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 cm^2
- AVI < 0.6 cm^2/m^2 BSA (ESC)
- Peak velocity > 4m/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 cm^2: ΔP_{mean} 21 mm Hg, V_{max} 3.3 m/s
- ΔP_{mean} 40 mm Hg: AVA of 0.75 cm^2
- V_{max} 4.0 m/s: AVA of 0.82 cm^2

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

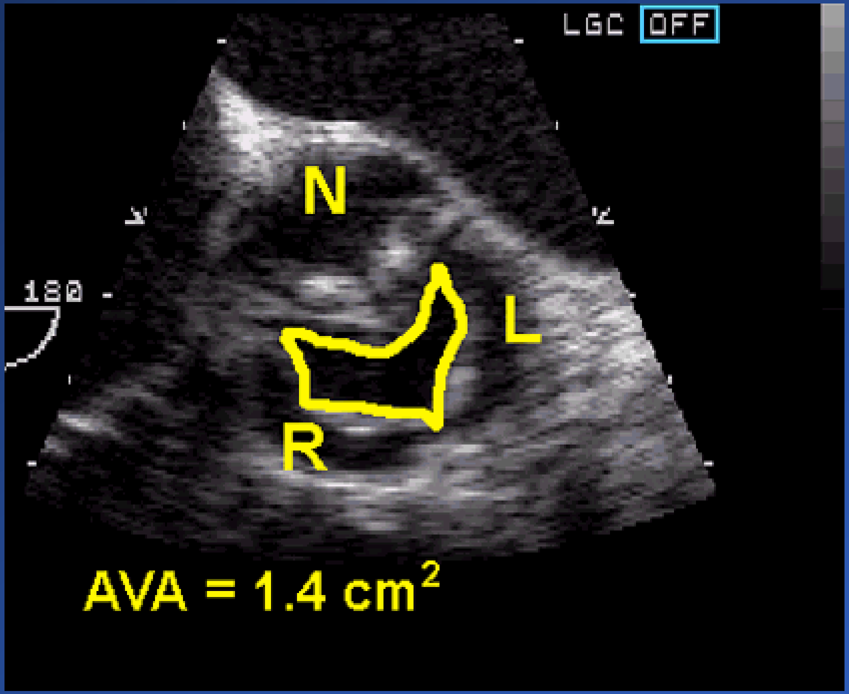
Table 2 Percentage of patients diagnosed with severe aortic stenosis depending on which echocardiographic criterion was used

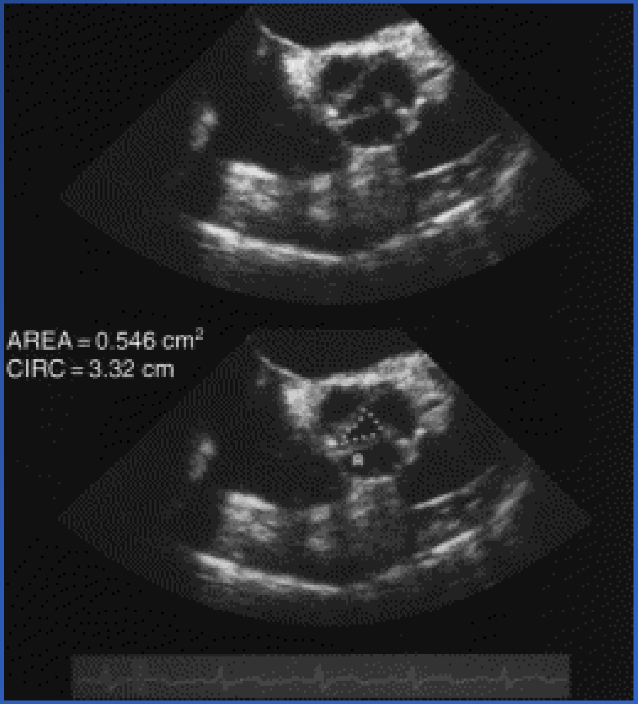
Guidelines/ recommendations	Parameter	Patients with severe stenosis
AHA/ACC[3]	AVA $< 1.0\ cm^2$	69%
ESC[2]	AVA/BSA $<0.6\ cm^2$	76%
Otto[4]	$V_{max} > 4.0$ m/s	45%
AHA/ACC[3]	$\Delta P_m > 40$ mmHg	40%

AVA, aortic valve area; BSA, body surface area; V_{max}, peak flow velocity; ΔP_m, mean pressure gradient.

Minners J, et al. EHJ 2008

Anatomic (Geometric) Orifice Area



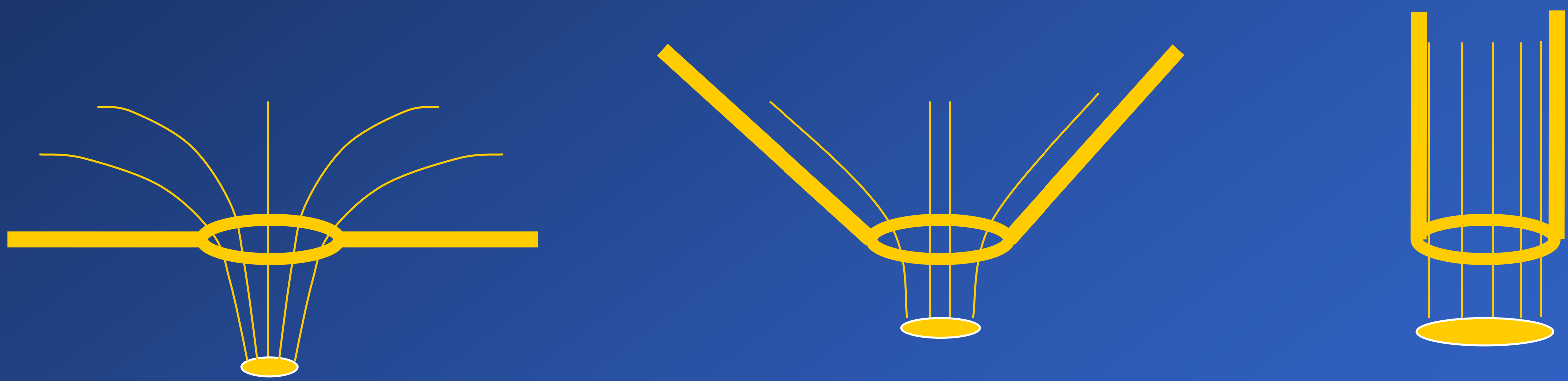


Can (only) be assessed by direct imaging

Effective Orifice Area (EOA)

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

flat plate | **funnel** | **tube**

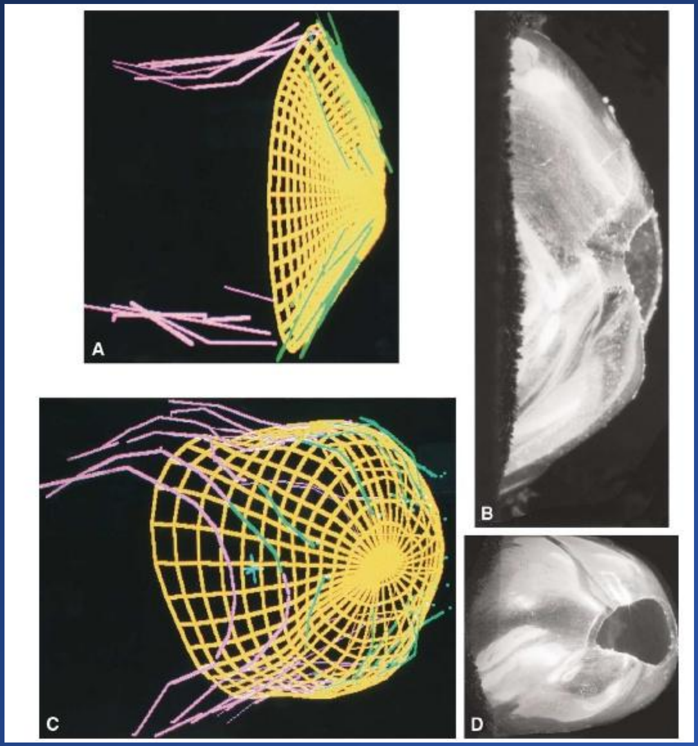


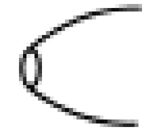
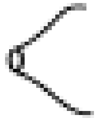
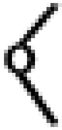
0.6 | **0.8** | **1.0**

C_c = Effective Orifice Area / Anatomic Orifice Area

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

Effective Orifice Area (EOA)



	Domed	Intermediate	Flattened
Anatomic area			
1.0 cm²	0.9	0.85	0.76
0.75 cm²	0.88	0.83	0.74
0.5 cm²	0.85	0.81	0.71

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

Gilon D, et al. Circulation 2002

Gorlin Formula

Torricelli's Law describes flow across a round orifice:

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

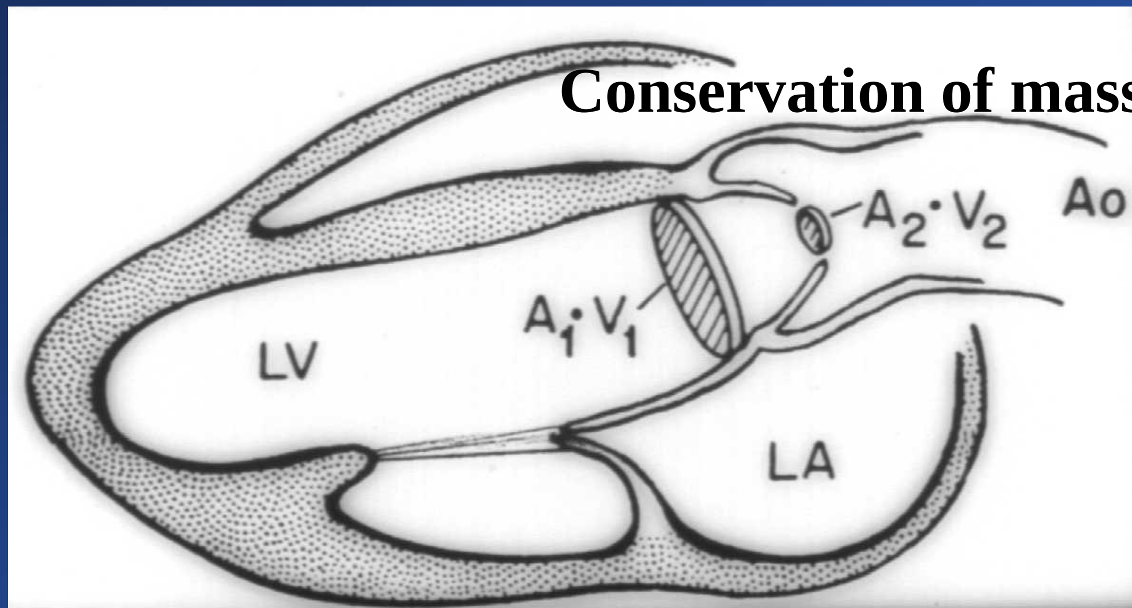
$$\text{Area } [cm^2] = \frac{\text{Flow rate } [cm^3/s]}{\text{Velocity } [cm/s] \times C_c}$$

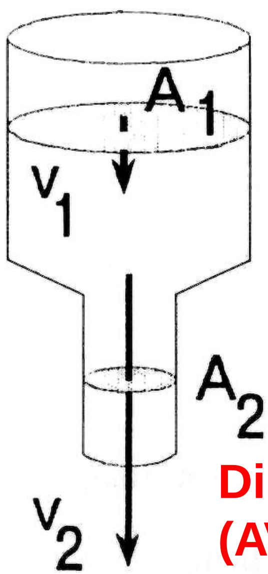
$$\text{Area} = \frac{CO/(DFP \text{ or } SEP)(HR)}{44.3 \; C \sqrt{\Delta P}}$$

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)



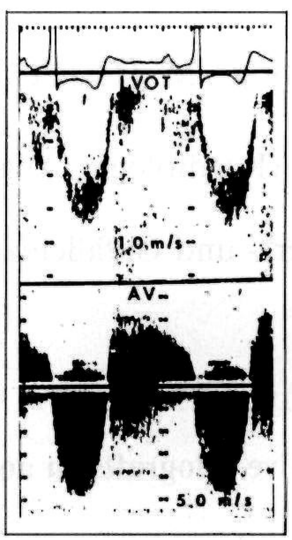


$$A_1 \times \bar{v}_1 = A_2 \times \bar{v}_2$$

$$A_{AV} = A_{LVOT} \times \frac{V_{LVOT}\ \text{(PW)}}{V_{MAX}\ \text{(CW)}}$$

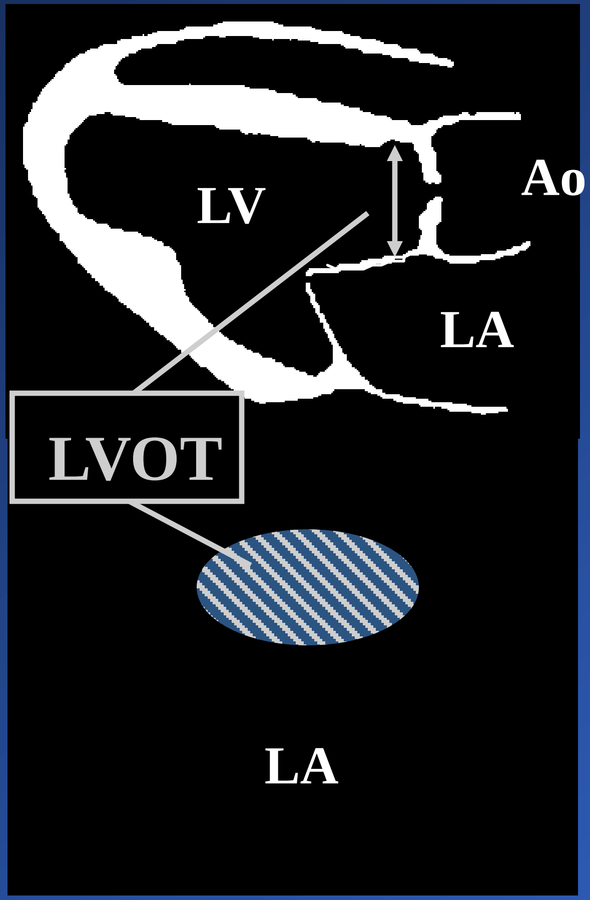
Dimensionless Index

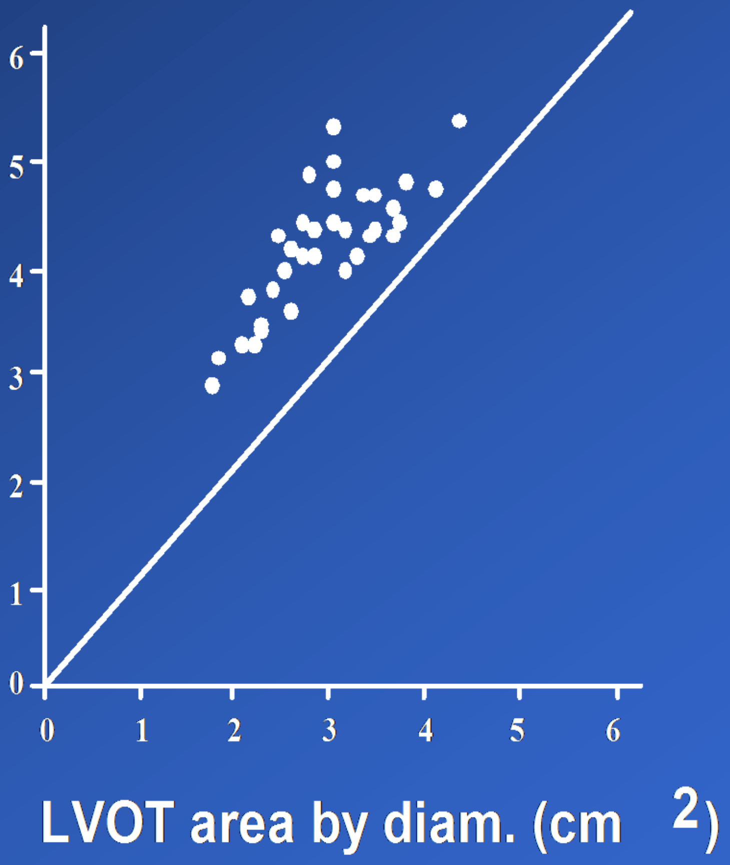
(AVA normalized for body size)



