Advanced Hemodynamic Issues in Aortic Stenosis

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Agenda

- What is severe aortic stenosis?
- Anatomic Orifice Area versus Effective Orifice Area
  - Gorlin Formula
  - Continuity Equation
- Pressure Recovery and Energy Loss
- Comprehensive hemodynamic assessment
  - Valvular Load (Gradients, Stroke Work Loss, Energy Loss)
  - Vascular Load (Systemic Arterial Compliance)
  - Ventriculovascular Impedance (Z)
- Low-pressure, low area stenosis with preserved LV function?
- How to solve inconsistencies
Current Guideline Definition of Severe AS

- AVA < 1.0 cm²
- AVI < 0.6 cm²/m² BSA (ESC)
- Peak velocity > 4 m/s
- Mean Gradient > 40 mm Hg (previously 50)
Inconsistencies of echocardiographic criteria for the grading of aortic valve stenosis

2427 Patients with normal LV fx

- AVA of 1.0 cm²: \( \Delta P_{\text{mean}} \) 21 mm Hg, \( V_{\text{max}} \) 3.3 m/s
- \( \Delta P_{\text{mean}} \) 40 mm Hg: AVA of 0.75 cm²
- \( V_{\text{max}} \) 4.0 m/s: AVA of 0.82 cm²

ESC guidelines 2007: “Severe AS is unlikely if the CO is normal and the mean gradient is < 50 mm Hg”

Minners J, et al. EHJ 2008
Inconsistencies of echocardiographic criteria for the grading of aortic valve stenosis

Table 2 Percentage of patients diagnosed with severe aortic stenosis depending on which echocardiographic criterion was used

<table>
<thead>
<tr>
<th>Guidelines/recommendations</th>
<th>Parameter</th>
<th>Patients with severe stenosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHA/ACC&lt;sup&gt;3&lt;/sup&gt;</td>
<td>AVA &lt; 1.0 cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>69%</td>
</tr>
<tr>
<td>ESC&lt;sup&gt;2&lt;/sup&gt;</td>
<td>AVA/BSA &lt;0.6 cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>76%</td>
</tr>
<tr>
<td>Otto&lt;sup&gt;4&lt;/sup&gt;</td>
<td>$V_{max}$ &gt;4.0 m/s</td>
<td>45%</td>
</tr>
<tr>
<td>AHA/ACC&lt;sup&gt;3&lt;/sup&gt;</td>
<td>$\Delta P_m$ &gt; 40 mmHg</td>
<td>40%</td>
</tr>
</tbody>
</table>

AVA, aortic valve area; BSA, body surface area; $V_{max}$, peak flow velocity; $\Delta P_m$, mean pressure gradient.
Anatomic (Geometric) Orifice Area

Can (only) be assessed by direct imaging
Effective Orifice Area (EOA)

Flow contracts distal to the anatomic orifice depending on the inlet geometry.

- **flat plate**: $C_c = 0.6$
- **funnel**: $C_c = 0.8$
- **tube**: $C_c = 1.0$

The effective orifice area is the CSA of the vena contracta (in the absence of pressure recovery).

$C_c = \text{Effective Orifice Area} / \text{Anatomic Orifice Area}$
Valve shape determines the effective orifice area and therefore the hemodynamic burden. The same anatomic orifice area may thus generate different gradients depending on valve shape.

