Assessment of Cardiac Hemodynamics by Echocardiography

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Caesarea, 2010

Flow Rate, Volume

Not constant (pulsatile flow)

↙ ↘

Flow rate = CSA x Flow velocity

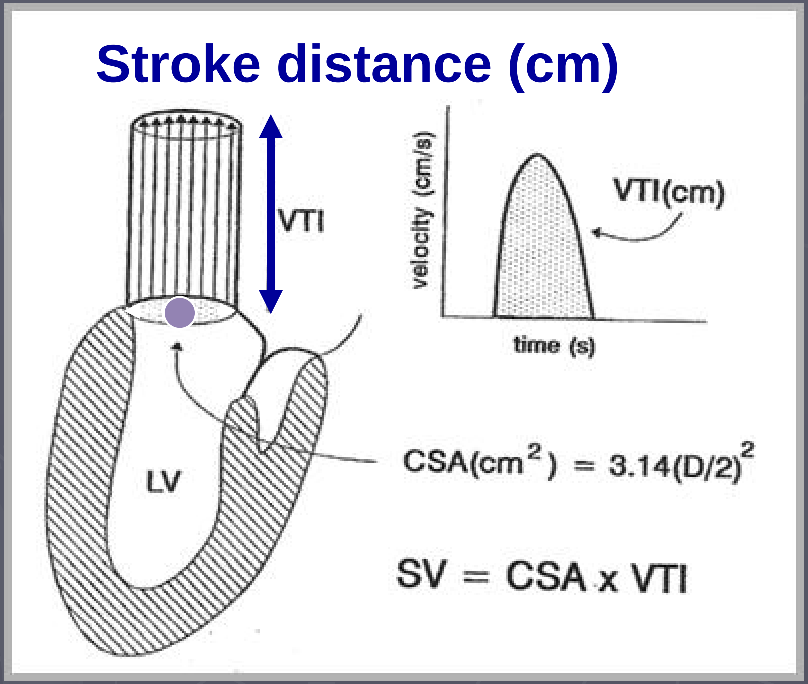
(cm^3/s) (cm^2) (cm/s)

$$CSA = \pi \times r^2 = \pi \times (D/2)^2$$

Volume = CSA x $\int$ Velocity (time) **VTI**

(cm^3) (cm^2) (cm)

Stroke Volume - LVOT

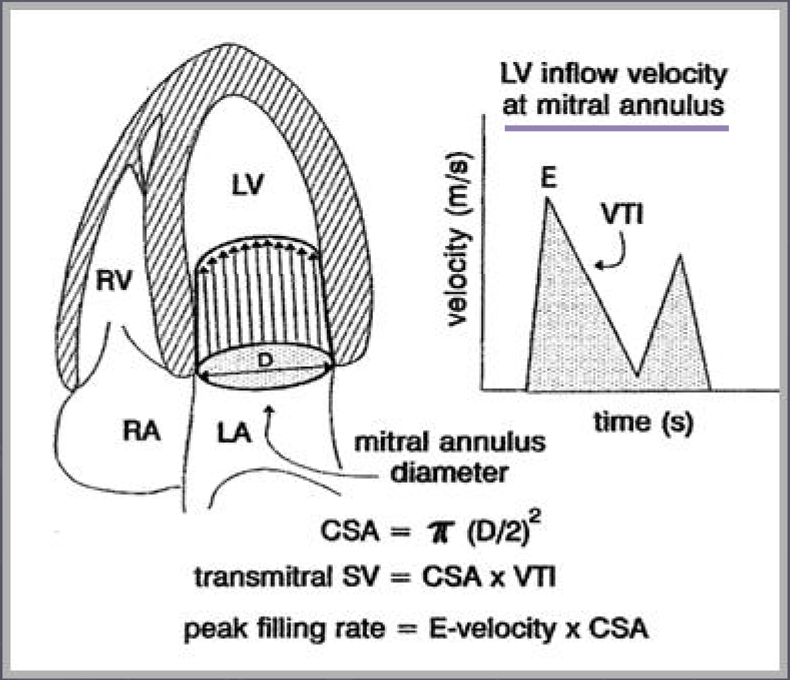


- Assumptions:
  - Circular orifice
    - Constant orifice size
  - Flat velocity profile
    - Laminar flow
  - Velocity & orifice measurements
    - At the same level

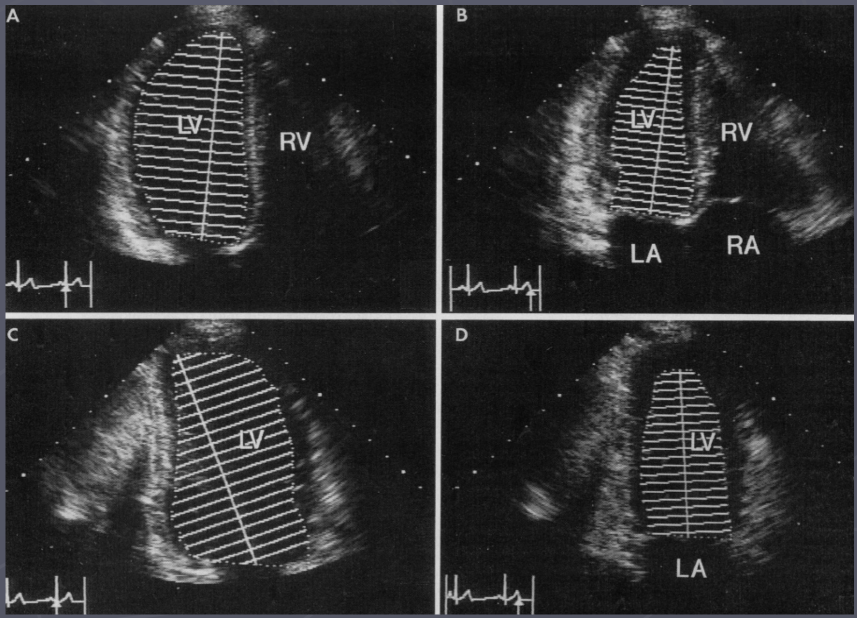
Assessment of forward stroke volume

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

SV – Other Techniques



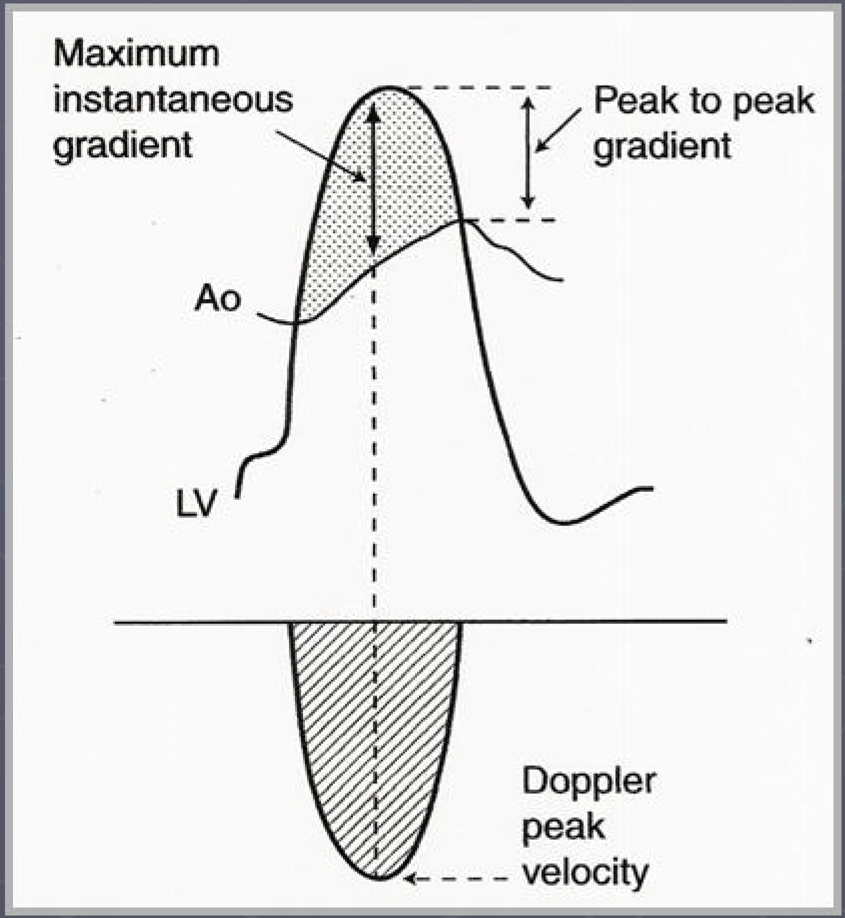
LV volumes



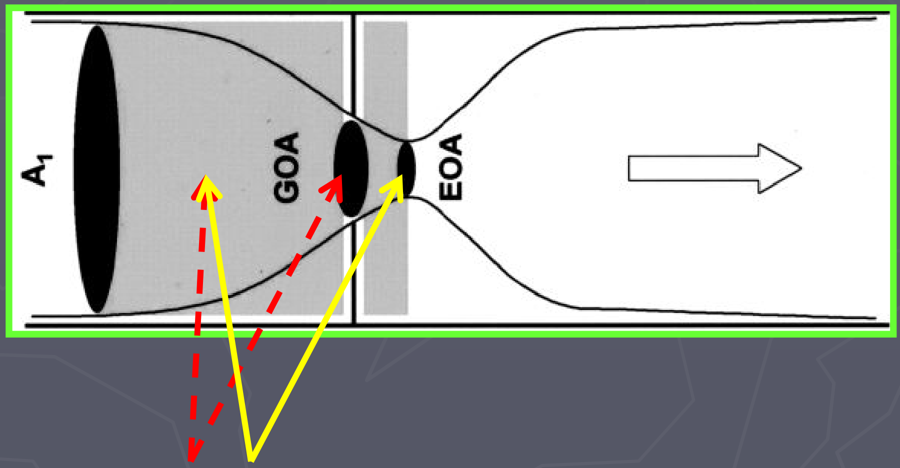
- MR / AR → **LV output ≠ forward (systemic) output**
- LV SV = forward (systemic) SV + regurgitant volume (MR/AR)

