Aortic Stenosis

Going Beyond the Gradient

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Conflicts of interest: GE, Abbott, Edwards (honoraria)

61 yo Man with Severe AS

Known AS x 2 years, progressive DOE x 6 months

Moderate LVH
LVEF 50%
Mild AR

\[ \Delta p = 153/101 \text{ mmHg} \]

AVA = 0.7 cm$^2$

Symptomatic AS that is Severe by $\Delta p$ and AVA

That’s all we need! When do we need more?

- Pressure gradient: Simplified Bernoulli equation
  - Physical principles
  - Pitfalls
    - Pressure gain
    - Misalignment
    - Vena contracta
    - Proximal velocity
    - Inertia
    - Pressure recovery
- Valve area: Continuity equation
  - Physical principles
  - Pitfalls
    - Flow profile
    - Vena contracta

Continuous Wave Doppler

Converting Velocity into Pressure

Conservation of energy: Bernoulli equation

\[ \Delta p = \frac{1}{2} \rho \left( v_1^2 - v_2^2 \right) + M \frac{dv}{dt} + R(t) \]

Convective
Inertial
Viscous
Accelration
Component
Dissipation

For flow that is 1) inviscid (as cardiac flow is), 2) through a restrictive orifice (negligible inertial component), and 3) with $v_1 >> v_2$, this reduces to:

\[ \Delta p = 4 v_1^2 \]

\[ \Delta p = (2v)^2 \]
Quantification of aortic stenosis (AS) gradient:

- Doppler: Continuous Wave Mode

\[ 5 \text{ m/sec} = 100 \text{ mmHg} \]

Peak AS Gradient (mmHg):

\[ y = 0.96x + 1.2 \]

\[ R = 0.96 \]

\[ \text{Catheter} \]

\[ \text{Doppler} \]

\[ \Delta p = 4v^2 \]

\[ \Delta p = (2v)^2 \]

Quantification of valvular gradients:

\[ \Delta p = 4v^2 \]

\[ \Delta p = (2v)^2 \]

Currie, et al., JACC 1986; 7: 800

Echo-Doppler for assessing valvular stenosis:

- Planimetry
- Pressure gradient: Simplified Bernoulli equation
  - Physical principles
  - Pitfalls
    - Over/under gain
    - Misalignment
    - Tunnel
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The Simplified Bernoulli Equation

Impact of Gain

Too little

Too much

Just right!!
Doppler Equation

Impact of Ultrasound Misalignment

$$V = \frac{2f_0}{c} V \cos \theta$$

**Right Sternal Boarder View**

Dilated ascending aorta, good view of AV

NEVER accept a gradient from just one window

At a minimum: Ap5, Ap3, RUSB, SSN ± SC

The tighter the valve, the smaller the target

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**Case Study**

28 yo man with exertional dyspnea

- **History:**
  - Truck driver with known bicuspid AV since age 6
  - Cath at 14: no need for balloon valvotomy
  - Progressive exertional dyspnea over several years, must rest when mowing lawn
- **Outside echo:** “Moderately severe” AS and AI, AV gradient 32/17 mmHg, LV 6.9/3.9 cm
- **PE:** BP 96/50 (RA), 102/70 (LA), 118/82 (R pop) P 64, slow carotids, 4/6 SEM, harsh diastolic murmur
- **EKG:** LVH with strain
- **Meds:** None

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**Echo-Doppler for Assessing Valvular Stenosis**

- **Planimetry**
- **Pressure gradient:** Simplified Bernoulli equation
  - Physical principles
  - Pitfalls
  - Tunnel
  - Proximal velocity
  - Inertia
  - Pressure recovery
- **Valve area:** Continuity equation
  - Physical principles
  - Pitfalls
  - Flow profile
  - Vena contracta

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**The Simplified Bernoulli Equation**

Impact of Viscosity

- Viscosity increases $\Delta p$ beyond $4v^2$
- $\Delta p = 4\mu \frac{V_{max} L}{r^2}$
- $= .01$ mmHg/cm for 100 cm/sec flow in LVOT ($r = 1$ cm)
- $= 1$ mmHg/cm for 100 cm/sec flow in 1 mm ($r$) coronary
- Negligible for stenotic valves (small $L$)
- Only of concern in long tunnel-like stenosis and arterial and venous flow
Echo-Doppler for Assessing Valvular Stenosis

- Planimetry
  - Pressure gradient: Simplified Bernoulli equation
    - Physical principles
    - Pitfalls
    - Over/under gain
    - Misalignment
    - Tunnels
    - Proximal velocity
    - Inertia
    - Pressure recovery
  - Valve area: Continuity equation
    - Physical principles
    - Pitfalls
    - Flow profile
    - Vena contracta
  - When is cath necessary?