Continuity Equation

Undetestimates AVA by an average of 0.2 cm^2



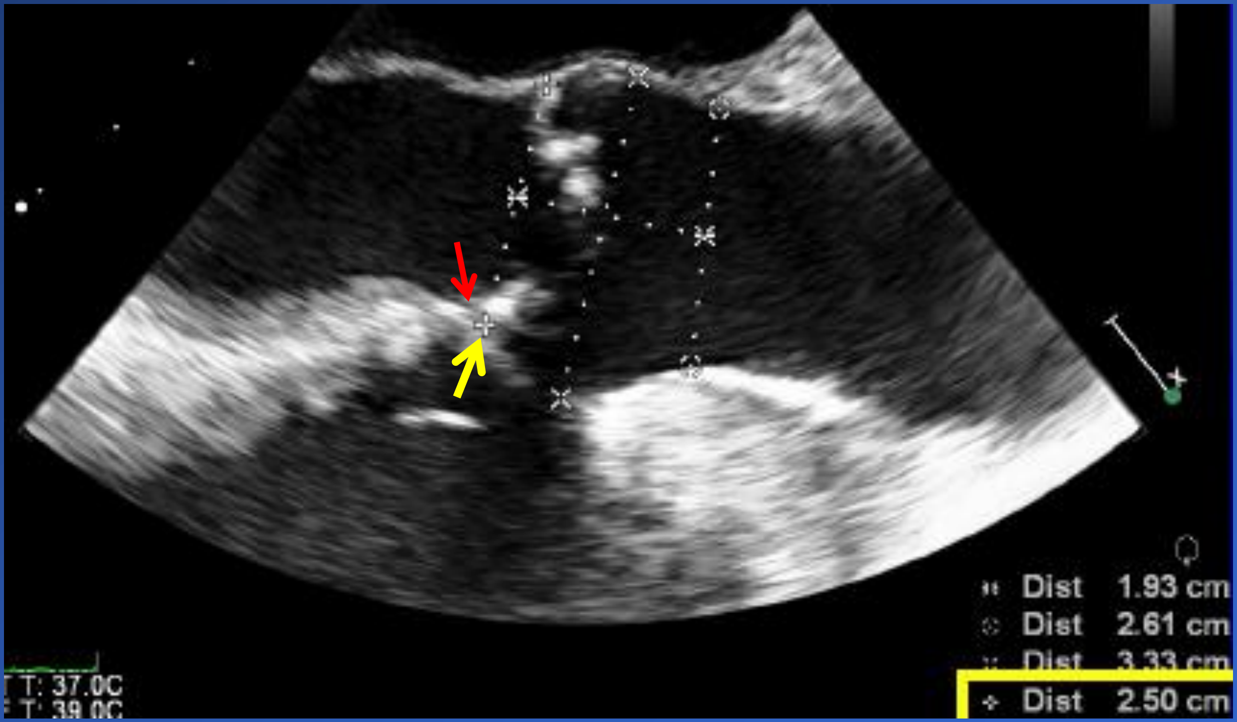


Underestimates LVOT Area by assuming circular shape

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

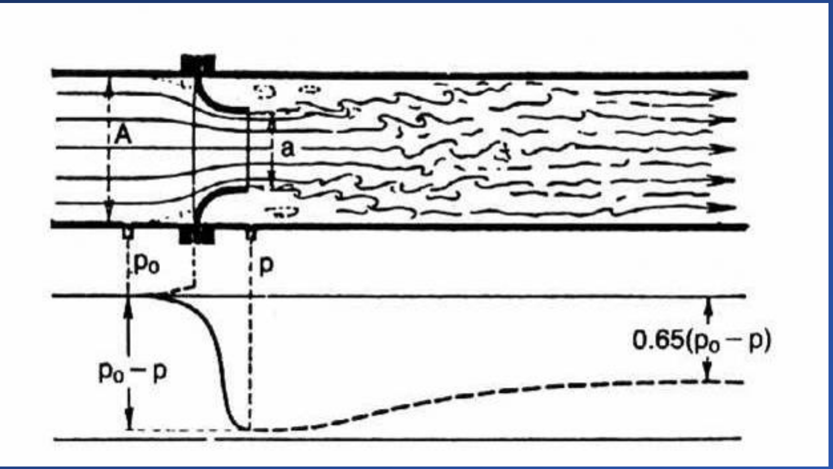
Continuity Equation

- **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!)**

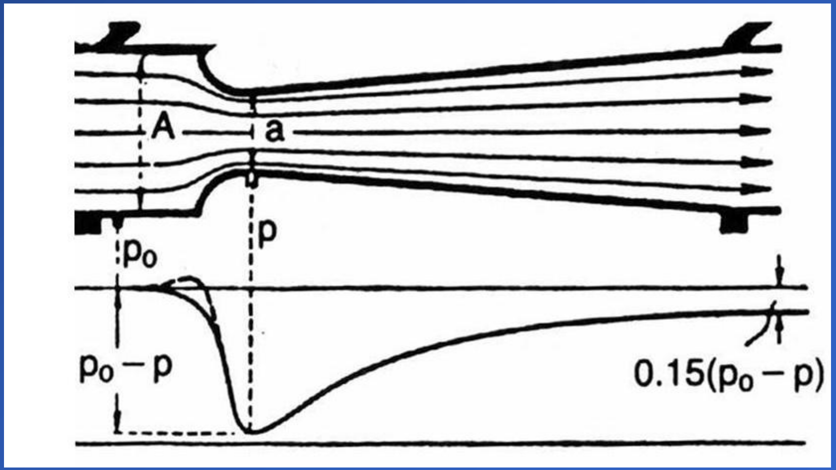


Pressure Recovery

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



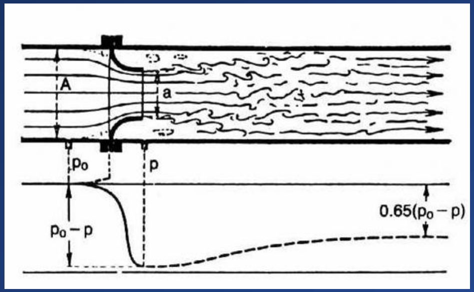
Abrupt outflow (nozzle): turbulence, head loss

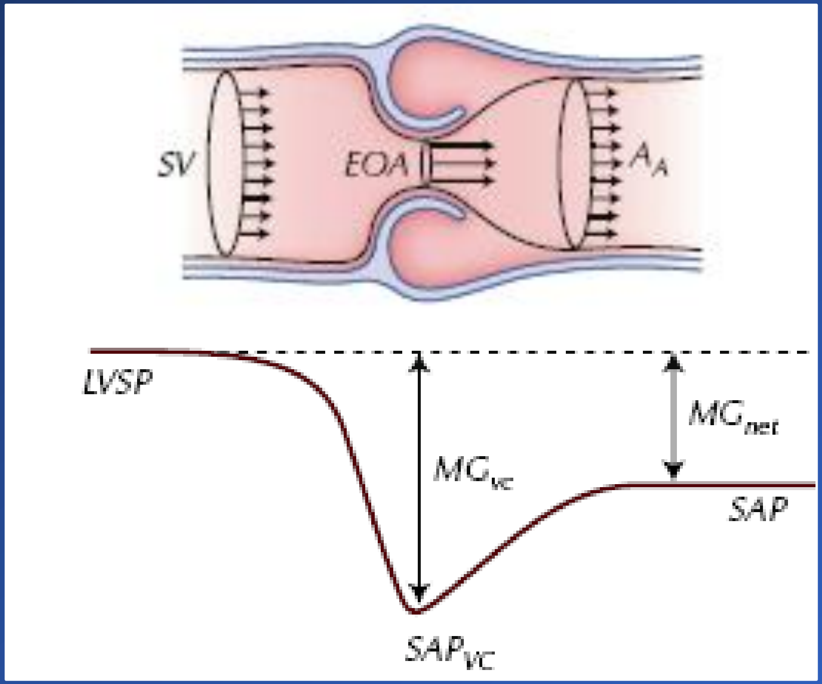


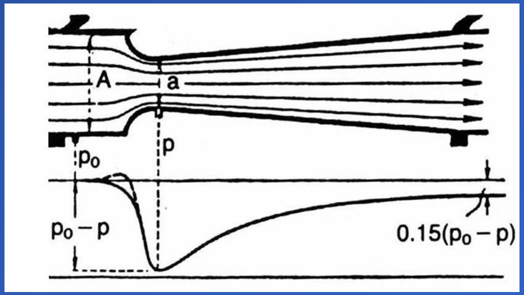
Gradually expanding outflow: eliminates flow separation and recovers the pressure drop

