Doppler techniques and quantification

Bart Bijnens

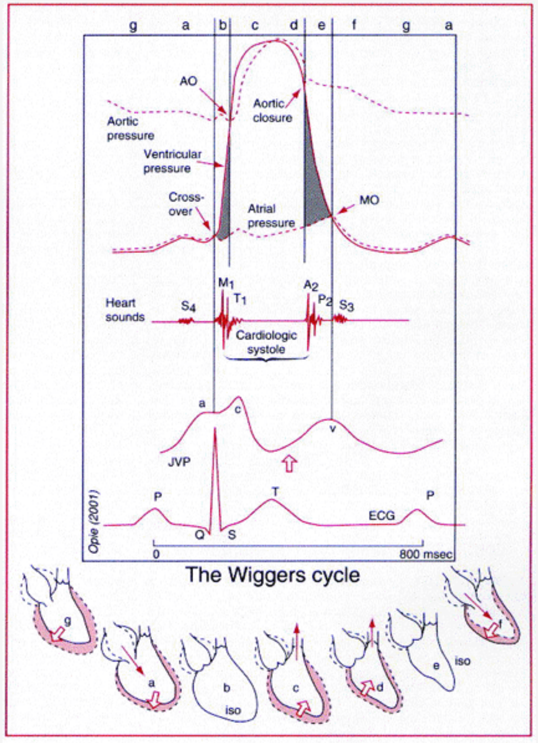
UNIVERSITAT POMPEU FABRA
Dept. of Information and Communication Technologies

Institució Catalana de Recerca i Estudis Avançats

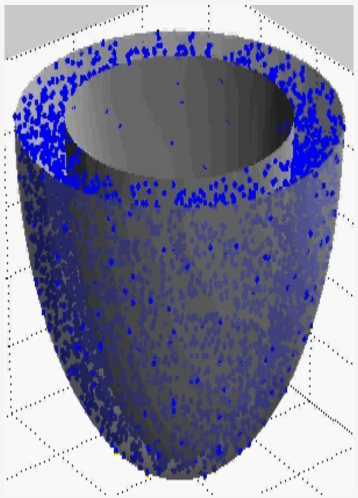
KULeuven

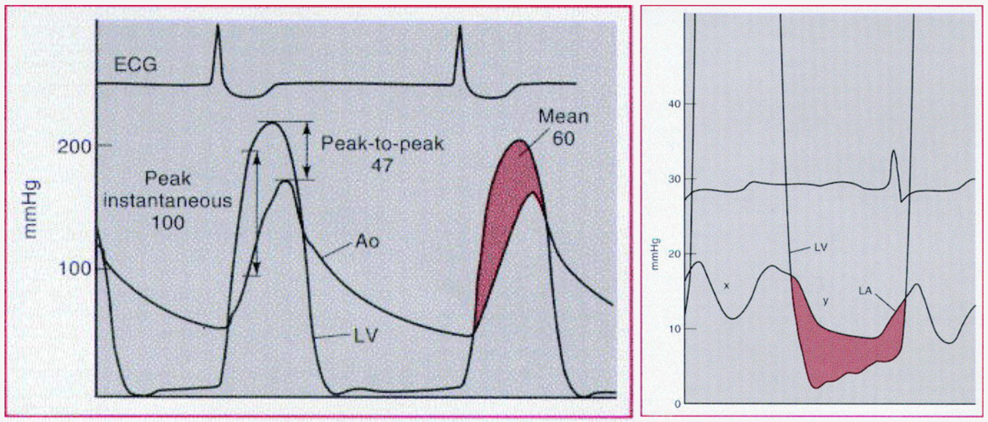
The heart as a volume pump

- The main function of the heart is to maintain the required ***cardiac output***
- Thus, it is a volume pump, trying to ***generate a certain volume flow*** under *all* cardiac conditions.
- The heart muscle has to develop force to ***generate pressure gradients*** that result in volume flow
- For this, the heart muscle has a ***unique structure and resulting deformation pattern***.