The Simplified Bernoulli Equation
Impact of Proximal Velocity

- $\Delta p = 4(v_2^2 - v_1^2)$
  - Neglecting $v_1$ overestimates the gradient
- If $v_1 < \frac{1}{4}v_2$, then $\Delta p$ overestimates by < 6%
- Important in significant AI and subvalvular narrowing
  - Both increase $v_1$ for any given flow rate.

Echo-Doppler for Assessing Valvular Stenosis

- Planimetry
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  - When is cath necessary?
Pressure Recovery
Balancing Potential and Kinetic Energy

As this goes down... Might this goes up?

Potential Energy

Kinetic Energy

Pressure

St. Jude Bileaflet Valve
Unique Geometry

Circulation 1995; 92: 3464-3472

Does This Really Happen in Patients???

Pressure Recovery in St. Jude Valves
Numerical Simulation

Velocity Magnitude

Pressure

Circulation 1995; 92: 3464-3472

36yo Man with High AVR Gradients

High flow, high gradient

Good LV function

Δp = 74/33 mmHg
CT Scan

No clear prosthetic dysfunction

Echo-Doppler for Assessing Valvular Stenosis

- Planimetry
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- Valve area: Continuity equation
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- When is cath necessary?

TEE Long-Axis View

Trivial prosthetic regurgitation

Calculation of Stroke Volume

Volume Calculation

\[
\pi r^2 = A
\]

\[
V = A \times TVI = \text{Stroke distance (cm)}
\]

Volume of a Cylinder

\[
\text{Area (cm}^2 \times \text{distance (cm)} = \text{Volume (cm}^3\]

Transgastic PW Doppler

High stroke volume  2 gradients, 48 and 70 mmHg

Conservation of Mass: Continuity Equation

Aortic Valve Area Continuity Equation

\[
A_{AV} \times \bar{V}_{AV} = A_{LVOT} \times \bar{V}_{LVOT}
\]

\[
A_{AV} = 0.785 \times (D)^2 \times \bar{V}_{AV}
\]
Echo-Doppler for Assessing Valvular Stenosis

• **Gradient**
  - Pressure gradient: Simplified Bernoulli equation
    - Physical principles
    - Pitfalls
      - Over/under gain
      - Misalignment
      - Tunnels
      - Proximal velocity
      - inertia
      - Pressure recovery
  - Valve area: **Continuity equation**
    - Physical principles
    - Pitfalls
      - Flow profile
      - Vena contracta
  - When is cath necessary?

Possible reasons for larger area than gradient would suggest

1) High output state (anemia, fever, hyperthyroid, beri beri, etc)
2) Aortic insufficiency
3) LVOT smaller than measured

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68 yo Man with DOE

Sometimes there’s a discrepancy between gradient and valve area

\[ \Delta p = \frac{65}{33} \text{ mmHg} \]
\[ \frac{1.00}{2.67} \times 0.785 \times (2.0)^2 = 1.2 \text{ cm}^2 \]

Upper Septal Hypertrophy

*Annular Measurement Not Reflective of Flow Area*

Use LV stroke volume instead of LVOT flow

\[ SV = 52 \text{ cm}^3 \]
\[ \text{AV VTI} = 92 \text{ cm} \]
\[ = 0.6 \text{ cm}^2 \]

Clear flow acceleration in LVOT

Seems more reasonable…
**Why is AS Underestimated?**

- LVOT measurement pretty reasonable
- Gradient MIGHT be underestimated
  - PW Doppler obtained only from apical 5 view
  - Sample volume too close to AV
  - Vmax = 0.58 m/sec (NOT 1.2)
  - Velocity incompatible with LV function
- LVOT too big
- Gradient too low
- LVOT velocity too high
- One of the above
- Some of the above
- All of the above

**Low gradient AS is NOT a mystery. It’s ALL about the flow!**
Clinical issues:
1) Does pt. have fixed AS or “pseudo-stenosis”?
2) Does patient have contractile reserve?
3) Will the patient benefit from AVR?