Aortic Stenosis

Transvalvular Pressure Gradients



Doppler does not measure AV pressure gradient directly



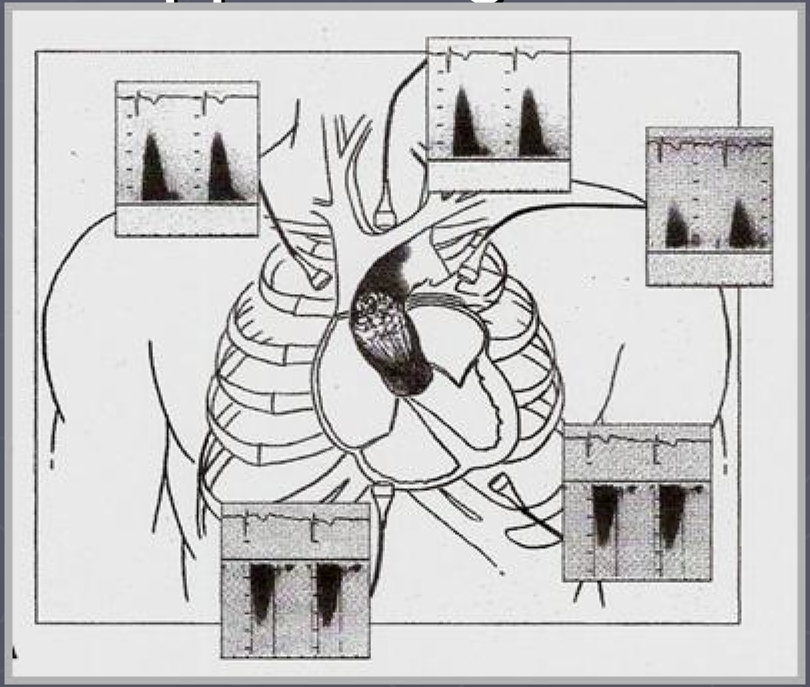
$\Delta P_{Doppler} = P_{LV} - P_{vena\ contracta}$

ΔP – Aortic Stenosis

- ~ Constant relationship between peak & mean ΔP: AVMG ≈ 2/3 AVPG
- Severe AS (AVA <1.0 cm^2)
  - Vmax > 4.0 m/s (peak ΔP >60 mmHg, mean >40)
  - Assumption: normal transaortic flow (SV)
  - Incorrect assumption
    - LV / RV dysfunction / MR / TR ++ → ΔP ↓
      - Low-gradient AS
    - Hyperdynamic LV / AR ++ → ΔP ↑

ΔP AS – Pitfalls

- Inadequate Doppler alignment

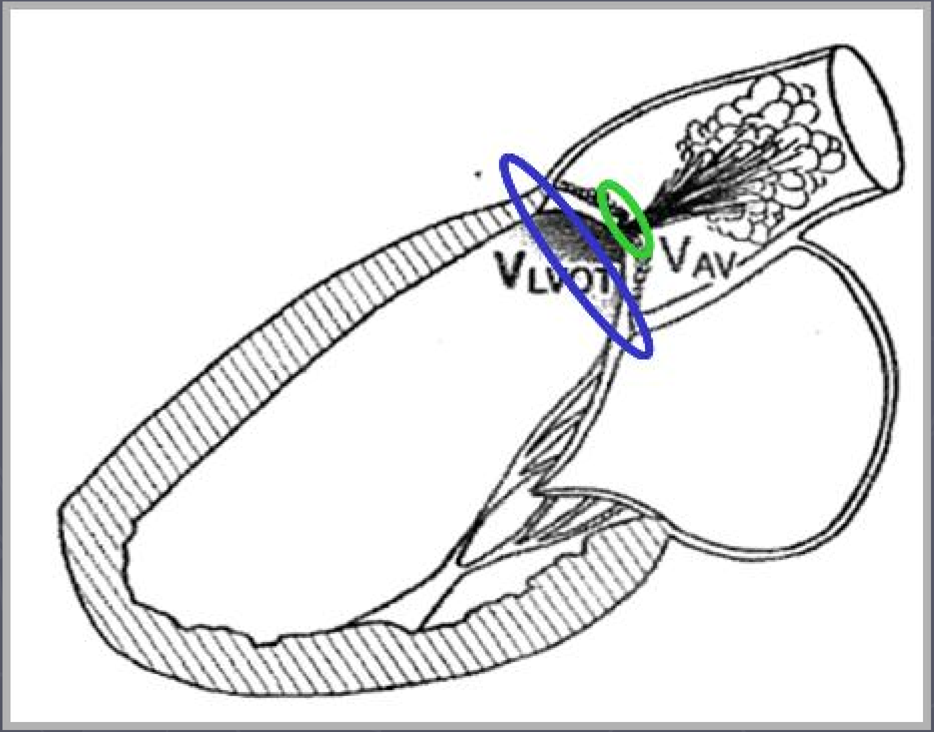


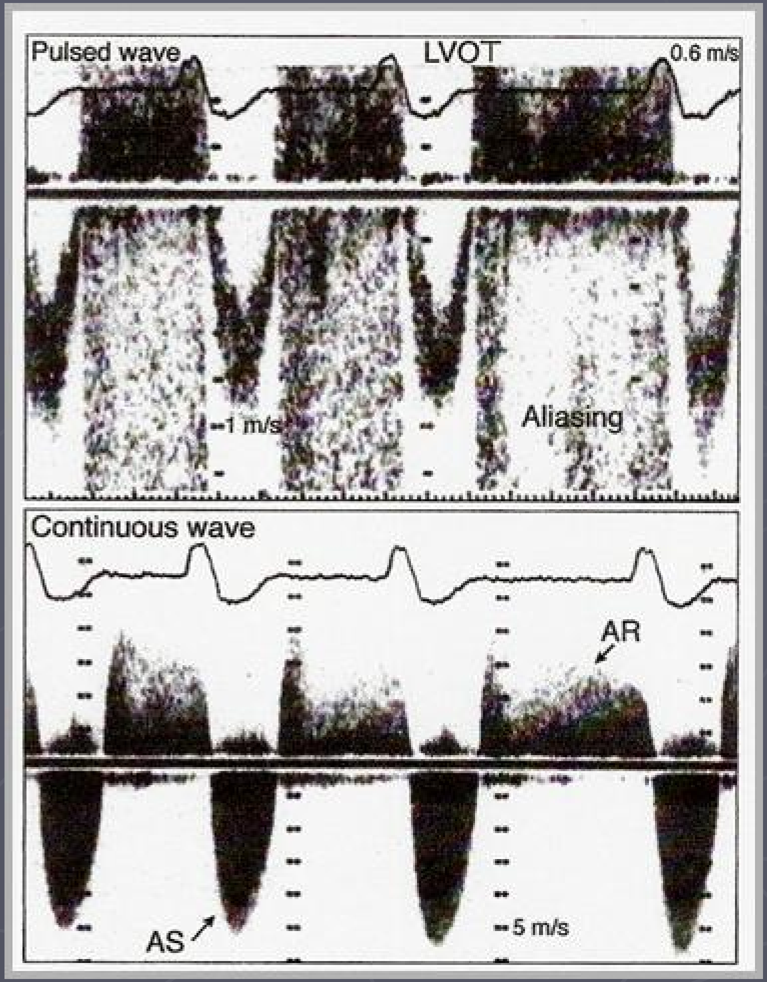
- Serial stenoses
  - Subaortic / mid-LV & aortic