Anderson & Becker
Cardiac Anatomy '80

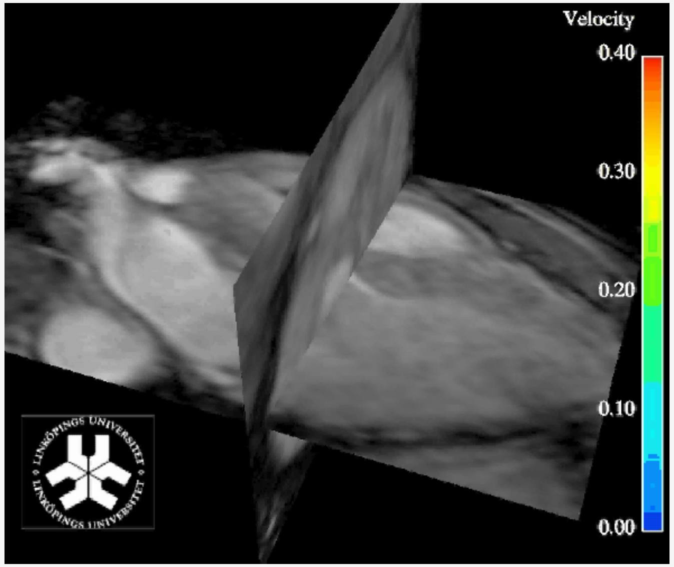




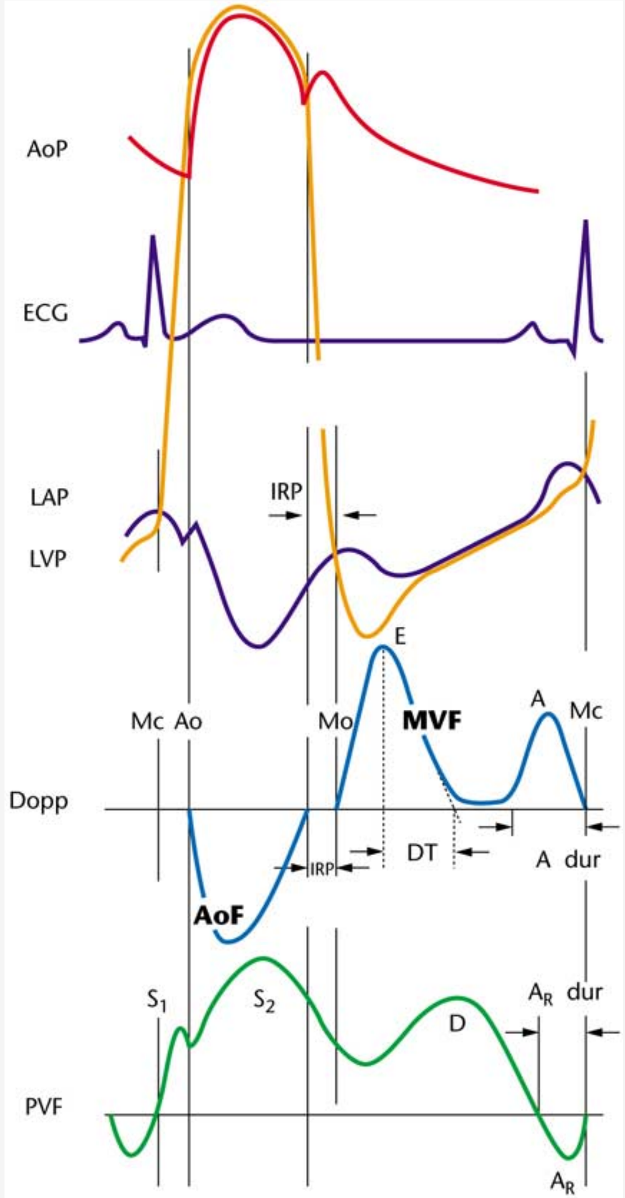
Braunwald, Heart Disease (6th ed)

Blood flow

Blood flow is continuous, accelerating and decelerating during the cycle due to pressure gradients, without sudden changes in the momentum of the particles, to obtain energy efficiency



Linkoping University, Sweden



ESC Texbook of Cardiovasc. Med., 2006

Hemodynamic data: what to quantify?