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

Pressure Recovery

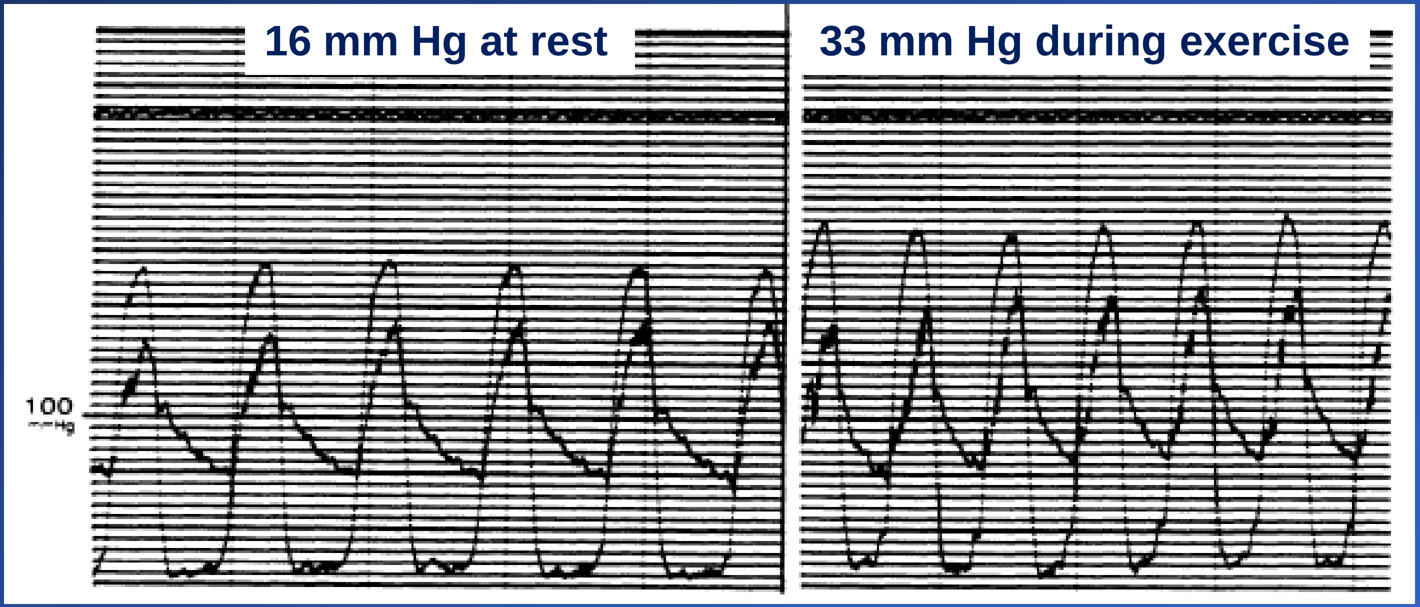






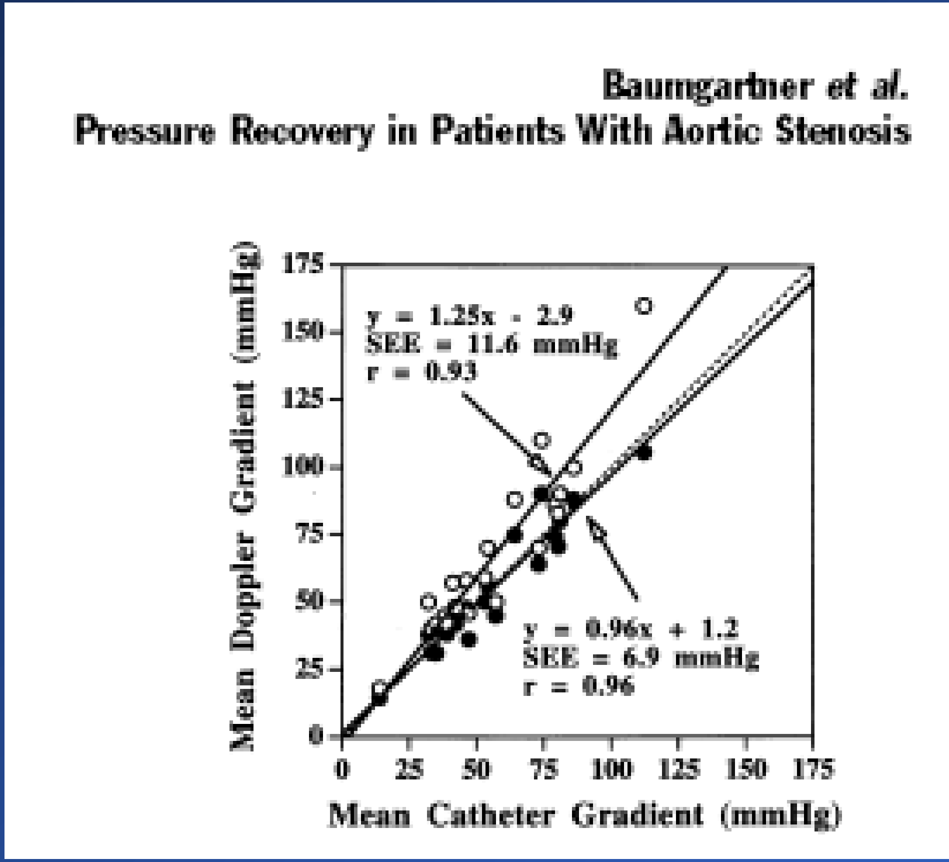
- **Degree of pressure recovery determined by relationship between the size of the cross-sectional area of the vena contracta (EOA) and the area of the ascending aorta (A_A)**
- **More pressure recovery if aortic diameter is < 3.0 cm (particularly small aortic root) and less severe AS**

Pressure Recovery

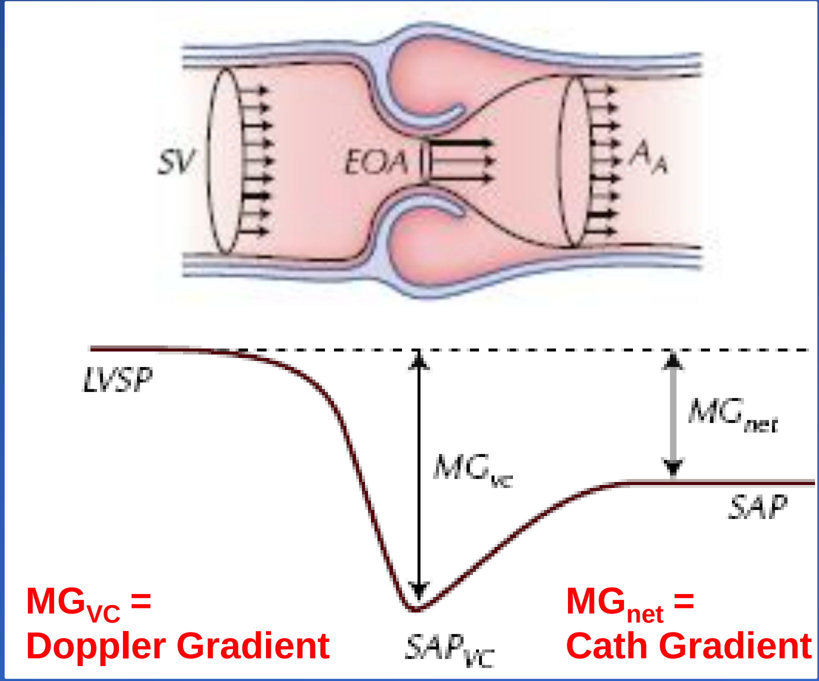


Laskey and Kussmaul, Circulation 1994

Pressure Recovery: Overestimation of Catheter Mean Gradients by Doppler Ultrasound



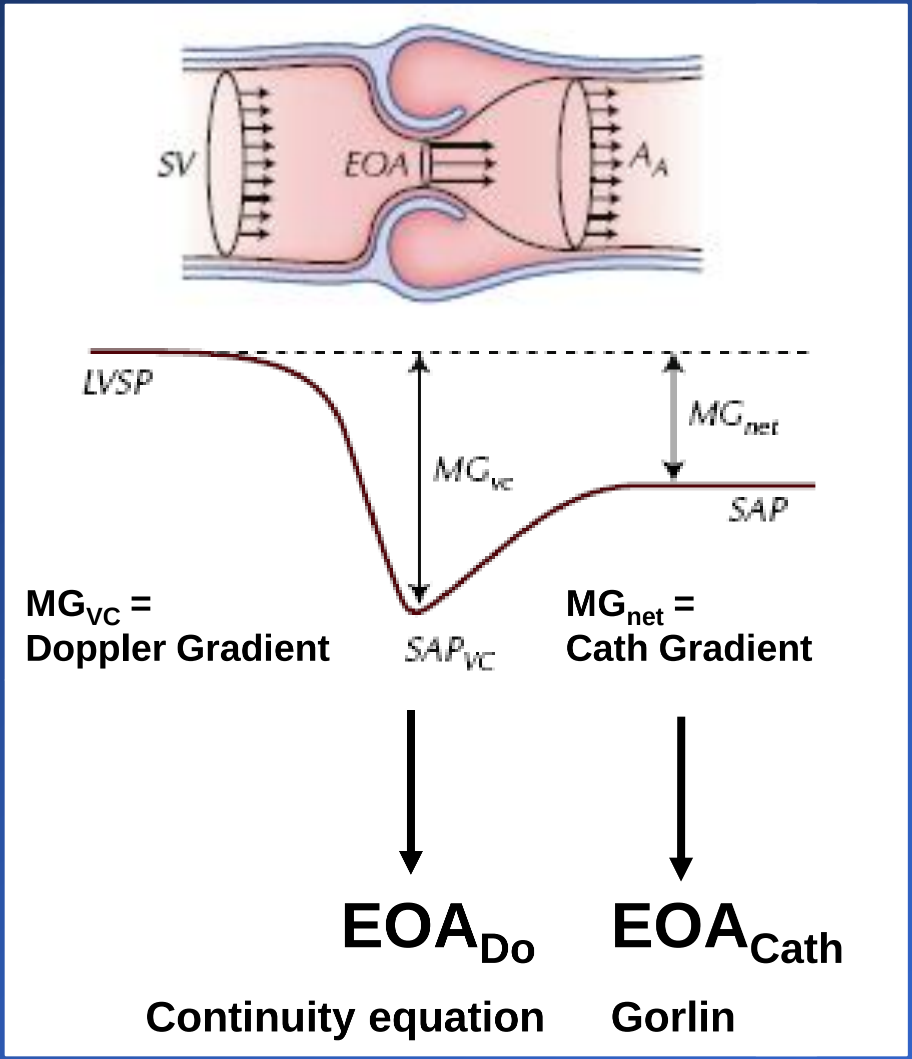
$$P_3 - P_2 = 4v_{CW}^2 \cdot 2\frac{AVA_c}{AoA} \cdot \left(1 - \frac{AVA_c}{AoA}\right).$$