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

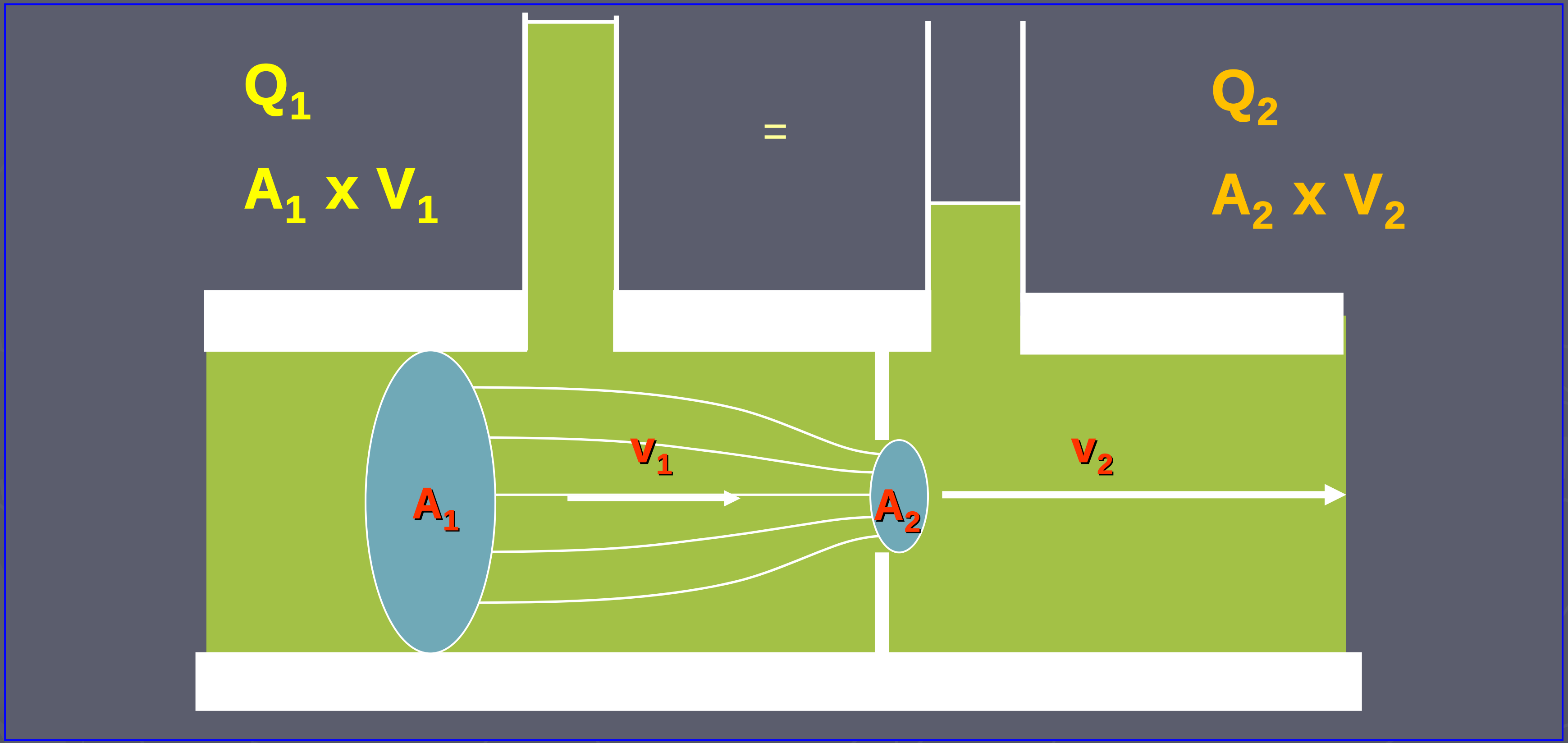
AVA – Continuity Equation





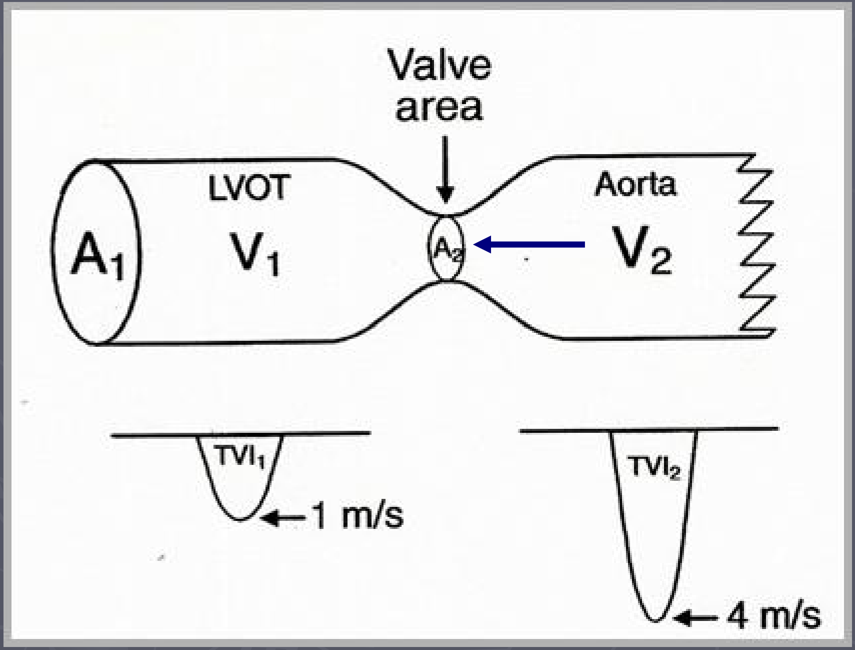
- Conservation of mass

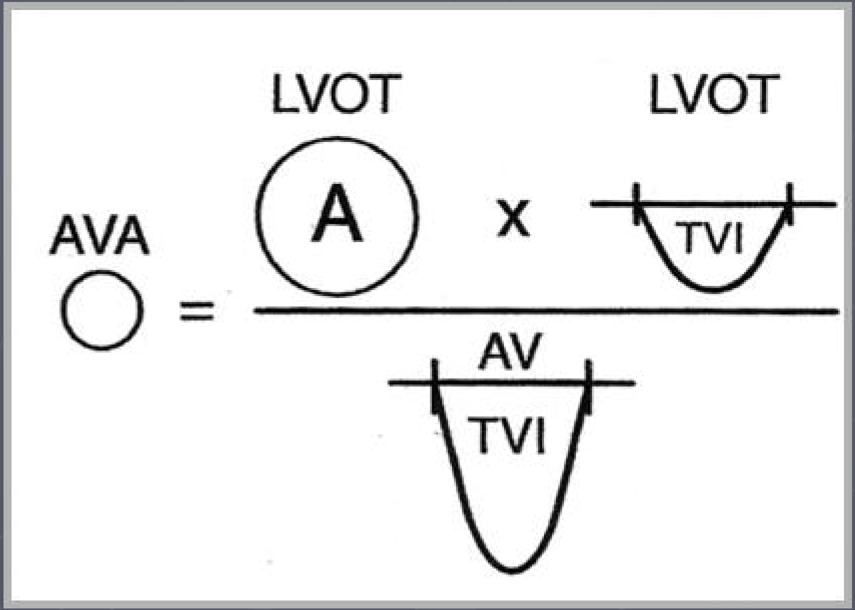
What causes the pressure gradient across a stenotic valve?



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: Q1 = Q2. Since Q = A x v, it follows that if A decreases, v must increase.

AVA – Continuity Equation





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

Continuity Equation – Pitfalls

Inadequate PW sample location in LVOT

Too close (to AoV) → AVA ↑

Too far (within LV) → AVA ↓

$$\textbf{AVA} = CSA_{(LVOT)} \times \frac{VTI_{(LVOT)}}{VTI_{(AS)}}$$

Usually underestimated (→ AVA ↓)

Mistake²

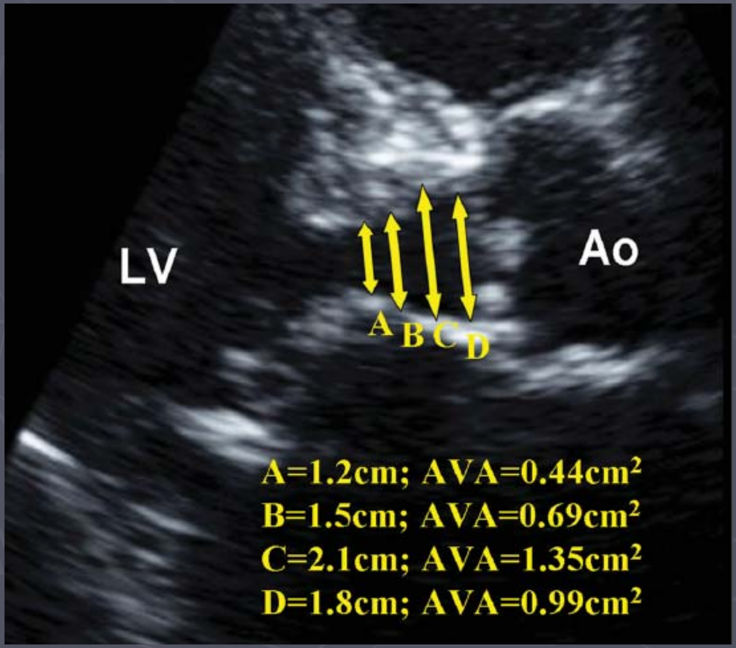
Inadequate alignment with max flow velocity

European Heart Journal (2008) **29**, 2526–2535
doi:10.1093/eurheartj/ehn022

CLINICAL RESEARCH
Imaging

Assessing aortic valve area in aortic stenosis by continuity equation: a novel approach using real-time three-dimensional echocardiography

Kian Keong Poh[1,2], Robert A. Levine[1], Jorge Solis[1], Liang Shen[3], Mary Flaherty[1], Yue-Jian Kang[1], J. Luis Guerrero, and Judy Hung[1*]



- 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

$$AVA = CSA_{(LVOT)} \times \frac{VTI_{(LVOT)}}{VTI_{(AS)}}$$

← Dimensionless index

Index	AS severity
• > 1/2.5	Mild
• 1/2.5-1/4	Moderate
• < 1/4	Severe
• (< 1/5	Critical)

Shortcut

Calculate with peak velocities

VTI ratio ≈ Peak V ratio

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Cardiac Ultrasound

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

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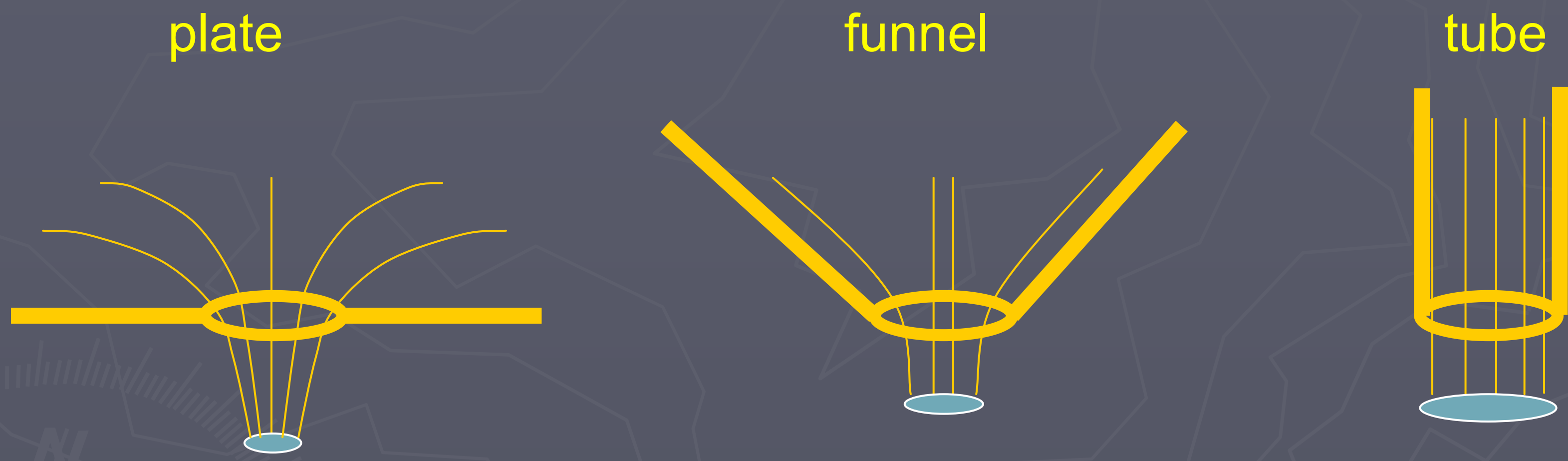
Lyes Kadem, ENG,† Philippe Pibarot, DVM, PHD, FACC*†
Sainte-Foy and Montreal, Quebec, Canada