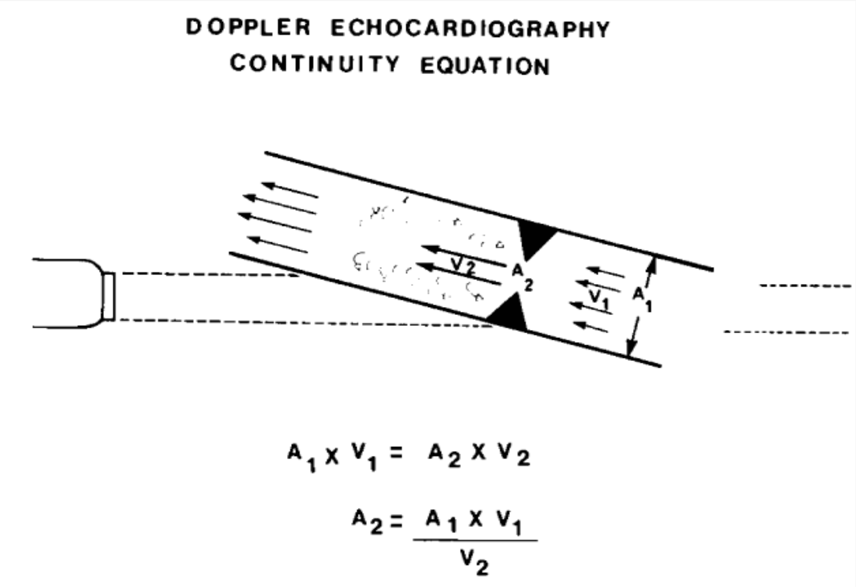
Hemodynamics = dynamics of the blood = temporal behaviour of bloodflow

- **(I) Resulting volume displacements** during the cardiac cycle
  - Stroke volumes and cardiac output
  - Regurgitant volumes due to valve incompetence
  - Shunt volumes and pulmonary-systemic flow ratio
- **(II) Altered flow due to altered valve geometry (valve area)**
  - Stenosis
  - Regurgitation
  - Abnormal connections (VSD, ASD,…)
- **(III) Pressures & pressure gradients** as driving forces for blood flow
  - ΔP between ventricles and atria determining filling
  - ΔP between ventricles and large arteries determining ejection
  - P in the different heart chambers determining the ΔP controlling the blood flow
    - LV ED pressure
    - LA pressure
    - PA pressure
  - P generation is related to myocardial function

Basic Physical Principles

Continuity of flow

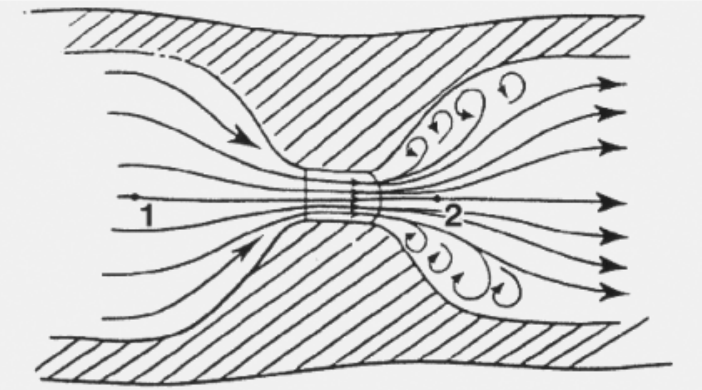
if there is no loss of fluid,
at each cross section of the tube, the same volume-flow (cross section × velocity) is passing



Volumes and valve areas

Bernoulli equation

describes the relation between pressures and velocities for fluid flow, based on the conservation of energy



Bernoulli Equation

$$P_1 - P_2 = \underbrace{\tfrac{1}{2}\rho(V_2^2 - V_1^2)}_{\text{Convective acceleration}} + \underbrace{\rho\int_1^2 \frac{d\vec{v}}{dt}\,d\vec{s}}_{\text{Flow acceleration}} + \underbrace{R(\vec{V})}_{\text{Viscous friction}}$$

P_1 = pressure at location 1
P_2 = pressure at location 2
ρ = mass density of the blood 1.06×10^3 kg/m^3
V_1 = velocity at location 1
V_2 = velocity at location 2