Gorlin Formula

Torricelli’s Law describes flow across a round orifice:

\[
\text{Flow rate [cm}^3/\text{s}] = \text{Area [cm}^2] \times \text{velocity [cm/s]} \times C_c
\]

\[
\text{Area [cm}^2] = \frac{\text{Flow rate [cm}^3/\text{s}]}{\text{Velocity [cm/s]} \times C_c}
\]

\[
\text{Area} = \frac{\text{CO}/(\text{DFP or SEP})(\text{HR})}{44.3 \times C \sqrt{\Delta P}}
\]

Empiric constant  \( C \) set at 1 for AV and 0.85 for MV

Aims to estimate anatomic AVA, but actually calculates aortic EOA
Continuity Equation (EOA)

Conservation of mass:

\[ A_1 \times \bar{v}_1 = A_2 \times \bar{v}_2 \]

Dimensionless Index (AVA normalized for body size):
Continuity Equation

Undertestimates AVA by an average of 0.2 cm²

Underestimates LVOT Area by assuming circular shape

Baumgartner H et al (Cardiology 1990;77:101-11)
Continuity Equation

- Oval shape of the LVOT (in systole less than in diastole)
- Underestimation of the full LVOT diameter d/t calcification making the diameter appear smaller than it is (by TEE usually 1-2 mm larger!)
Pressure Recovery

Outlet geometry allowing gradual expansion of streamlines eliminates flow separation and prevents turbulence (pressure recovery).

Abrupt outflow (nozzle): turbulence, head loss

Gradually expanding outflow: eliminates flow separation and recovers the pressure drop

Prandtl L, Tietjens O: Applied Hydro- and Aeromechanics, New York, Dover 1957
Pressure Recovery

- Degree of pressure recovery determined by relationship between the size of the cross-sectional area of the vena contracta (EOA) and the area of the ascending aorta ($A_A$).
- More pressure recovery if aortic diameter is < 3.0 cm (particularly small aortic root) and less severe AS.
Pressure Recovery

16 mm Hg at rest

33 mm Hg during exercise

Laskey and Kussmaul, Circulation 1994
Pressure Recovery: Overestimation of Catheter Mean Gradients by Doppler Ultrasound

Observed (open circles) and corrected Doppler gradients (filled circles) versus gradients

Pressure Recovery: Underestimation of Catheter-Derived EOA by Doppler Ultrasound

\[ MG_{VC} = \text{Doppler Gradient} \]

\[ MG_{net} = \text{Cath Gradient} \]

\[ EOA_{Do} \]

Continuity equation

\[ EOA_{Cath} \]

Gorlin
Pressure Recovery: Underestimation of Catheter-Derived EOA by Doppler Ultrasound

Table 2. Theoretical Values of Doppler-Derived Effective Orifice Areas for Given Catheter-Derived Effective Orifice Areas and Aortic Diameters*

<table>
<thead>
<tr>
<th>Catheter-Derived EOA (cm²)†</th>
<th>Aortic Diameter = 2.0 cm (A_A = 3.14 cm²)</th>
<th>Aortic Diameter = 3.0 cm (A_A = 7.07 cm²)</th>
<th>Aortic Diameter = 4.0 cm (A_A = 12.6 cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50 (1.69)</td>
<td>1.02</td>
<td>1.24</td>
<td>1.34</td>
</tr>
<tr>
<td>1.00 (1.13)</td>
<td>0.76</td>
<td>0.88</td>
<td>0.93</td>
</tr>
<tr>
<td>0.75 (0.85)</td>
<td>0.61</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>0.50 (0.56)</td>
<td>0.43</td>
<td>0.47</td>
<td>0.48</td>
</tr>
</tbody>
</table>

*These values were derived from Equations 2 and 3. †The EOA value in parentheses was calculated from the Gorlin equation with the use of a constant of 44.3.

EOA = effective orifice area; A_A = cross-sectional area of the aorta.
Recovered EOA: Energy Loss Coefficient (ELC) is the net EOA

\[
\text{ELC} = \frac{\text{EOA}_c \times A_A}{A_A - \text{EOA}_c}
\]

\[
\text{ELI} = \frac{\text{ELC}}{\text{BSA}}
\]

The ELC essentially equals the AVA calculated by the Gorlin formula which uses the net gradient (after pressure recovery).