Coefficient of contraction

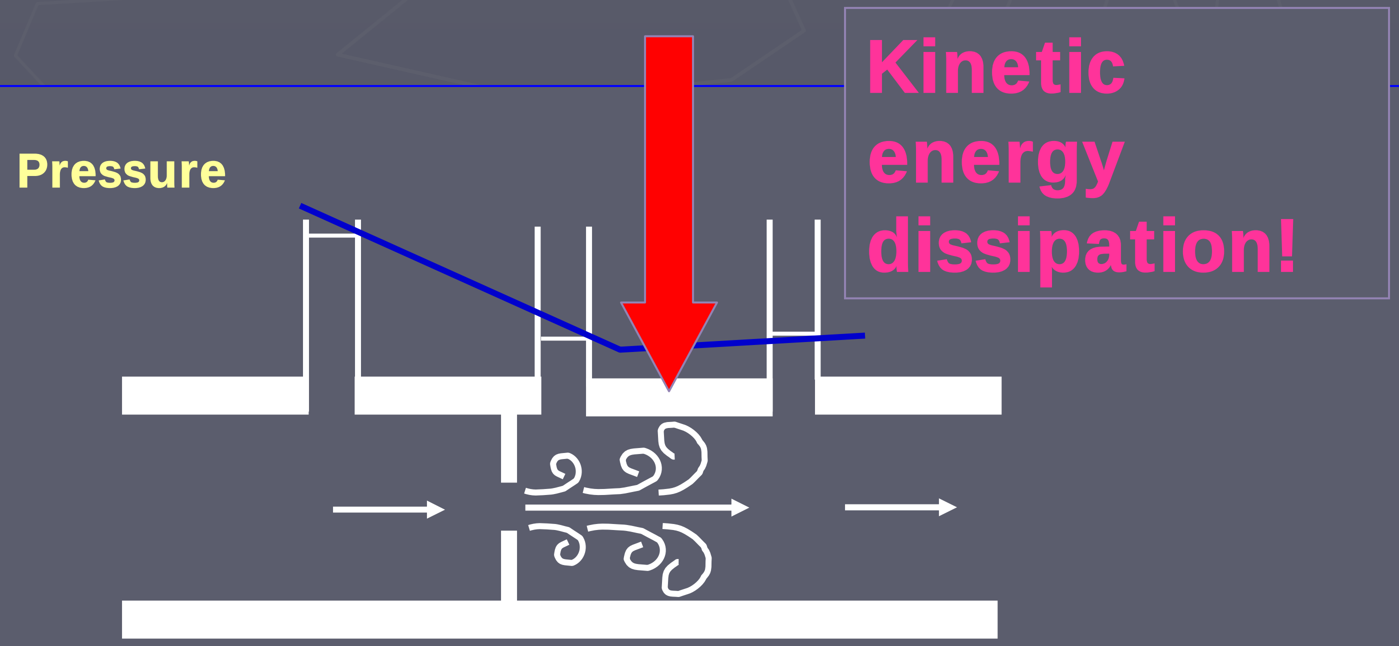


0.6 | 0.8 | 1.0

ה-ERO הוא פונקציה של צורת ה-Inlet

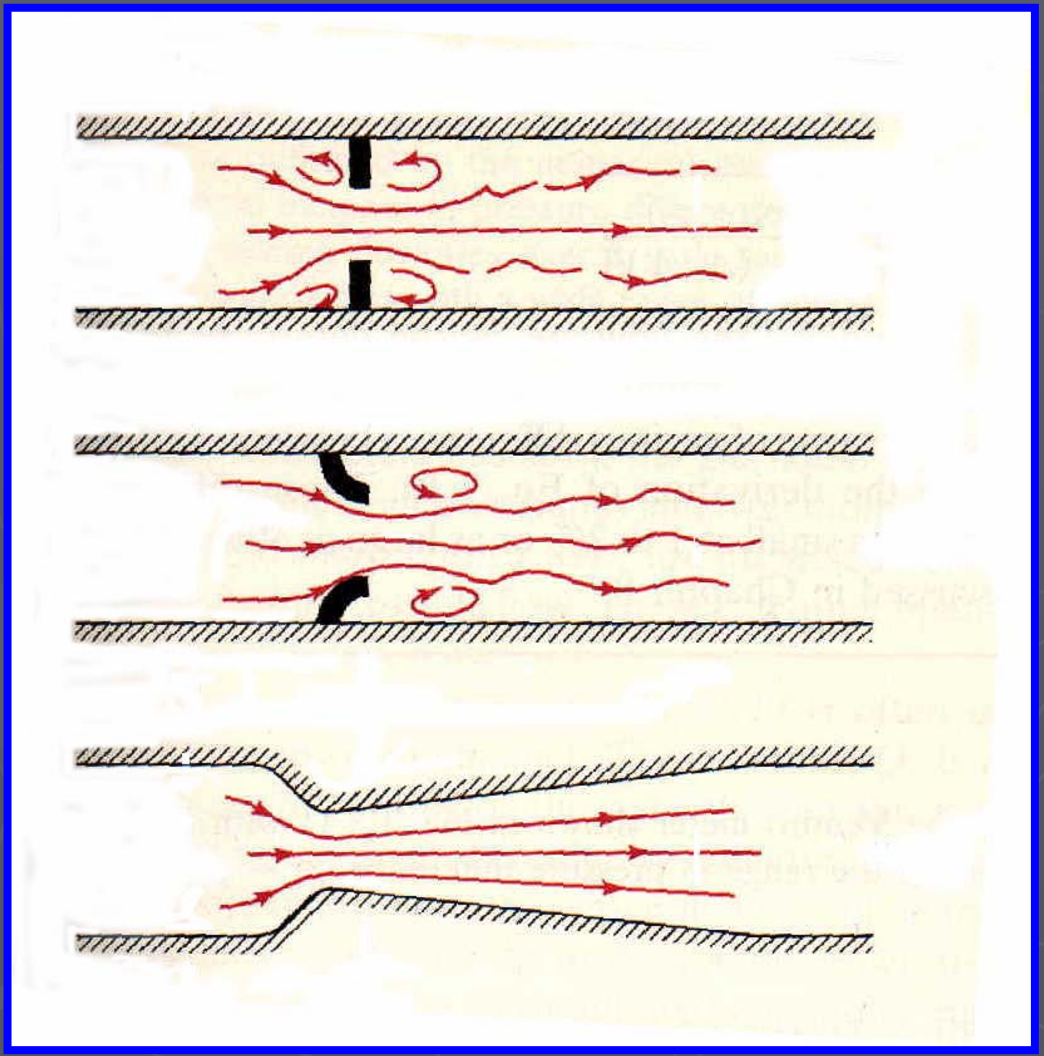
Pressure Recovery

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)

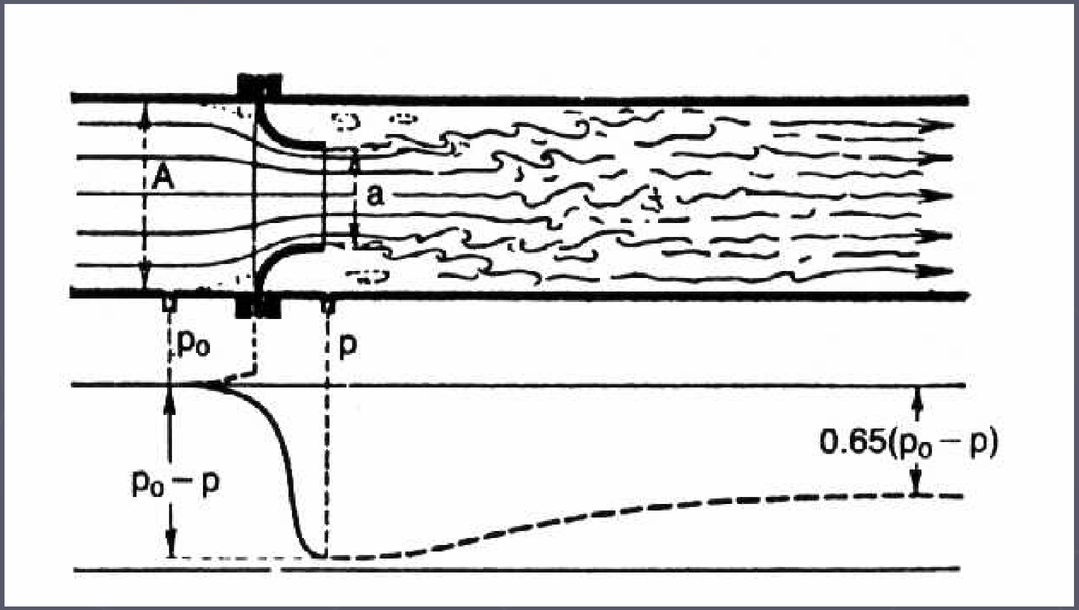


Orifice Meter

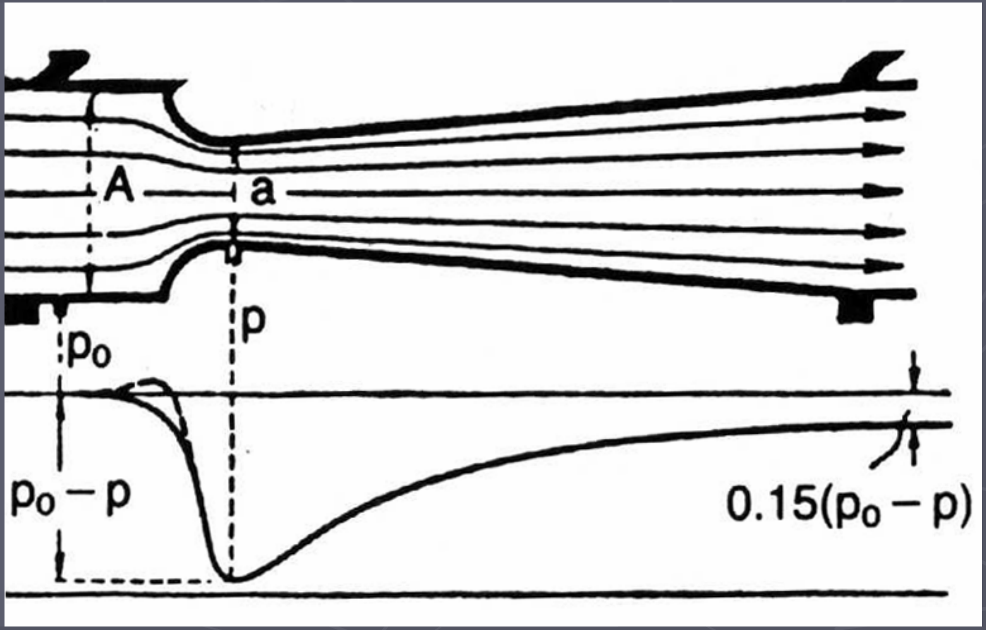
Nozzle Meter

Venturi Meter

Munson, Young, Okiishi: Fundamentals of Fluid Mechanics, New York 1990



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

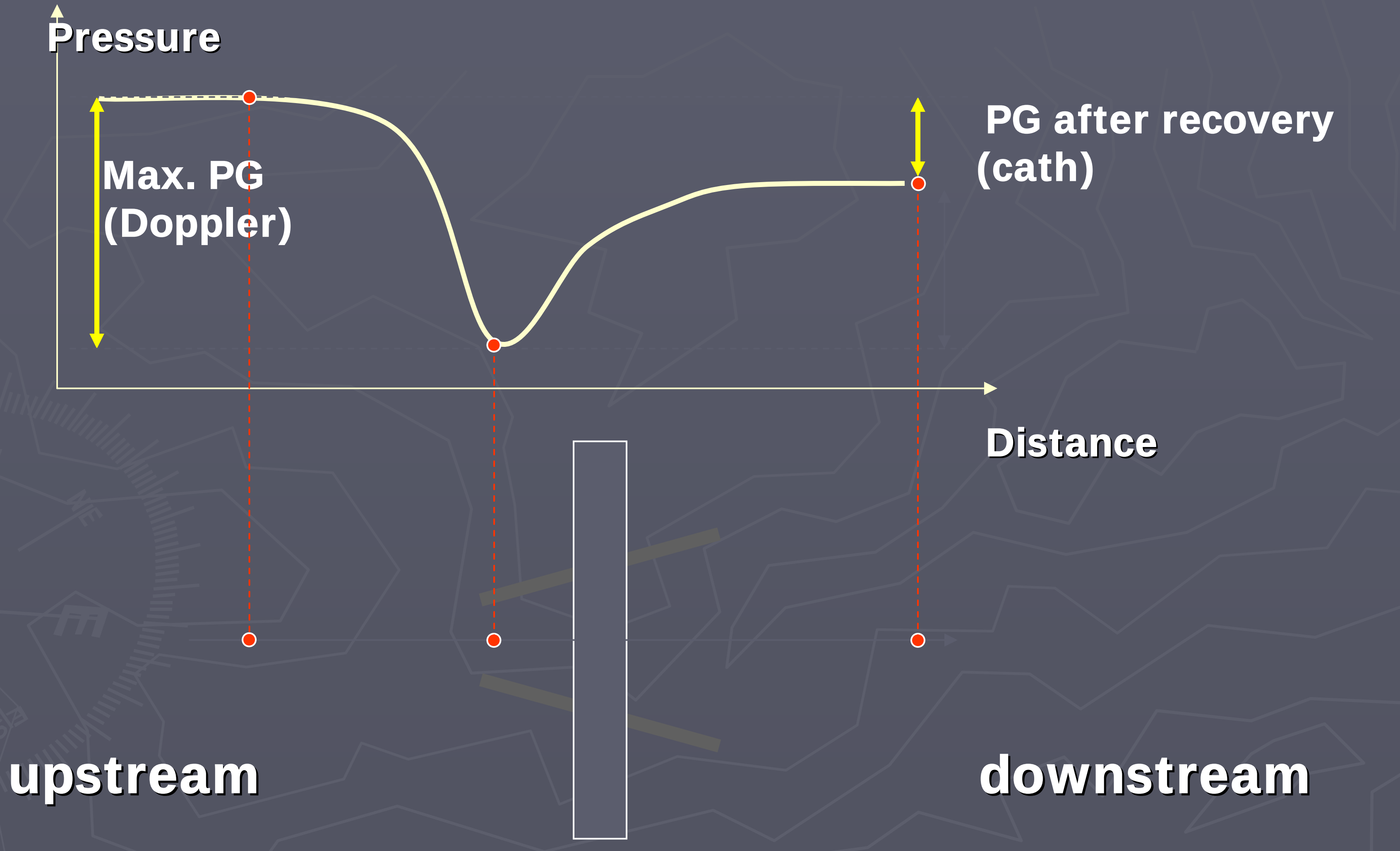


In a well-designed **Venturi meter** the head loss is only 15 %.

