AVA<1cm²
ΔP_{mean}>40mmHg

Severe Aortic Stenosis with Low Gradient
MIG: 36 mmHg
LVOT AV = 0.2
3 m/s
0.6 m/s
Area/Gradient Mismatch
AVA<1cm²
ΔP_{mean}<40mmHg
Aortic Stenosis
Low Flow/Low Gradient/Low EF

Risk Stratify
Dobutamine Stress
Projected AVA
AV Calcium Score
Strain Imaging

Low EF Area Gradient Mismatch

Risk Stratify
Dobutamine Stress
Dobutamine Echocardiography

Baseline Doppler hemodynamics

Flow Reserve? ≥ 20% SV

True Severe AS (D2) IIa

Pseudo Severe AS

Vmax Vmean

Mean gradient AV Area

SVI 27 – 48
AVA 0.6 – 0.8 cm²
AV mean gradient 20 – 43 mmHg
Case

- 62 y/o male
- STEMI and subsequent CABG five years ago
- Recurrent heart failure x 3 months
Stroke Volume = CSA x TVI

= 0.785 (2.2 cm)² x

= 53 cm³
\[
\text{Area}_{AV} = \frac{0.785 \times (2.2\text{cm})^2 \times (\_\_\_\_)}{(\_\_\_\_\_)}
\]

\[
= 0.9 \text{ cm}^2, \text{ MG 24mmHg}
\]
### Dobutamine Stress

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV Stroke Volume</td>
<td>53– 91ml</td>
</tr>
<tr>
<td>Mean AV Gradient</td>
<td>24 – 52mmHg</td>
</tr>
<tr>
<td>Valve Area</td>
<td>0.9cm² – 1.0cm²</td>
</tr>
</tbody>
</table>

### Low EF Area Gradient Mismatch

- Risk Stratify
- Projected AVA
Projected AV Area ≤ 1-1.2 cm²

Dobutamine Stress Echocardiography
for Management of Low-Flow,
Low-Gradient Aortic Stenosis

Indexed AVA_proj ≤ 0.55 cm²/m²
AVA_proj ≤ 1 cm²

Guidelines criteria:
MG_peak ≥ 40 mm Hg and AVA_peak ≤ 1 cm²
AVA_peak ≤ 1 cm²
MG_peak ≥ 40 mm Hg

Mortality Hazard Ratio (95% Confidence Interval)

LVOT Aortic Valve

Rest
SV = 53 ml
AVA = 0.9 cm²
Velocity = 0.8 m/s
TVI = 14 cm
ET = 0.31

Peak
SV = 91 ml
AVA = 1.0 cm²
Velocity = 3.0 m/s
TVI = 56 cm
Q_mean = 325 ml/s

AVA_proj = 0.96 cm²

LVOT Aortic Valve

Rest
Velocity = 1.3 m/s
TVI = 24 cm
ET = 0.28

Peak
Velocity = 5.0 m/s
TVI = 90 cm

Low EF Area Gradient Mismatch

Risk Stratify
Stroke Flow Rate

LVOT

Velocity=0.8m/s
TVI=14cm
SV= 53ml
AVA=0.9cm²
ET=0.31
\( Q_{mean} = \frac{53}{0.31} = 171\text{ml.s}^{-1} \)

LVOT

Velocity=1.3m/s
TVI=24cm
SV= 91ml
AVA=0.9cm²
ET=0.28
\( Q_{mean} = \frac{91}{0.28} = 325\text{ml.s}^{-1} \)
## Resting Aortic Valve Area at Normal Transaortic Flow Rate Reflects True Valve Area in Suspected Low Gradient Severe Aortic Stenosis

<table>
<thead>
<tr>
<th>Q &lt; 200 ml/s</th>
<th>n</th>
<th>Rest AVA, cm²</th>
<th>Stress AVA, cm²</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48</td>
<td>0.74±0.12</td>
<td>0.89±0.25</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Q ≥ 200 ml/s</td>
<td>19</td>
<td>0.85±0.09</td>
<td>0.89±0.12</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Interpretation:** If normal resting flow rate, the corresponding AVA is likely to represent the true hemodynamic severity of the stenosis and further “flow correction” with SECHO is not likely required.

---

## Aortic Stenosis

**Low Flow/Low Gradient/Low EF**

**Risk Stratify**

**AV Calcium Score**
Impact of Aortic Valve Calcification, as Measured by MDCT, on Survival in Patients with Aortic Stenosis

Aortic Valve Calcium Burden
1. 1651 AU previous study
2. >1200 (1600) AU (W), >2000 (3000) AU (M)
3. 300 AU/cm² (W), 500 AU/cm² (M)
4. Less Likely: <800 AU (W), <1600 AU (M)

Aortic Stenosis
Low Flow/Low Gradient/Low EF
Risk Stratify
Strain Imaging
Case

• 75 year old male
• Presents with dyspnea and syncope
• HTN (treated BP 150/75)
• Grade III/VI mid peaking systolic murmur LSB
Echocardiography
Normal EF Area Gradient Mismatch

- LVEF 55%
- AV Mean G 26mmHg
- AVA 0.8cm²
- AVA index 0.45cm²/m²
- LVEDV 88ml
- SVi 32 ml/m²
Flow Versus EF

• So why is the Flow Low?
  