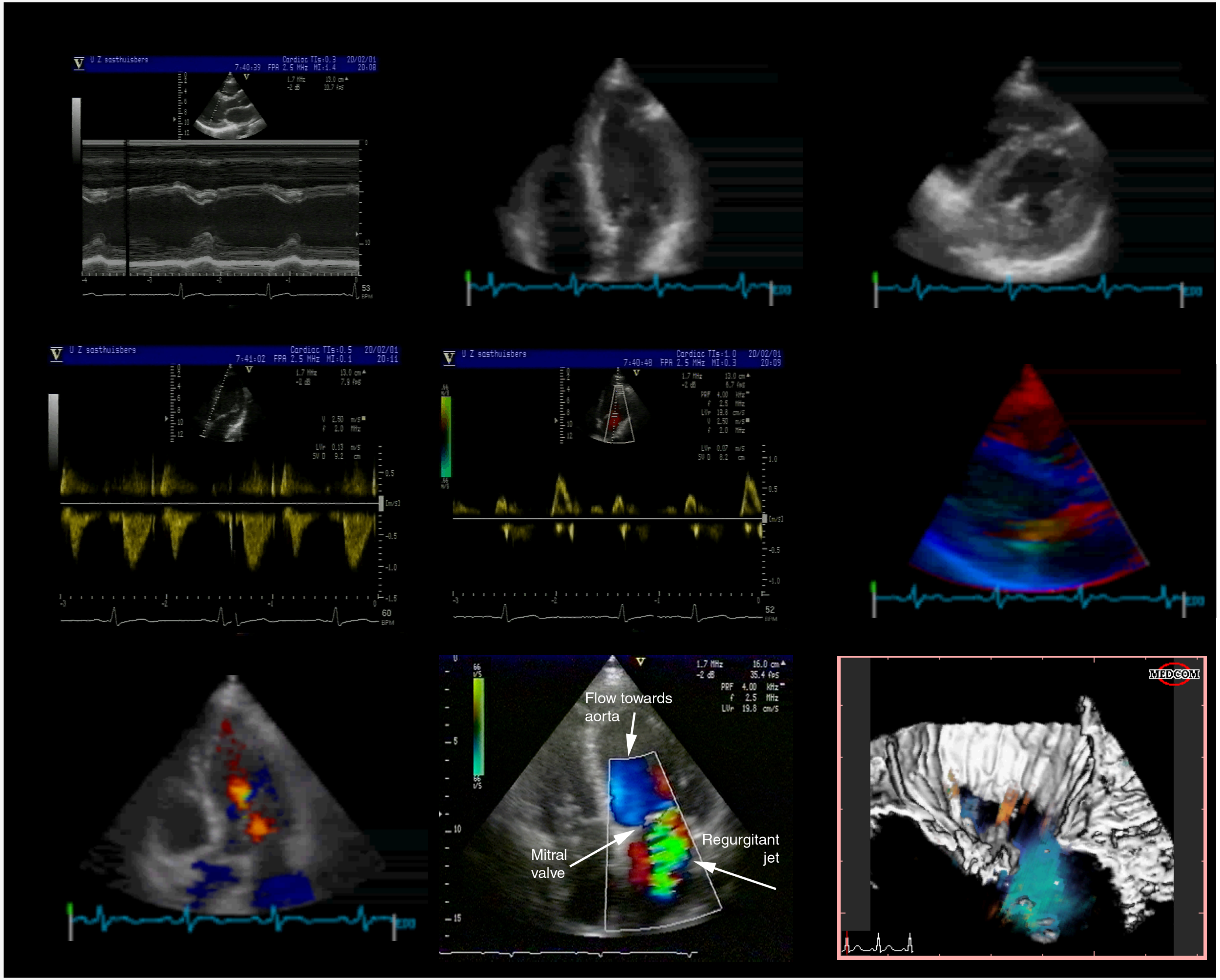
Pressure gradients

Available information from echocardiography ?