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)



- 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.

$$ELCo = \frac{EOA_{Dop} \times A_A}{A_A - EOA_{Dop}} = \frac{Q}{50\sqrt{EL}}$$

EL index = ELCo/BSA

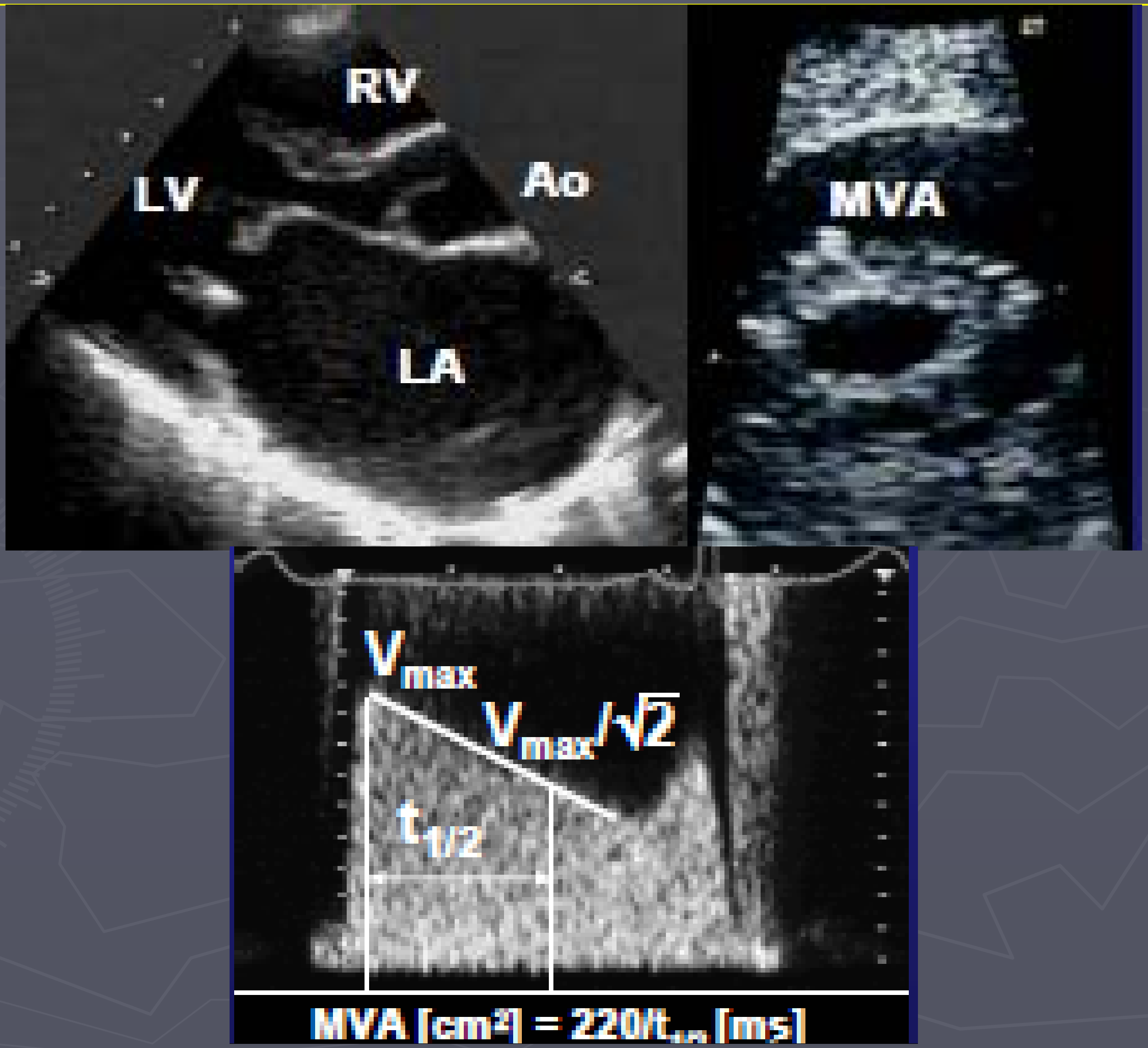
EOA cath or EL index **≤0.55-0.6 cm^2/m^2** is indicative of severe AS

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

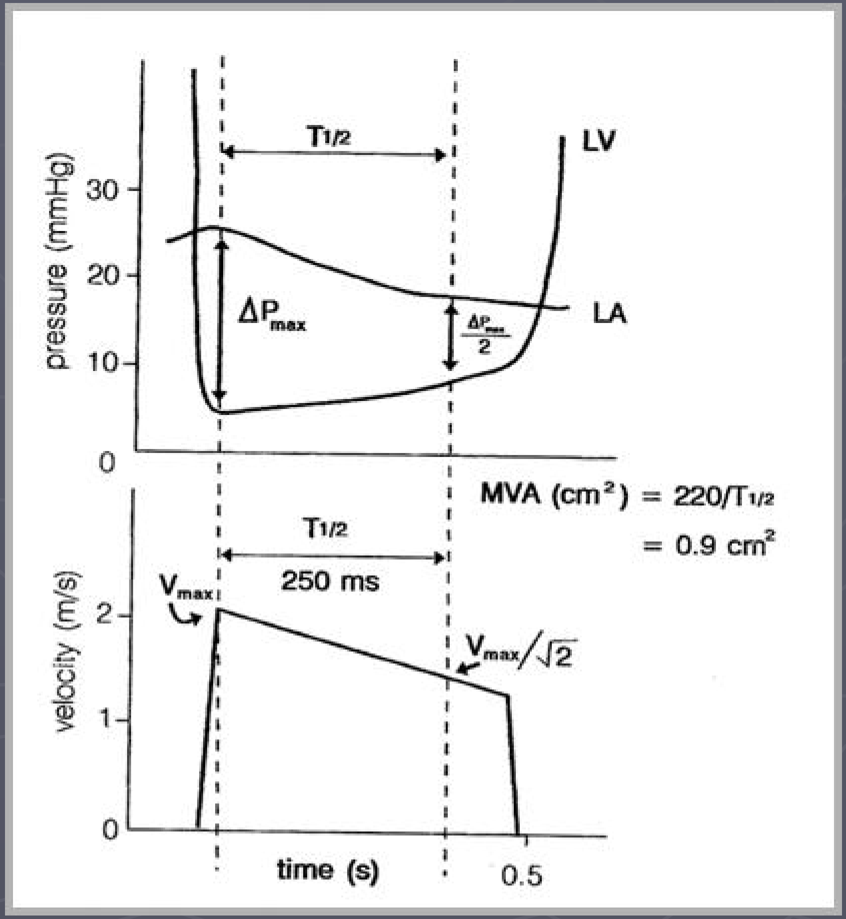
- Other factors (beside pressure recovery) can be associated with AVG – AVA dissociation (low gradients but severe valve area stenosis)
  - Low cardiac output (LV dysfunction)
  - Small stroke volume in LV with nEF
  - Valvulo-arterial impedance (the impact of SBP)