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

Baumgartner, et al. J Am Coll Cardiol 1999

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



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

JACC Vol. 41, No. 3, 2003
February 5, 2003:435–42

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

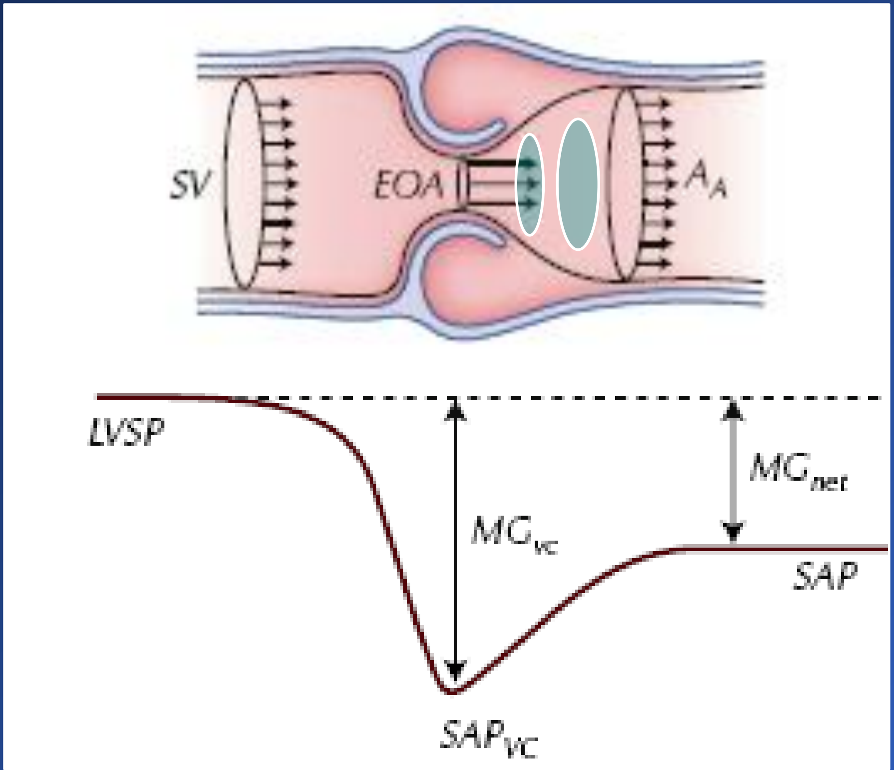
Catheter-Derived EOA (cm^2)†	Doppler-Derived EOA (cm^2)		
	Aortic Diameter = 2.0 cm (A_A = 3.14 cm^2)	Aortic Diameter = 3.0 cm (A_A = 7.07 cm^2)	Aortic Diameter = 4.0 cm (A_A = 12.6 cm^2)
1.50 (1.69)	1.02	1.24	1.34
1.00 (1.13)	0.76	0.88	0.93
0.75 (0.85)	0.61	0.68	0.71
0.50 (0.56)	0.43	0.47	0.48

*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.

Garcia, et al. J Am Coll Cardiol 2003

Recovered EOA: Energy Loss Coefficient (ELC) is the net EOA



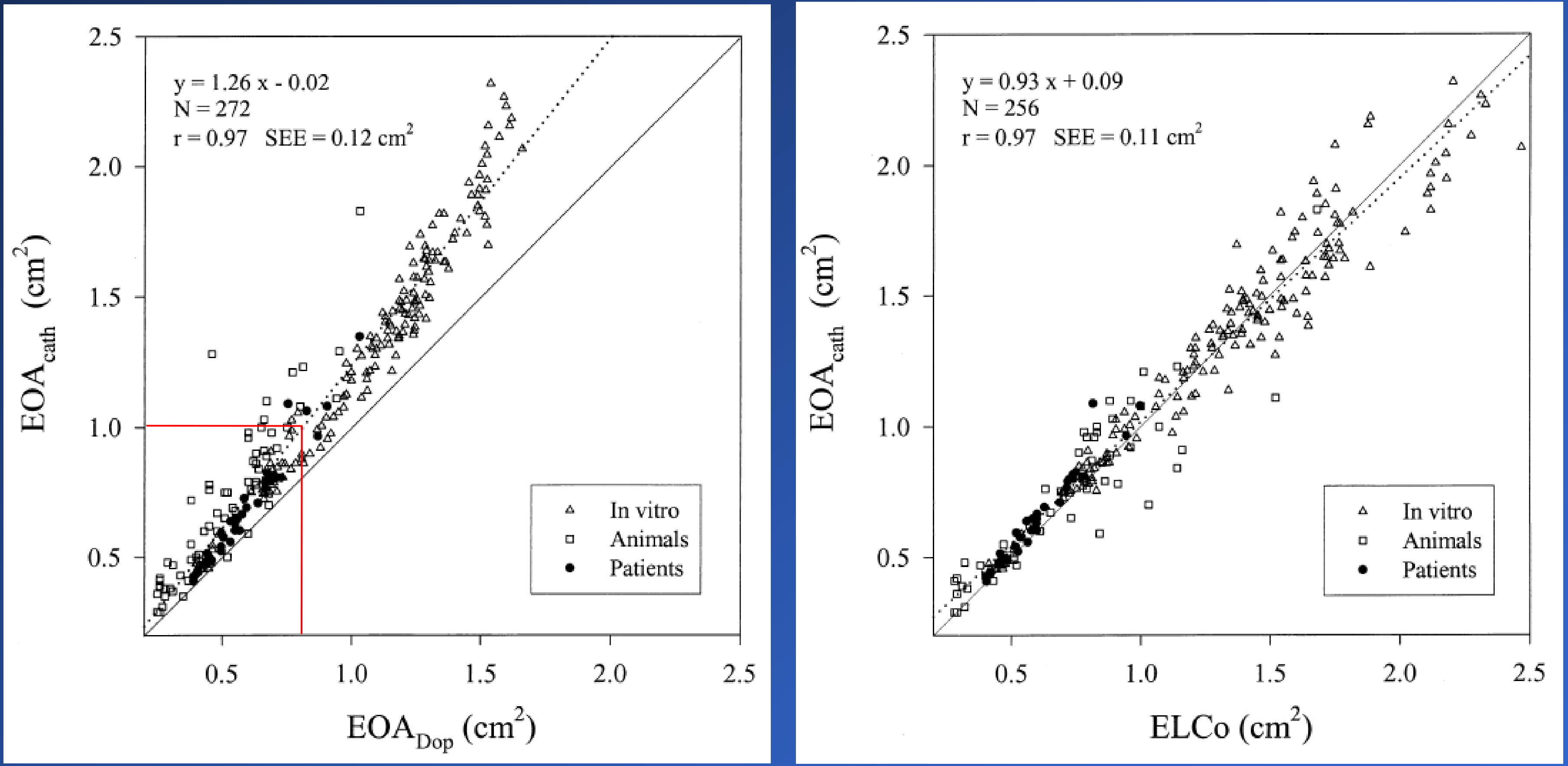
$$ELC = \frac{EOA_c \times A_A}{A_A - EOA_c} \quad cm^2$$

$$ELI = \frac{ELC}{BSA} \quad \frac{cm^2}{m^2}$$

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

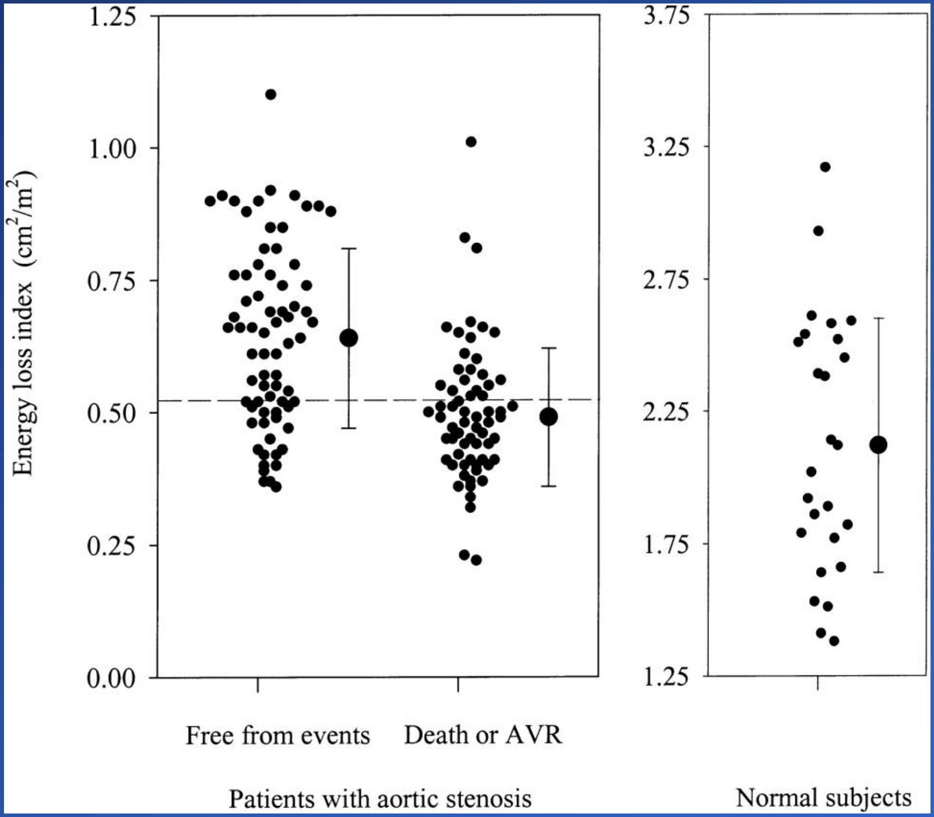
Garcia, et al. J Am Coll Cardiol 2003

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



Garcia, et al. J Am Coll Cardiol 2003

Energy Loss Index predicts outcome better than Gradients, EOA, EF



138 pts, retrospective

Garcia, et al. Circulation 2000

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 cm^2 ($LVOT_D$ 18.5 mm)
- Height 158 cm, weight 60 kg, BSA 1.61 m^2
- EOAI = 0.53 cm^2/m^2
- Aortic diameter immed above STJ = 2.7 cm
- ELC = 0.99 cm^2 (Gorlin)
- ELI = 0.62 cm^2/m^2
- EOA expected with a commonly used and commercially available size 21 bioprosthesis: 1.2 cm^2 (size 19: 1.01 cm^2)

Is it severe AS requiring AVR?