Severe AS/LV Dysfunction - Dobutamine
45 patients (prospectively studied)
LVEF = 29%
AVA = 0.7 cm²
Mean gradient = 26 mm Hg

Dobutamine 5-20 mcg/kg/min

Severe AS/LV Dysfunction: Timing of Intervention

Aortic Stenosis: Timing of Intervention

Recommendations

<table>
<thead>
<tr>
<th>Recommendations</th>
<th>COR</th>
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<tbody>
<tr>
<td>AVR is reasonable for asymptomatic patients with very severe AS (stage C1, aortic velocity ≥5 m/s) and low surgical risk</td>
<td>Ila</td>
<td>B</td>
</tr>
<tr>
<td>AVR is reasonable in asymptomatic patients (stage C1) with severe AS and decreased exercise tolerance or an exercise fall in BP</td>
<td>Ila</td>
<td>B</td>
</tr>
<tr>
<td>AVR is reasonable in symptomatic patients with low-flow/low-gradient severe AS with reduced LVEF (stage D2) with a low-dose dobutamine stress study that shows an aortic velocity ≥4 m/s (or mean pressure gradient ≥40 mm Hg) with a valve area ≤1.0 cm² at any dobutamine dose</td>
<td>Ila</td>
<td>B</td>
</tr>
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</table>
Assess AVA at 250 mL/sec

Classification of in vitro valves

Classification of surgical AS

Circulation 2006; 113: 711-21

What About Low Flow with Normal EF?

Clinical Outcome in Asymptomatic Severe Aortic Stenosis

Insights From the New Proposed Aortic Stenosis Grading Classification

Porzio Lancellotti, MD, PhD; Johan Magee, PhD; Ewan Dowal, MD; Philemon Dario, MD; Denis Ouwerkerk, MD, PhD; Monika Russe, MD; Catherine Seymours, MD; Bernard Coutet, MD, PhD; Luc A. Piret, MD, PhD

Lige and Brussels, Belgium; Rome, France and Quebec, Canada

- 150 AS pts, all ax with AVA<1 cm², EF>55% and neg ETT
- Stratified by mean gradient (40 mmHg) and stroke volume index (35 mL/m²)
- Followed for 27±12 months for death or AVR

Lancellotti et al. JACC 2012; 59: 235-43

Low Flow Low Gradient is Particularly Bad

Prognosis in LFLGAS w/ Preserved EF

Plus Impact of AVR

Aortic Stenosis: Timing of Intervention

Recommendations

AVR is reasonable in symptomatic patients who have low-flow/low-gradient severe AS (stage D3) who are normotensive and have an LVEF ≥50% if clinical, hemodynamic, and anatomic data support valve obstruction as the most likely cause of symptoms

IIa C

AVR is reasonable for patients with moderate AS (stage B) (aortic velocity 3.0–3.9 m/s) who are undergoing other cardiac surgery

IIa C

AVR may be considered for asymptomatic patients with severe AS (stage C1) and rapid disease progression and low surgical risk

IIb C

Lancellotti et al. JACC 2015; 66: 2594-2603

AV Calcification for Risk Stratification

Shimizu et al. JIC Heart & Vasc 2015: 9: 95-99
Impact of Aortic Valve Calcification, as Measured by MDCT, on Survival in Patients With Aortic Stenosis

- 794 pts at 3 centers
- Echo & CT scan for AV Ca++
- 5 year fu
- End point: Survival with medical management

Clavel et al, JACC 2014: 64: 1202-13

Many PLFLG AS pts have Amyloidosis
91 yo Man with Severe DOE

EF = 37%

\[
\Delta p = 45/23 \text{ mmHg, AVA } 0.8 \text{ cm}^2
\]

GLS = -7.1%
Apical sparing

Many PLFLG AS pts have Amyloidosis
91 yo Man with Severe DOE

EF = 37%

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\]

GLS = -7.1%
Apical sparing

Impact of Strain and BNP on Survival in AS
551 Pts w/ AVA<1.3 cm\(^2\) and LVEF>50%

Goodman et al, JAHA 2016; 5: e002561

Keep These Tips in Mind!

- Pressure gradient: Simplified Bernoulli equation
  - Physical principles
  - Pitfalls
    - Overshadow gain
    - Misalignment
    - Numerical
    - Proximal velocity
    - Inertia
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Exercise in Paradoxical LFLGAS?

The Functional Significance of Paradoxical Low-Gradient Aortic Valve Stenosis

Perez del Villar et al, JACCi 2017: 10: 29-39

Impact of Strain and BNP on Survival in AS

551 Pts w/ AVA<1.3 cm\(^2\) and LVEF>50%

Goodman et al, JAHA 2016; 5: e002561

Exercise Testing in Paradoxical Low-Flow Aortic Stenosis

Where is the Truth?

Perez del Villar et al, JACCi 2017: 10: 29-39

Comparison of Fick Method and Doppler SVI in Exercise Testing for Aortic Stenosis

Perez del Villar et al, JACCi 2015: 10: 25-32

Doppler SVI matched Fick at rest and 50% VO\(_{\text{max}}\) but underestimated at 100% (or did Fick overestimate Doppler SVI)