Mitral Stenosis

Mitral stenosis



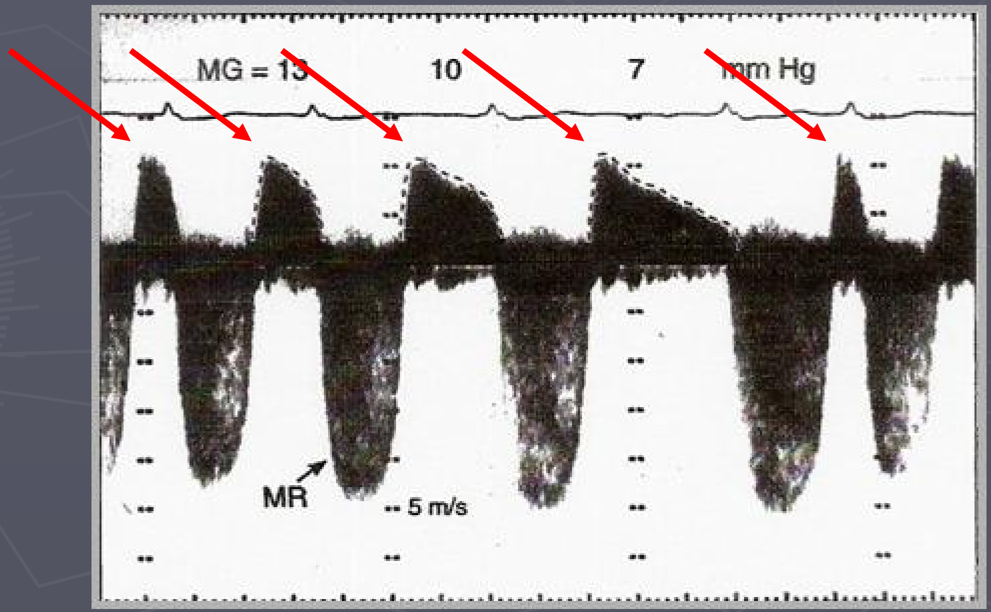
Transvalvular Pressure Gradients



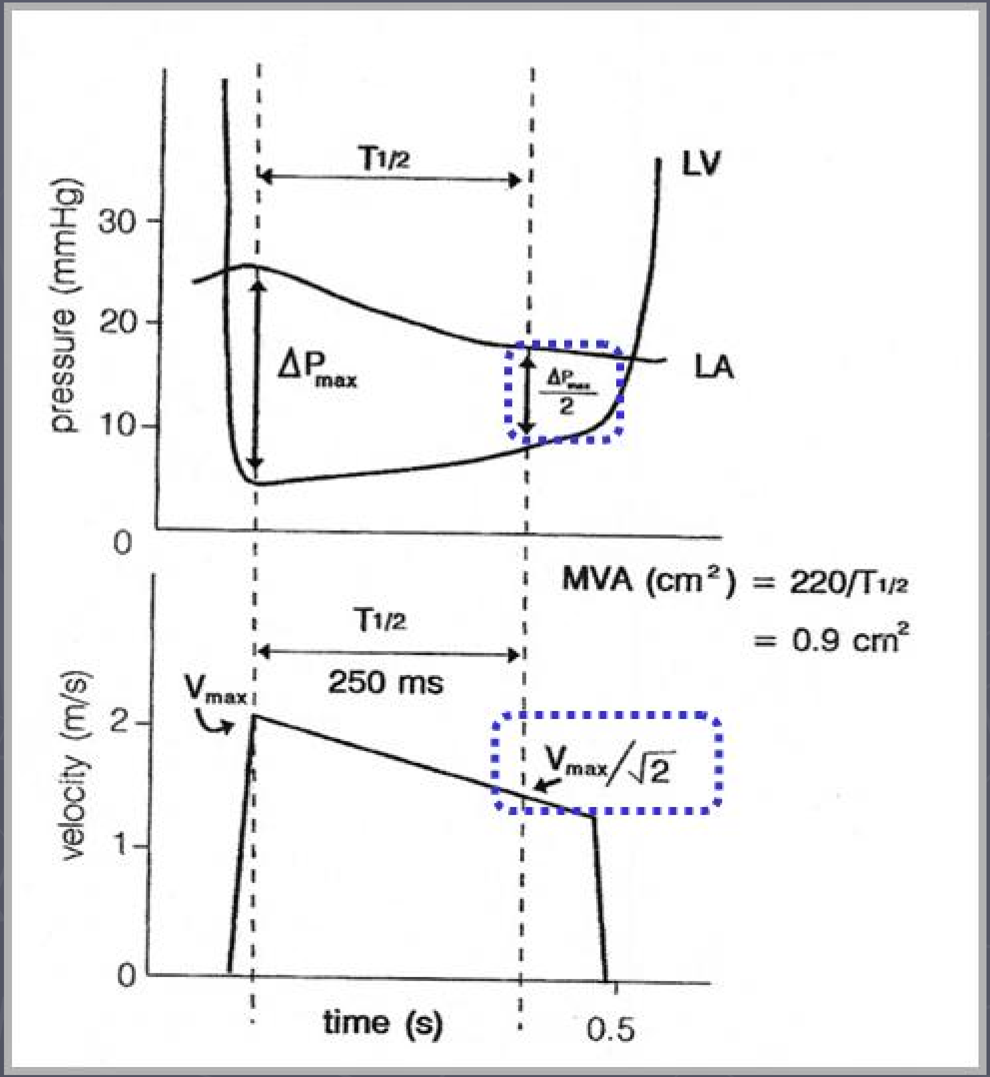
ΔP – Mitral Stenosis

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

Peak ↔ mean ΔP



MVA – Pressure Halftime



MVA = 220 / P $t_{1/2}$

- $P \propto V2$

  $V \propto sqr(P)$

- $P_{max} \rightarrow ½\ P_{max}$

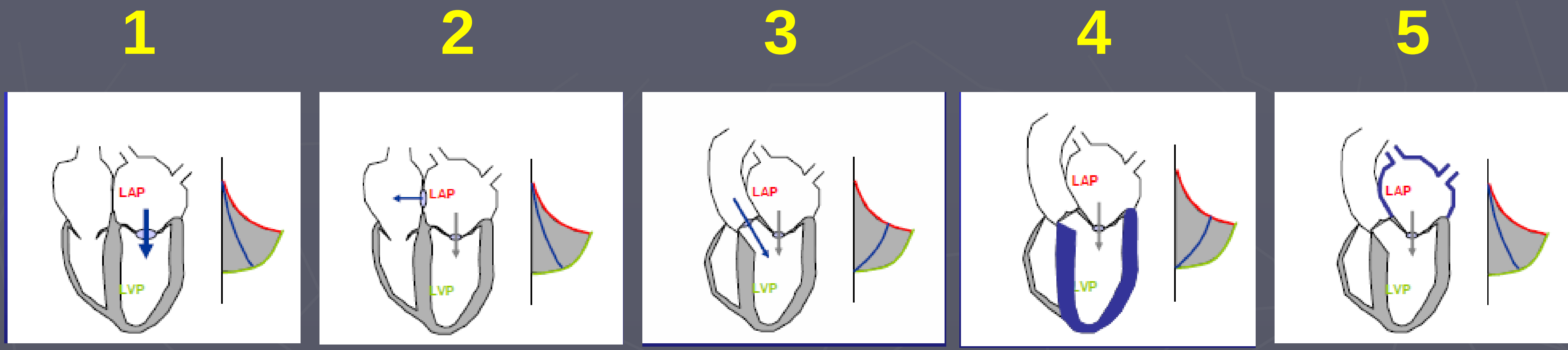
  $V_{max} \rightarrow sqr(½)\ V_{max}$

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 ↓ = severe MS
  - Calculated MVA > expected (morphology, ΔP)
    - May still be severe MS !

*Exception – Mild MS & LV relaxation ↓↓ (HHD)

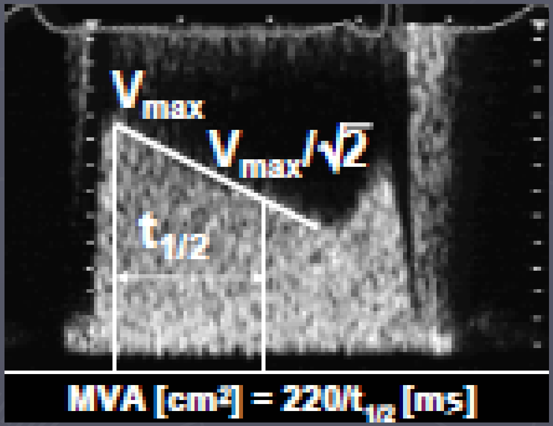
Pressure Half-Time

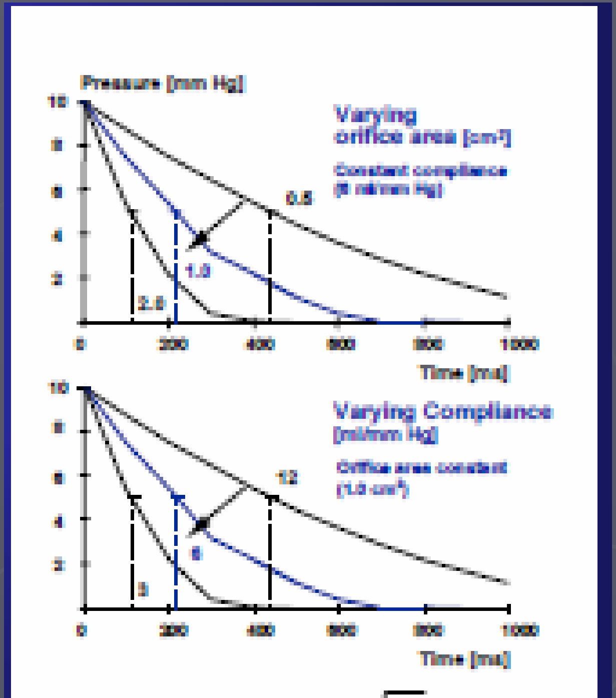


1. **The larger the MVA, the more rapidly LAP drops, and diastolic LVP increases (equilibrium is reached quickly) - t1/2 will be shortened.**

However,

2. **LAP may also drop rapidly if LA has a second outlet (ASD) - t1/2 will be shortened.**
3. **Or LVP may rise rapidly if LV fills from a second source (AR) - t1/2 will be shortened.**
4. **Or LVP may rise rapidly if LV is stiff (low ventricular compliance) - t1/2 will be shortened.**
5. **Or LAP may drop rapidly if LA is stiff (low atrial compliance) - t1/2 will be shortened.**



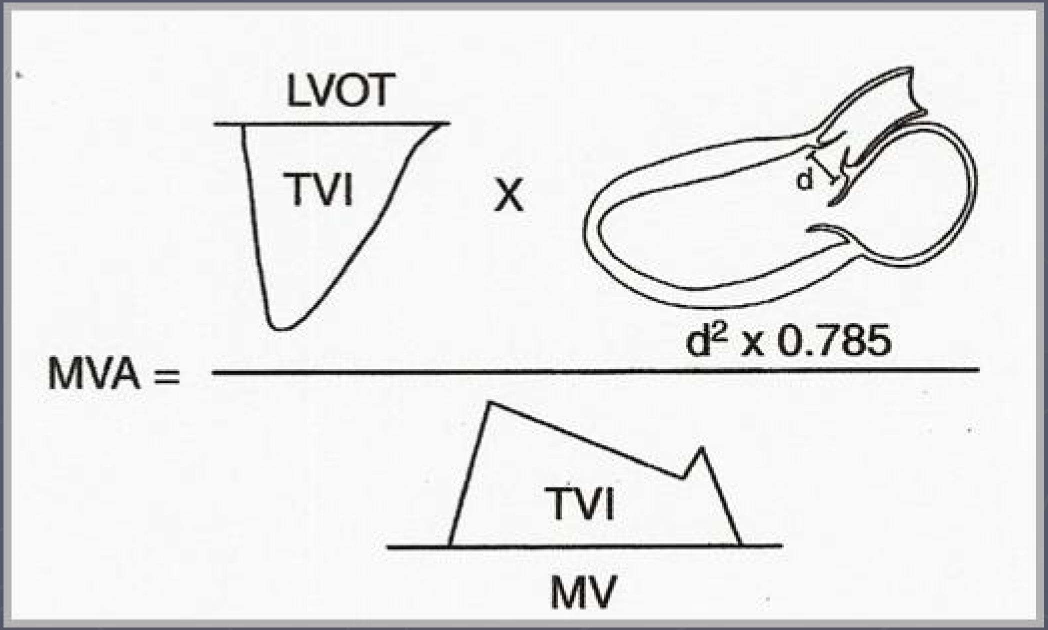


$$t_{1/2} = \frac{11.6 C_n \sqrt{p_o}}{MVA}$$

- **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 <u>mean gradient</u>, and <u>pulmonary artery pressure</u>, try <u>mitral valve planimetry</u>, and consider <u>exercise echo</u>