  **Preload**: Small LV volume (LVH)
  
  **Contractility**: Despite EF normal, contractility (&EF) impaired for degree of LVH
  
  **Afterload**: Global LV afterload (Valve and Vascular)

Approach to Patients with Normal EF Area Gradient Mismatch

1. Is the patient symptomatic? (exercise testing)
2. Is the stenosis severe?
3. Is the patient hypertensive?
4. GLS/contractility & Diastolic Function/RWT?
5. Other Causes of Low Flow? Mitral regurgitation
Aortic Stenosis
Low Flow/Low Gradient/NL EF

Risk Stratify
AV Calcium Score
Strain Imaging
Stroke Flow Rate

Novel Classification of AS with Normal EF
Aortic Stenosis
Reverse Area/Gradient Mismatch

Elevated Gradient Despite non-critical AS

Reverse Area/Gradient Mismatch
AVA > 1 cm²
$\Delta P_{\text{mean}} > 40$ mmHg

Courtesy Heidi Connolly
Causes of Reverse A/G Mismatch

- Errors of Measurement
- High Flow
- Pressure recovery
- Eccentric Jet
- Para-valvular Obstruction
- Prosthetic-valve specific

Errors of Measurements
Eccentric Mitral
Mitral Regurgitant Jet Versus Aortic Stenosis Jet

- Mitral regurgitation occupies IVC and IVR

High Flow

- Aortic regurgitation
- Hyperdynamic states (dialysis, anemia)
- Dimensionless Index
**Energy Loss Index**

- **Energy loss Co-efficient**
  \[ ELCo = \frac{AVA \times AAa}{AAa - AVA} \]
- **AVA = aortic valve area, AAa = aortic area**
- **Energy loss index: \( \frac{ELCo}{BSA} \)**
- **ELI < 0.52-0.76 cm²** has poor outcomes and severe AS
- **More significant with increase flow and moderate aortic stenosis**
Pressure Recovery/High Flow

EOA = 0.6 cm²
AAd = 2.2 cm
AAa = 3.8 cm²
EICo = 3.8x0.6/3.8-0.6

Eccentric Jet

• Case:
• 29 y/o male
• Carries a diagnosis of Asymptomatic severe AS
• Quit Law School
Cardiac Catheterization $P_{\text{mean}} = 50 \text{ mmHg}$, $\text{AVA} = 1 \text{ cm}^2$

$\text{AVA} = 2.61 \text{ cm}^2$

$P_{\text{mean}} = 57 \text{ mmHg}$

$\text{MIG} = 91 \text{ mmHg}$

Eccentric Jet
Eccentric Jet: Echo

Para-valvular Obstruction

• Sub-Aortic membrane
• Hypertrophic Obstructive Cardiomyopathy
• Supravalvular Obstruction
• Mitral valve Prosthesis
Sub-Aortic Membrane

Progressive Disease
- Other congenital anomalies in 50%
- VSD/PDA/Coarctation
- Shone's Complex
- Bicuspid AV
- Leftsided-SVC

Types: Membrane, fibromuscular ridge, Diffuse tunnel narrowing, mitral tissue

May Cause aortic regurgitation
Treatment: Surgery
- No symptoms: Catheter LVOT-A peak/Doppler Mean = 50 mmHg
- Symptoms: Catheter LVOT-A peak/Doppler Mean = 30-50 mmHg
- Adults may use Doppler Peak > 50 mmHg
- Resection/Konno procedure
Hypertrophic Obstructive Cardiomyopathy

Alcohol Septal Ablation or Surgery
High Risk features
ICD

Supra-Aortic Obstruction

Non-Familial Sporadic
William syndrome:
  - Elfin Facial
  - Hypercalcemia
  - Behavioral
  - Diagnosed by CVS and fetal echo

Familial Sporadic
Coronary anomalies
Types: Hour glass, Membrane, Diffuse narrowing: Surgery
Obstruction by Mitral Valve Prosthesis

- In addition to AVA and $\Delta P_{\text{mean}}$
- Flow SVI < 35 ml/m², Flow rate < 200 ml/s
- Flow eccentricity
- Pressure Recovery/ AV morphology

Think of global afterload in AS to the LV: Mixed AV disease/HTN
regardless of symptoms

- Area and Gradient may not match
- Echo/Cath/AV morphology provide complimentary NOT identical
data

Take Home Message
Severe Aortic Stenosis

Multimodality Approach

- In addition to AVA and $\Delta P_{\text{mean}}$
- Flow SVI < 35 ml/m², Flow rate < 200 ml/s
- Flow eccentricity
- Pressure Recovery/ AV morphology

- Think of global afterload in AS to the LV: Mixed AV disease/HTN
  regardless of symptoms
- Area and Gradient may not match
- Echo/Cath/AV morphology provide complimentary NOT identical
data
CONCLUSIONS

• For a given AV GOA
  The Gradient can be variable
  The EOA can be variable
  (Derived from gradient)
  The Area and Gradient may not match
  The Doppler and Catheter measures may not match

THANK YOU