Recovered EOA (Energy Loss Coefficient) corresponds to the Gorlin Orifice Area

\[ y = 1.26x - 0.02 \]
\[ N = 272 \]
\[ r = 0.97 \quad \text{SEE} = 0.12 \text{ cm}^2 \]

\[ y = 0.93x + 0.09 \]
\[ N = 256 \]
\[ r = 0.97 \quad \text{SEE} = 0.11 \text{ cm}^2 \]
Energy Loss Index predicts outcome better than Gradients, EOA, EF

138 pts, retrospective

Is it severe AS requiring AVR?

- 80 year old female, fatigue, mild SOB during effort
- PG 48/29 mm Hg, EF 55%
- EOAc = 0.85 cm² (LVOT_D 18.5 mm)
- Height 158 cm, weight 60 kg, BSA 1.61 m²
- EOAI = 0.53 cm²/m²
- Aortic diameter immed above STJ = 2.7 cm
- ELC = 0.99 cm² (Gorlin)
- ELI = 0.62 cm²/m²
- EOA expected with a commonly used and commercially available size 21 bioprosthesis: 1.2 cm² (size 19: 1.01 cm²)
Is it severe AS requiring AVR?

- 78 year old female, SOB during exercise
- PG 62/39 mm Hg, EF 58%
- EOAc = 0.76 cm² (LVOTₐ 22 mm)
- Height 170 cm, weight 70 kg, BSA 1.82 m²
- EOAI = 0.43 cm²/m²
- Aortic diameter immed above STJ = 3.4 cm
- ELC = 0.83 cm² (Gorlin)
- ELI = 0.46 cm²/m²
- EOA expected with size 23 bioprosthesis (commercial, frequently used): 1.51 cm²
Compare Hemodynamics to Anatomy

- Look at the valve (how calcified, how immobile, orifice)
- Look at the diameter of the STJ and $A_A$ (< 3 cm, especially 2.5 or less – consider pressure recovery, calculate ELC, ELI)
- Look at the aortic root size (what is the expected EOA of the implantable prosthesis)
Prognosis of Patients With Severe AS...

...40 years ago!

Latent period (increasing obstruction, Myocardial overload)

Onset of severe symptoms

Average age of death

Average survival (yrs)

Angina

Syncope

Failure

Ross, Braunwald
Circulation 1968
Prognosis of Patients With Severe AS 2008

Latent period (increasing obstruction, Myocardial overload)

HTN
Diabetes
CAD
PVD
CRF

Average age of death

Ross, Braunwald
Circulation 1968
Shift of etiology → shift in natural history and hemodynamics

- **Past:** Usually congenital or rheumatic
- **Today:** “Degenerative” = atherosclerotic; i.e., involving increased rigidity of the aorta and impaired LV function, d/t systolic HTN, diabetes, CAD, aging heart
- **Past:** Normal/High-normal CO AS
- **Today:** Normal/low-normal CO AS
AS no longer an isolated valvular problem

Need to Quantify:
1. Valvular obstruction
2. Vascular load
3. Global arterial afterload

1. Valvular Obstruction

Energy Loss Index

Severe:
\( ELI < 0.55 \text{ cm}^2/\text{m}^2 \)

2. Vascular Load

**BP**

May be pseudo-normalized by reduced CO in the presence of LV dysfx

**PP**

Systemic Arterial Compliance: Stroke Volume Index/Pulse Pressure

**Severe:**

SAC ≤ 0.6 ml/m²/mm Hg

3. Global Arterial Afterload

Valvuloarterial Impedance

\[ Z = \frac{\text{SAP} + \text{MG}_{\text{net}}}{\text{SVI}} \]

This index represents the cost in mm Hg for each systemic ml of blood indexed for body size pumped by the left ventricle during systole.