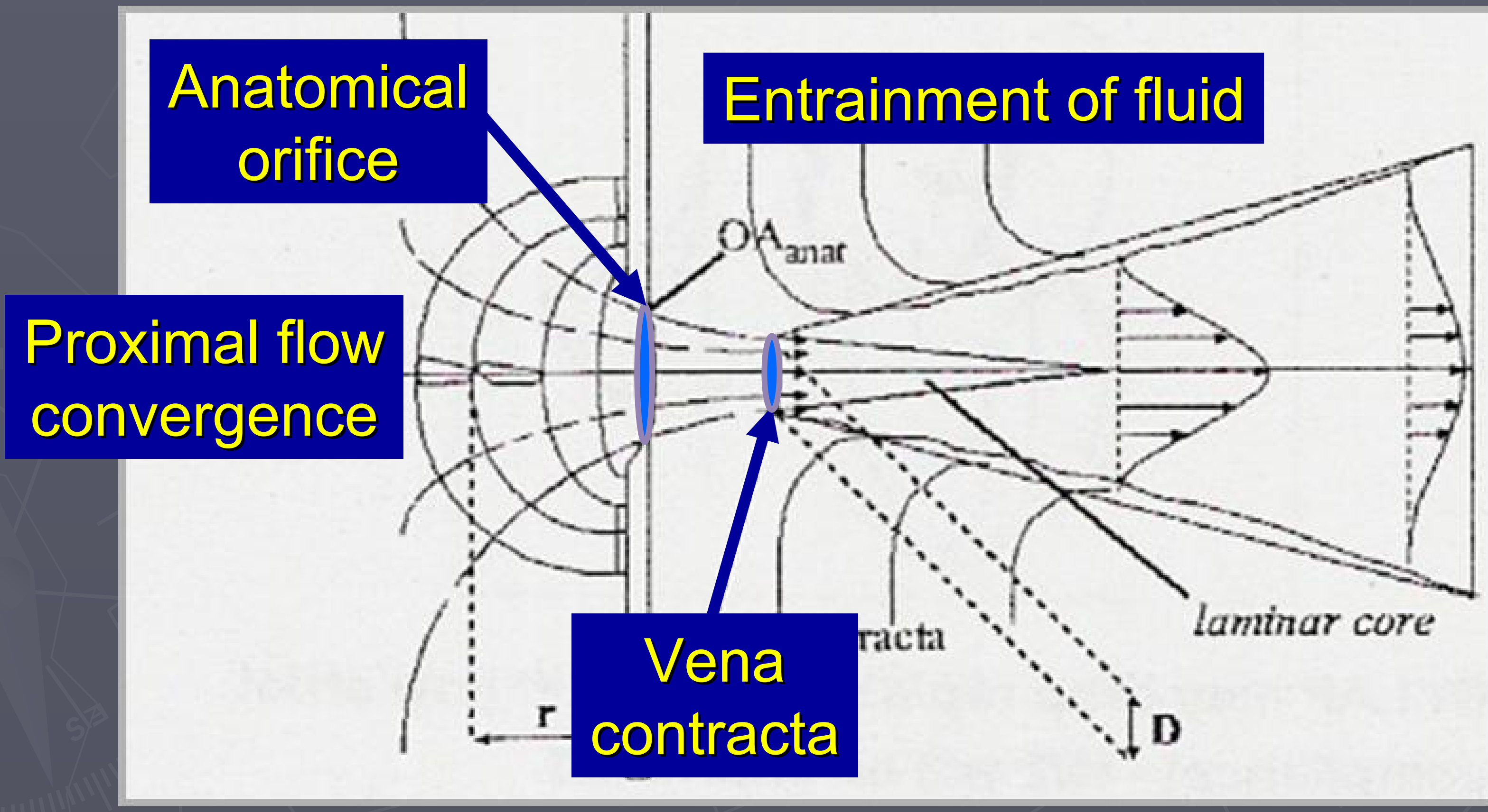
MVA – Continuity Equation



- Assumptions
  - No MR (MR ≤ mild)
  - No AR (AR ≤ mild)

Mitral Regurgitation

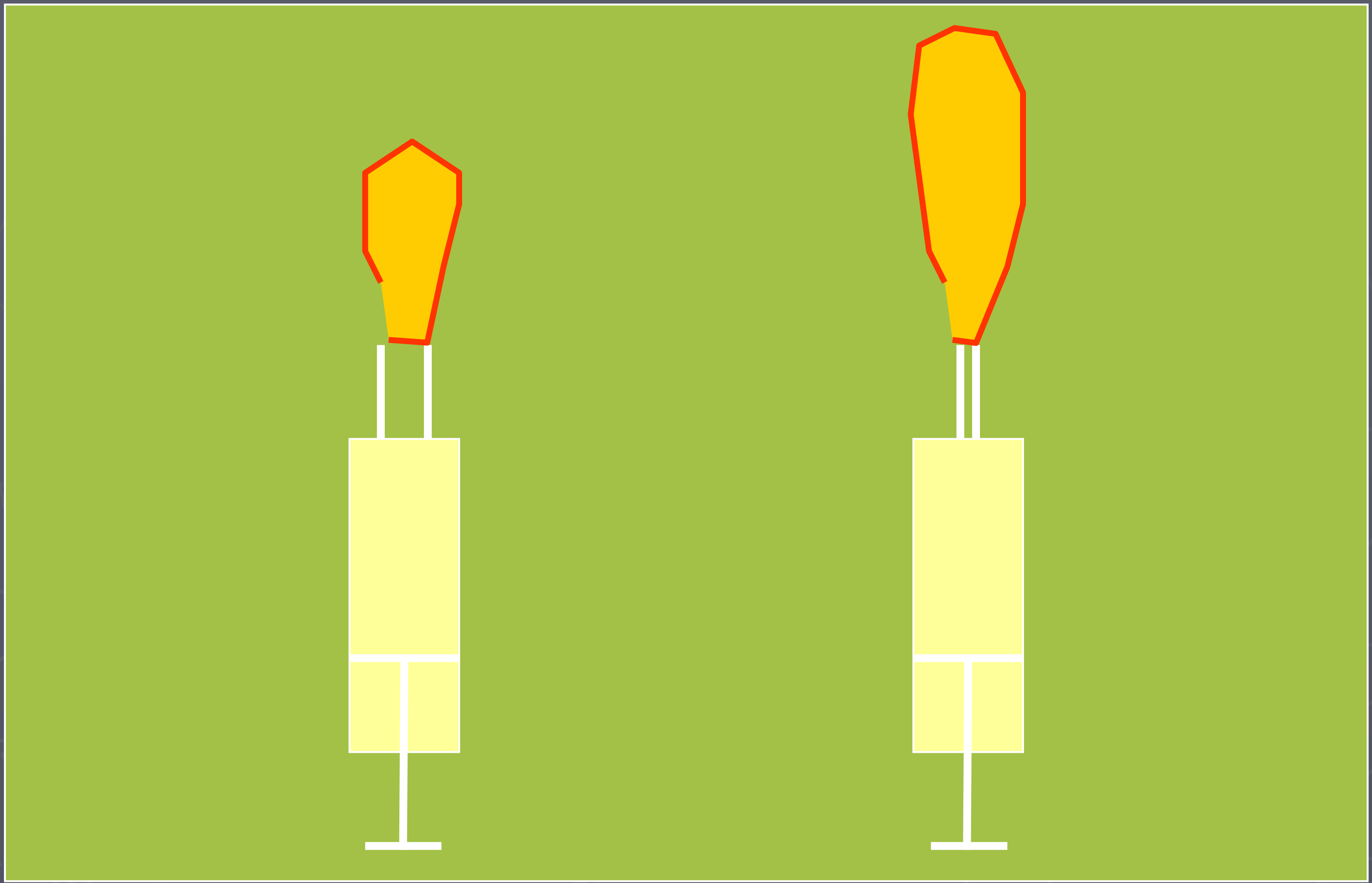
Qualitative Assessment
Color Flow Imaging



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 x VTI

MR PISA – Shortcut I

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

$$ERO = 6.28r^2 \times \frac{V_{aliasing}}{V_{regurg}}$$

MR PISA – Shortcut II

- $V_{aliasing} \rightarrow$ set @ 40 cm/s

  Assume V_{MR} ~ 5 m/s

  $\rightarrow$ ERO = r^2 / 2

$$\text{ERO} = 6.28r^2 \times \frac{V_{aliasing}}{V_{regurg}}$$

PISA – Caveats

- Multiple technical caveats
- Dynamic MR
  - Timing of measurement

    e.g. – MVP, ischemic MR
- Multiple MR jets
- Angle correction
  - Eccentric jets +++

MR Severity

	ERO (cm^2)	**RV** (ml)	**RF** (%)
► Mild (I)	<0.2	<30	<30
► Moderate (II)	0.2-0.3	30-45	30-40
► Mod-severe (III)	0.3-0.4	45-60	40-50
► Severe (IV)	>0.4	>60	>50

Grades III & IV = surgical MR

	>0.3	>45	>40

Aortic Regurgitation

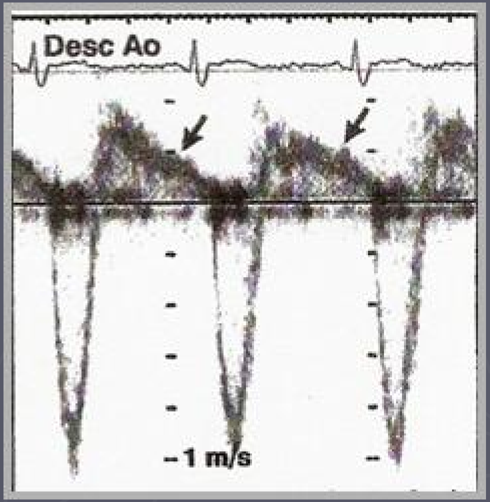
AR Severity (PISA / QD)

	ERO (cm^2)	RV (ml)	RF (%)
► Mild (I)	< 0.1	< 30	<30
► Moderate (II)	0.1-0.2	30-45	30-40
► Mod-severe (III)	0.2-0.3	45-60	40-50
► Severe (IV)	> 0.3	> 60	>50

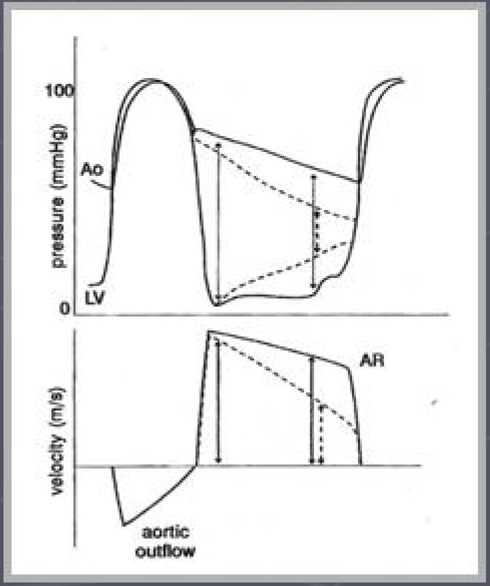
Grades III & IV = surgical AR

	> 0.2	> 45	>40

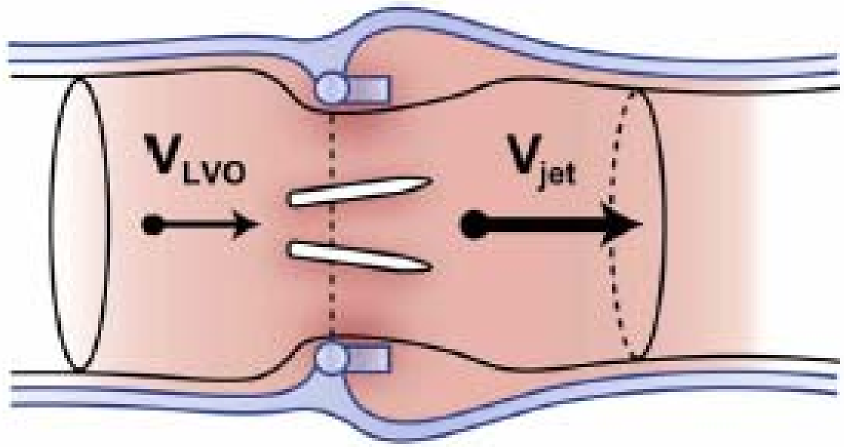
Additional Doppler Findings - AR



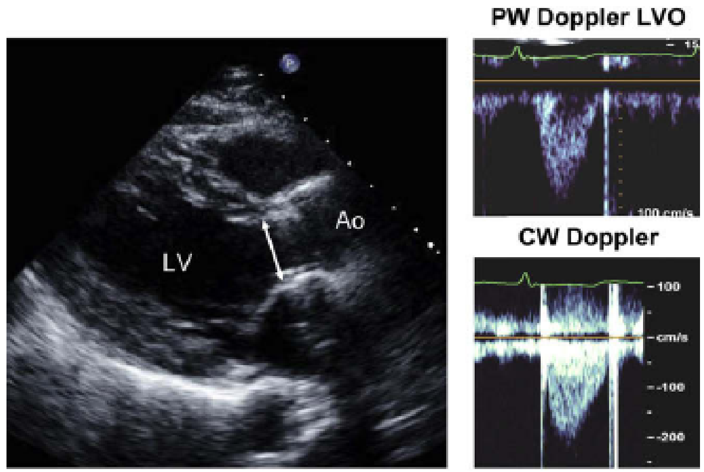
- Flow reversal – descending aorta
- P t1/2 – Multiple determinants
  - AR severity ↑ → P t1/2 ↓
  - LV compliance ↓ → P t1/2 ↓
  - SVR ↓ → P t1/2 ↓
- Do not confuse chronic with acute AR
- Cutoffs: >400 ms / 250-400 / <250 ms