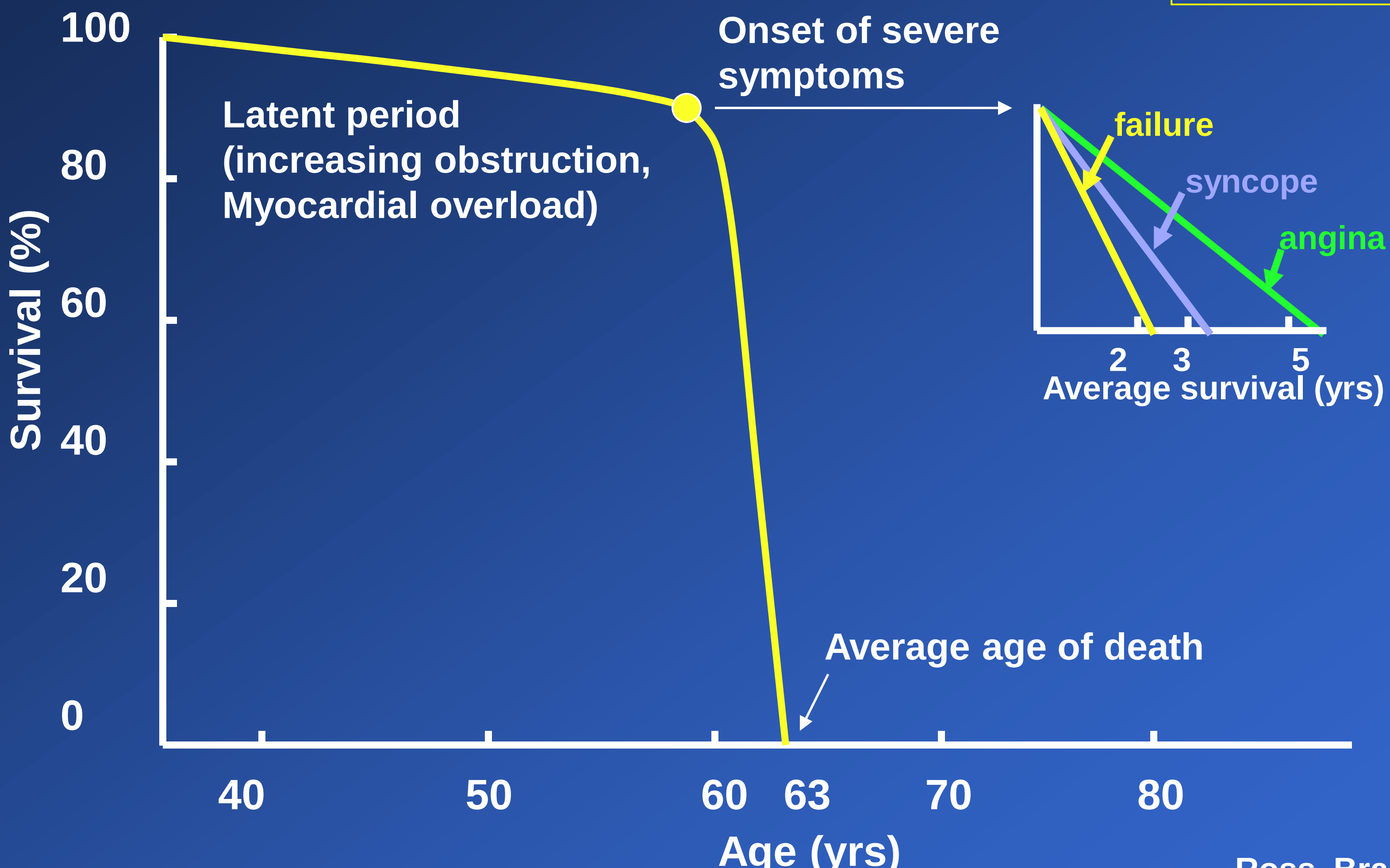
- 78 year old female, SOB during exercise
- PG 62/39 mm Hg, EF 58%
- EOAc = 0.76 cm^2 ($LVOT_D$ 22 mm)
- Height 170 cm, weight 70 kg, BSA 1.82 m^2
- EOAI = 0.43 cm^2/m^2
- Aortic diameter immed above STJ = 3.4 cm
- ELC = 0.83 cm^2 (Gorlin)
- ELI = 0.46 cm^2/m^2
- EOA expected with size 23 bioprosthesis (commercial, frequently used): 1.51 cm^2

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)

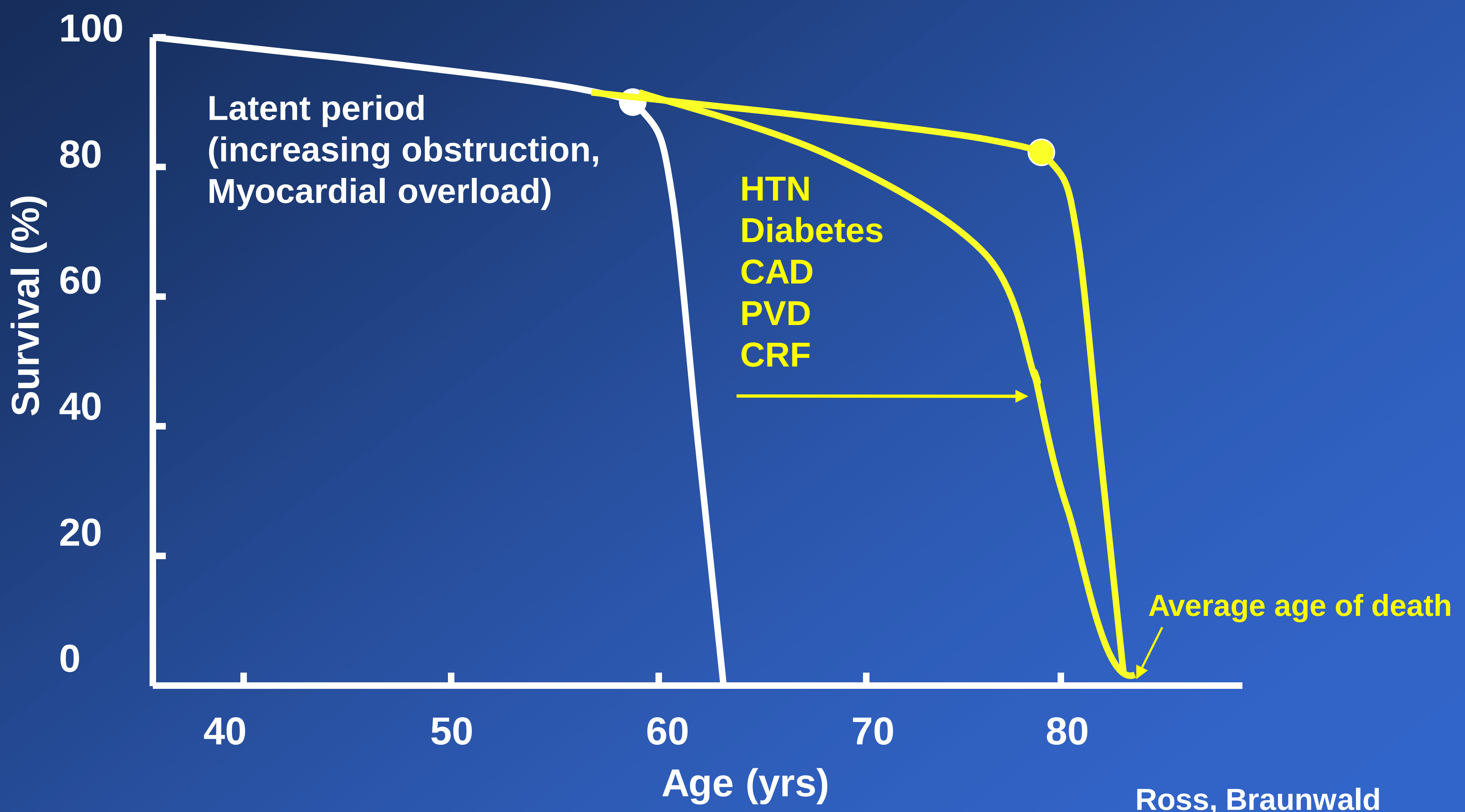
Prognosis of Patients With Severe AS...

…40 years ago!