Severe:
\[ Z \geq 4.5 \text{ mm Hg/ ml/m}^2 \]

Survival (%)

P = 0.003 (0.02*, 0.02**)

Number of patients at risk

Follow-up (years)

Reduced Systemic Arterial Compliance Impacts Significantly on Left Ventricular Afterload and Function in Aortic Stenosis
Implications for Diagnosis and Treatment

Martin Briand, MS,* Jean G. Dumesnil, MD, FACC,* Lyes Kadem, ENG, PHD,*† Antonio G. Tongue, MD,* Régis Rieu, ENG, PHD,† Damien Garcia, ENG, PHD,‡ Philippe Pibarot, DVM, PHD, FACC*

### Table 4. Independent Predictors of LV Systolic Dysfunction Defined as an LV Ejection Fraction <50%

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model Without $Z_{va}$</th>
<th></th>
<th>Model With $Z_{va}$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Odds Ratio (95% CI)</td>
<td>p Value</td>
<td>Odds Ratio (95% CI)</td>
<td>p Value</td>
</tr>
<tr>
<td>Female gender</td>
<td>—</td>
<td>—</td>
<td>3.5 (1.2–10.3)</td>
<td>0.025</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>25.2 (3.3–195.0)</td>
<td>0.001</td>
<td>16.7 (2.2–128.7)</td>
<td>0.007</td>
</tr>
<tr>
<td>ELI ≤0.50 cm²/m²</td>
<td>4.5 (1.8–11.5)</td>
<td>0.002</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SVi/PP ≤0.50 ml/m²/mm Hg</td>
<td>2.9 (1.1–7.6)</td>
<td>0.025</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$Z_{va}$ ≥5.0 mm Hg/ml/m²</td>
<td>N/A</td>
<td>N/A</td>
<td>4.2 (1.7–10.3)</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Paradoxical Low-Flow, Low-Gradient Severe Aortic Stenosis Despite Preserved Ejection Fraction Is Associated With Higher Afterload and Reduced Survival

Zeineb Hachicha, MD; Jean G. Dumesnil, MD; Peter Bogaty, MD; Philippe Pibarot, DVM, PhD

- 512 pts
- AVI < 0.6 cm²/m² BSA
- EF > 50%
- Normal Flow (NF) vs Low Flow (LF) - 35 ml/m²
- LF (35%): More female, lower gradient (32 ± 17 mm Hg vs 40 ± 15 mm Hg), lower EF (62 ± 8 vs 68 ± 7 %), smaller LV volumes

LF patients have markedly increased global LV afterload as evidenced by the valvulo-arterial impedance (29% higher) compared with the pts with the more classic features of severe AS.

Low flow rates comparable to those observed in patients with low-flow AS associated with low EF.

Low flow is d/t smaller cavity size with more pronounced concentric LVH (longstanding disease?)

Higher LV afterload by a combination of a similar stenosis severity, but a lower systemic arterial compliance compared with the NF group.

Paradoxical Low-Flow, Low-Gradient Severe Aortic Stenosis Despite Preserved Ejection Fraction Is Associated With Higher Afterload and Reduced Survival

Zeineb Hachicha, MD; Jean G. Dumesnil, MD; Peter Bogaty, MD; Philippe Pibarot, DVM, PhD

Inconsistent grading can be in part explained by SV (all SV were in the normal range, but somewhat lower SV accounted for obtaining AVA < 1 w/ $\Delta P_{\text{mean}} < 40$)

EOA by continuity is smaller than Gorlin AVA, and “adjustment to a cut-off value of 0.8 cm$^2$ might help”

Minners J, et al. EHJ 2008
Summary

- There is possibly a risk of underestimating disease severity in patients with low gradients secondary to low flow d/t severe vascular load (low SAC) in addition to valvular load because of normal EF.

- There is a clear risk of overestimating stenosis severity by underestimation of net EOA by the continuity equation (pressure recovery, LVOT area estimation).

- More comprehensive hemodynamic assessment can help balance these risk: All one needs for these calculations are 2 additional measurements: BP and diameter of ascending aorta at/above STJ.

- Don’t forget to look at the valve (and the patient).