Prosthetic Valves



$$\text{Doppler Velocity Index} = \frac{\text{Velocity}_{LVO}}{\text{Velocity}_{jet}}$$

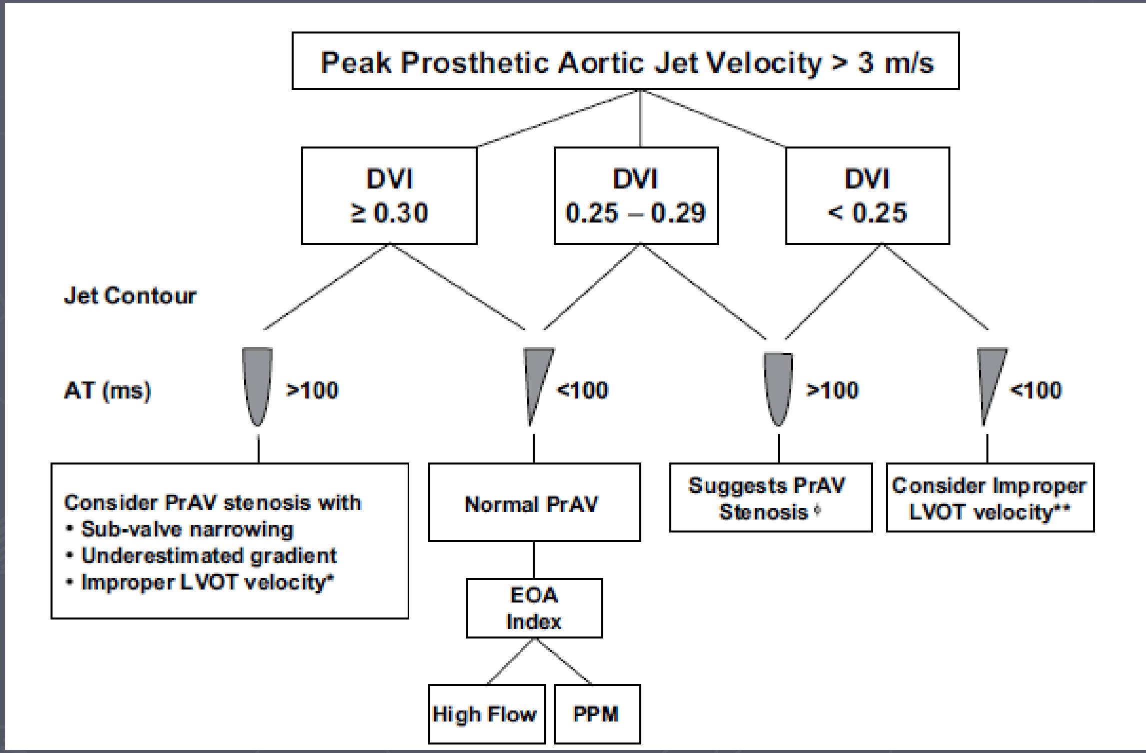


$$\text{Effective Orifice Area} = \frac{CSA_{LVO} \times VTI_{LVO}}{VTI_{JET}}$$

Table 5 Doppler parameters of prosthetic aortic valve function in mechanical and stented biologic valves*

Parameter	Normal	Possible stenosis	Suggests significant stenosis
Peak velocity (m/s)†	<3	3-4	>4
Mean gradient (mm Hg)†	<20	20-35	>35
DVI	≥0.30	0.29-0.25	<0.25
EOA (cm^2)	>1.2	1.2-0.8	<0.8
Contour of the jet velocity through the PrAV	Triangular, early peaking	Triangular to intermediate	Rounded, symmetrical contour
AT (ms)	<80	80-100	>100

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.

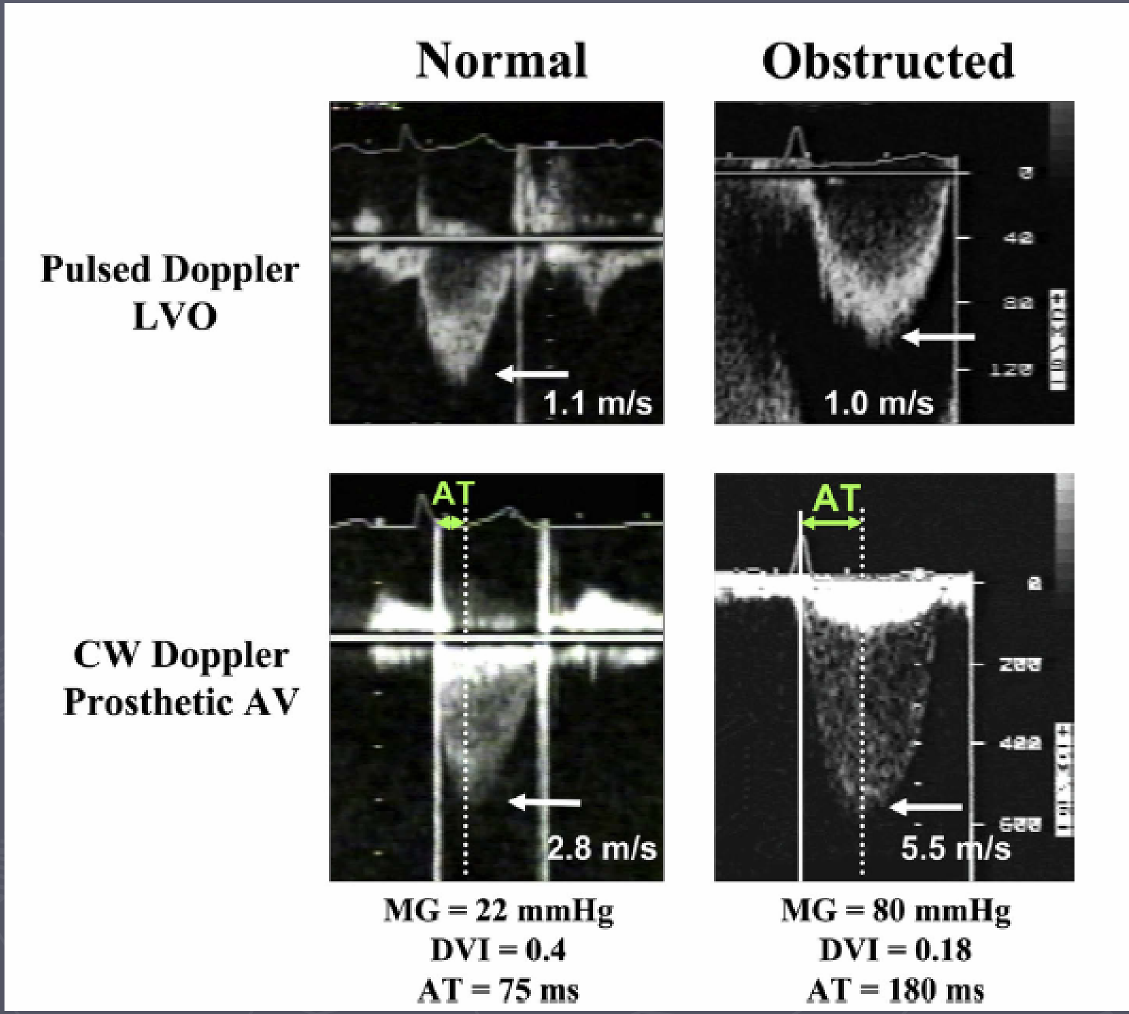


Peak Prosthetic Aortic Jet Velocity > 3 m/s
DVI ≥ 0.30
DVI 0.25 – 0.29
DVI < 0.25
Jet Contour
AT (ms)
>100
<100
>100
<100
Consider PrAV stenosis with
• Sub-valve narrowing
• Underestimated gradient
• Improper LVOT velocity*
Normal PrAV
Suggests PrAV Stenosis ◊
Consider Improper LVOT velocity**
EOA Index
High Flow
PPM

Table 9 Transthoracic echocardiographic findings suggestive of significant prosthetic MR in mechanical valves with normal pressure half-time

Finding	Sensitivity	Specificity	Comments
Peak mitral velocity ≥1.9 m/s*	90%	89%	Also consider high flow, PPM
VTI_{PrMV}/VTI_{LVO} ≥ 2.5*	89%	91%	Measurement errors increase in atrial fibrillation due to difficulty in matching cardiac cycles; also consider PPM
Mean gradient ≥ 5 mmHg*	90%	70%	At physiologic heart rates; also consider high flow, PPM
Maximal TR jet velocity > 3 m/s*	80%	71%	Consider residual postoperative pulmonary hypertension or other causes
LV stroke volume derived by 2D or 3D imaging is >30% higher than systemic stroke volume by Doppler	Moderate sensitivity	Specific	Validation lacking; significant MR is suspected when LV function is normal or hyperdynamic and VTI_{LVO} is <16 cm
Systolic flow convergence seen in the left ventricle toward the prosthesis	Low sensitivity	Specific	Validation lacking; technically challenging to detect readily

PrMV, Prosthetic mitral valve.
*Data from Olmos et al.[148] 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
1.0 m/s
CW Doppler
Prosthetic AV
AT
AT
2.8 m/s
5.5 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: $\mathbf{PG = 4 * (V_{dist}^2 - V_{prox}^2)}$

$PG = 4 * (23 - 4) = 76$ 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
      $\rightarrow$ 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 cm^2

Case #3

40 yo woman; MS; NYHA III

- MVA
  - Planimetry MVA: 1.3 cm2
  - P $t_{1/2}$ MVA: 1.3 cm2 (P t1/2: 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 ↓

Answer #4

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 ↓
5. LV compliance ↓

→ MVA ↑ (P t1/2 ↓)

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