Ross, Braunwald
Circulation 1968

Prognosis of Patients With Severe AS 2008

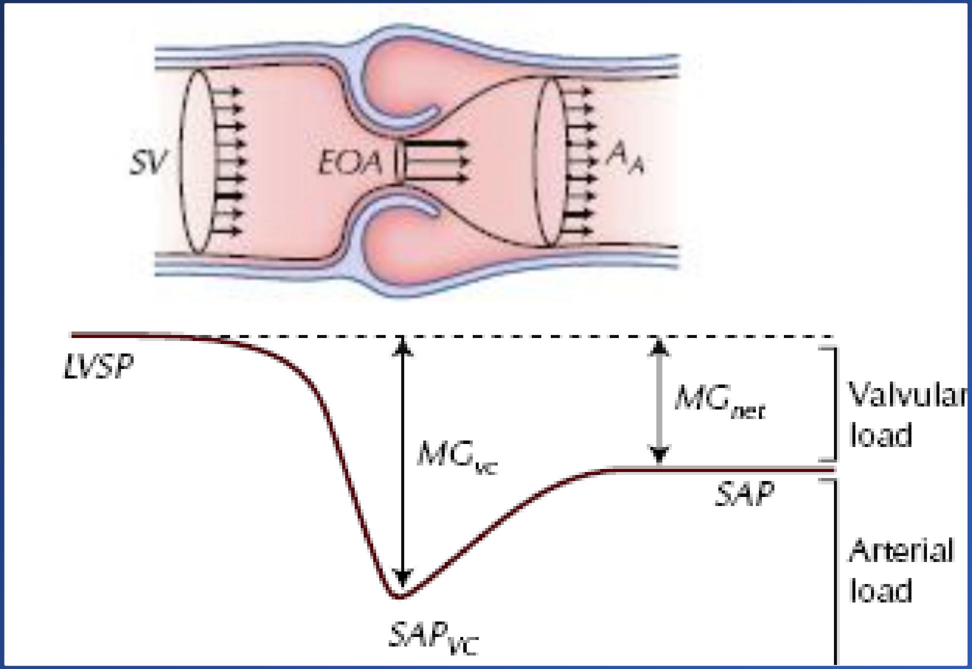


Ross, Braunwald
Circulation 1968

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



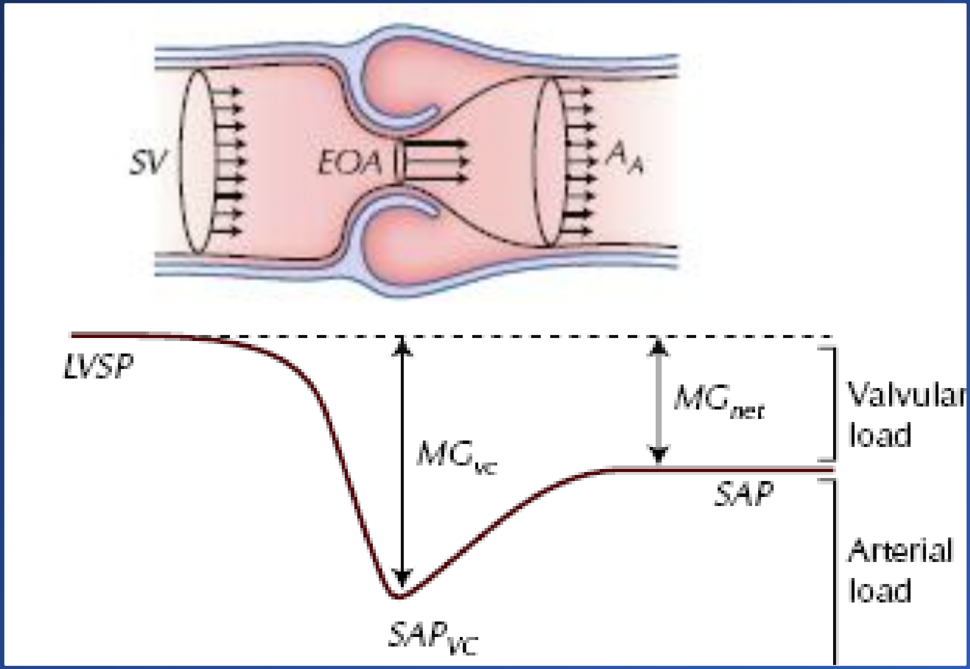
Need to Quantify:

1. Valvular obstruction
2. Vascular load
3. Global arterial afterload

Garcia, et al. Circulation 2000

Garcia, et al. J Am Coll Cardiol 2003

1. Valvular Obstruction

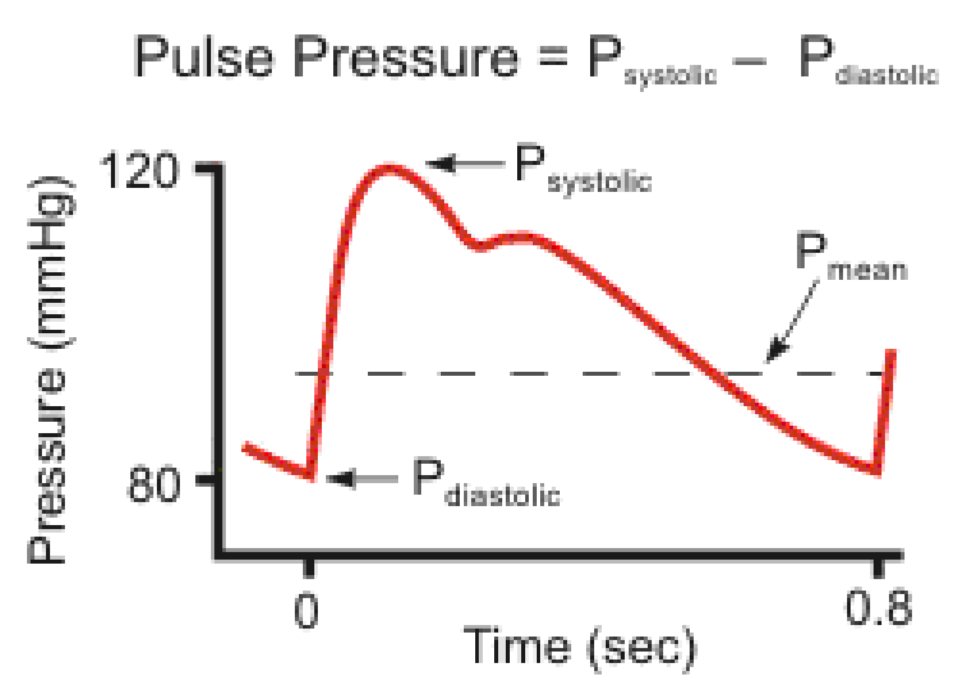


Energy Loss Index

Severe:
ELI < 0.55 cm^2/m^2

Garcia, et al. Circulation 2000
Garcia, et al. J Am Coll Cardiol 2003

2. Vascular Load



BP
PP

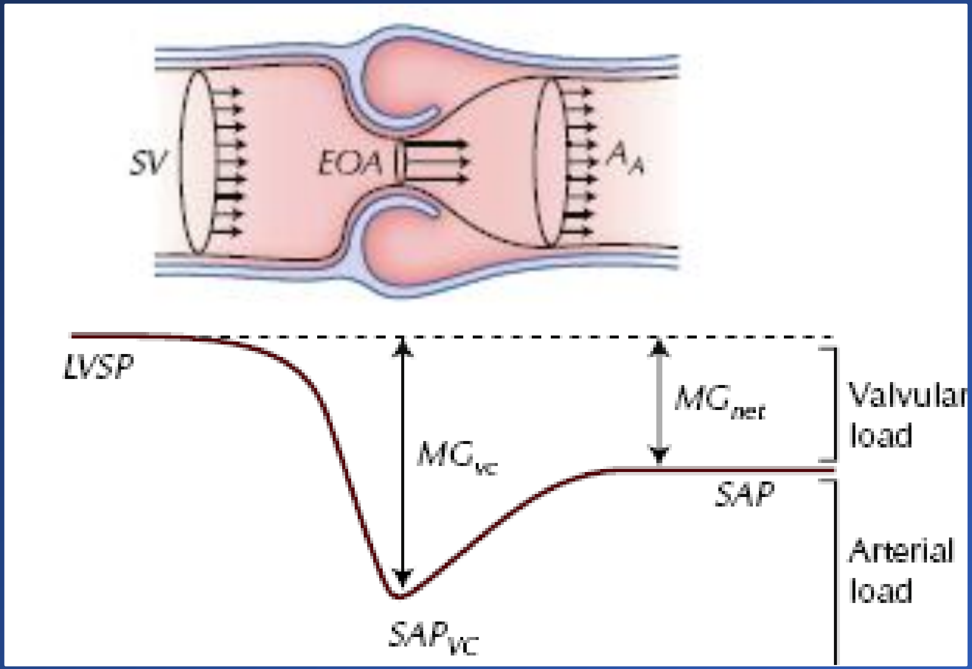
May be pseudo-normalized by reduced CO in the presence of LV dysfx

<u>Systemic Arterial Compliance</u>: Stroke Volume Index/Pulse Pressure

Severe:
SAC ≤ 0.6 ml/m²/mm Hg

Briand, et al. J Am Coll Cardiol 2005

3. Global Arterial Afterload



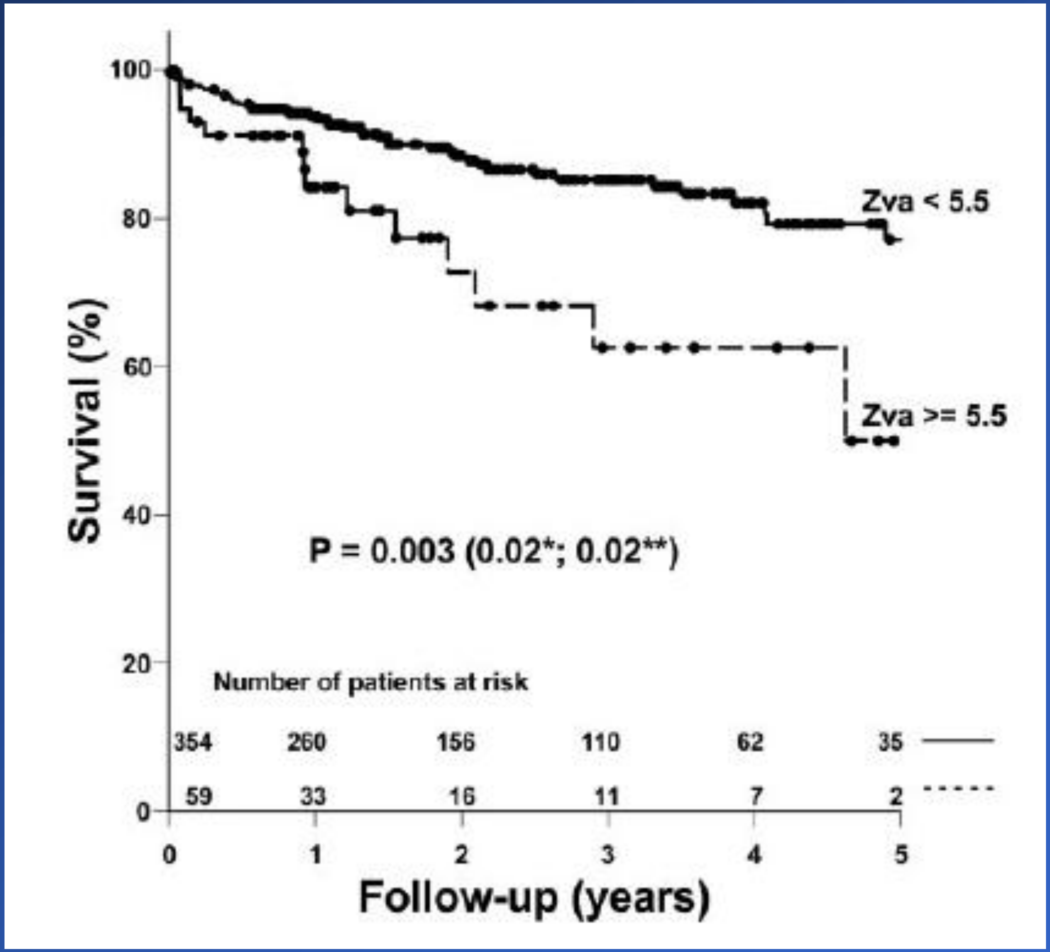
Valvuloarterial Impedance

$$Z = \frac{SAP + MGnet}{SVI}$$

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:
$Z \geq 4.5$ mm Hg/ ml/m^2

Briand, et al. J Am Coll Cardiol 2005



Hachicha, et al. Circulation 2007

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%

	Model Without Z_{va}		Model With Z_{va}	
Variable	**Odds Ratio (95% CI)**	**p Value**	**Odds Ratio (95% CI)**	**p Value**
Female gender	—	—	3.5 (1.2–10.3)	0.025
Coronary artery disease	25.2 (3.3–195.0)	0.001	16.7 (2.2–128.7)	0.007
ELI $\leq$0.50 cm^2/m^2	4.5 (1.8–11.5)	0.002	—	—
SVi/PP $\leq$0.50 ml/m^2/mm Hg	2.9 (1.1–7.6)	0.025	—	—
Z_{va} $\geq$5.0 mm Hg/ml/m^2	N/A	N/A	4.2 (1.7–10.3)	0.001

Briand, et al. J Am Coll Cardiol 2005

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 cm^2/m^2 BSA
- EF > 50%
- Normal Flow (NF) vs Low Flow (LF) - 35 ml/m^2
- LF (35%): More female, lower gradient (32 $\pm$ 17 mm Hg vs 40 $\pm$ 15 mm Hg), lower EF (62 $\pm$ 8 vs 68 $\pm$ 7 %), smaller LV volumes

Hachicha, et al. Circulation 2007

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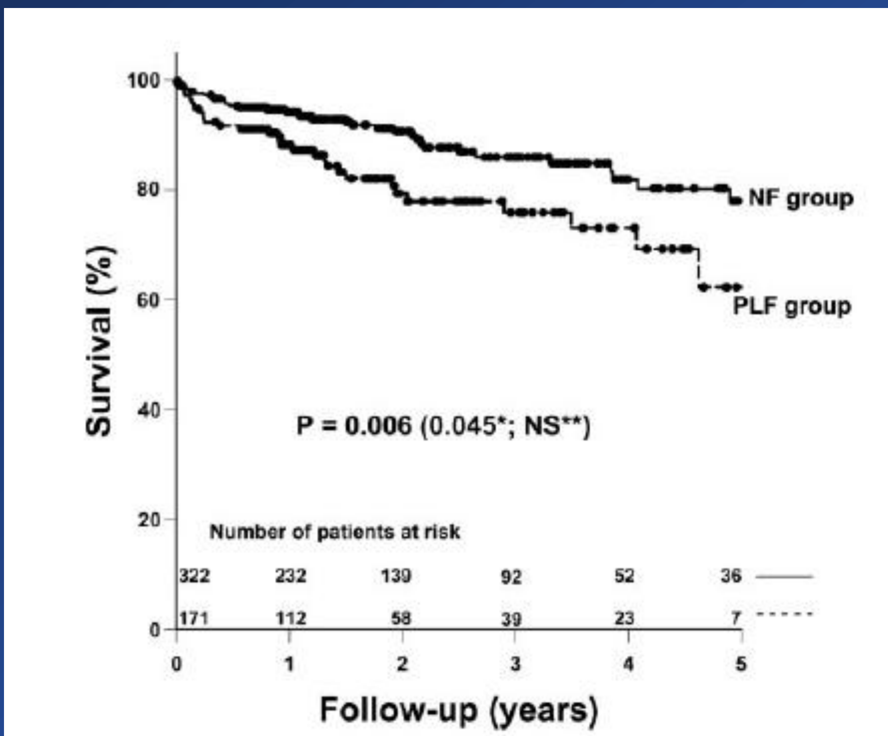
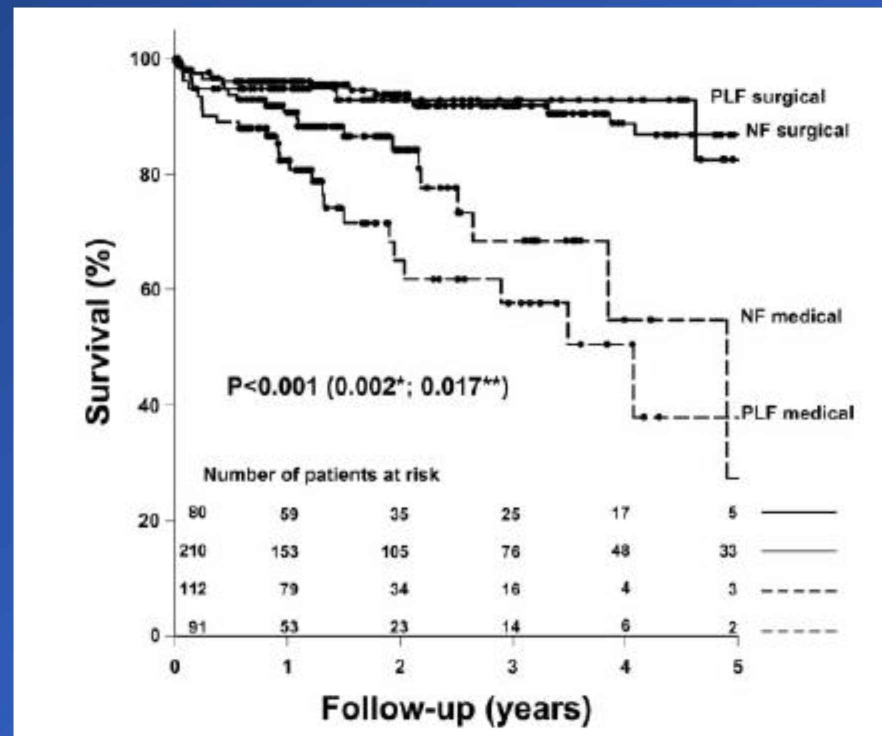
- **LF patients have markedly increased global LV afterload as evidenced by the valvulo-arterial impedance (29% higher) compared with the pts with the more classic features of severe AS**
- **Low flow rates comparable to those observed in patients with low-flow AS associated with low EF**
- **Low flow 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**

Hachicha, et al. Circulation 2007

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





Hachicha, et al. Circulation 2007

Inconsistencies of echocardiographic criteria for the grading of aortic valve stenosis

Consistent grading		Inconsistent grading	
AVA (cm^2)	≥1	AVA (cm^2)	≥1
ΔPm (mmHg)	≤40	ΔPm (mmHg)	>40
n	983	*n*	29
stroke volume (mL)	79 ± 15*	stroke volume (mL)	107 ± 15*
Inconsistent grading		**Consistent grading**	
AVA (cm^2)	<1	AVA (cm^2)	<1
ΔPm (mmHg)	≤40	ΔPm (mmHg)	>40
n	997	*n*	1338
stroke volume (mL)	66 ± 11*	stroke volume (mL)	70 ± 14*

- **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/ ΔP_{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)