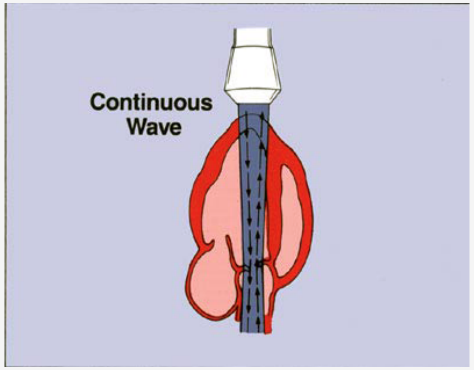
Geometry

Velocities

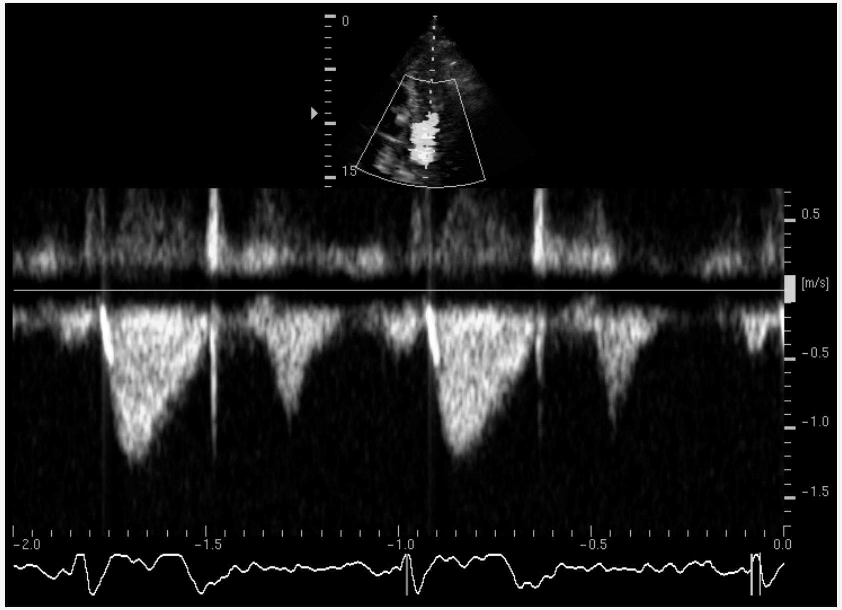
Flow patterns

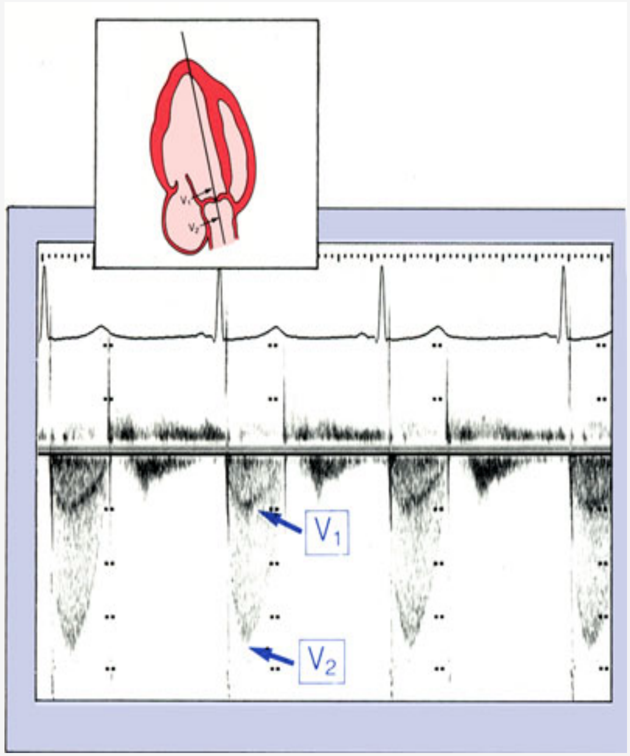


CW systems



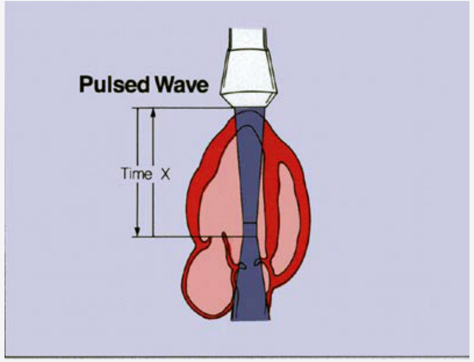
- No spatial information
- Several velocities in the beam: broad spectrum
- Attenuation: velocities from deeper tissue contribute less





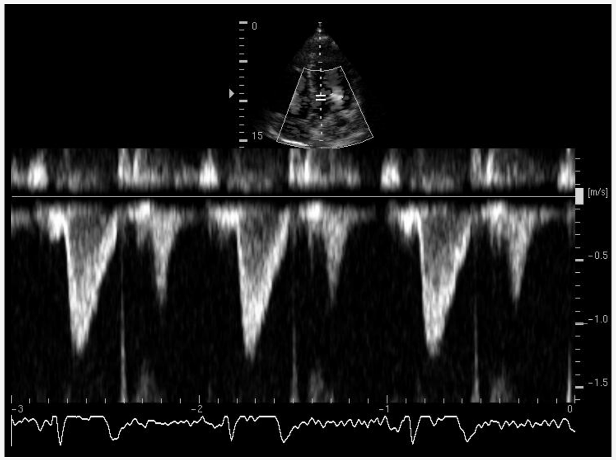
www.echoincontext.com: Kisslo & Adams

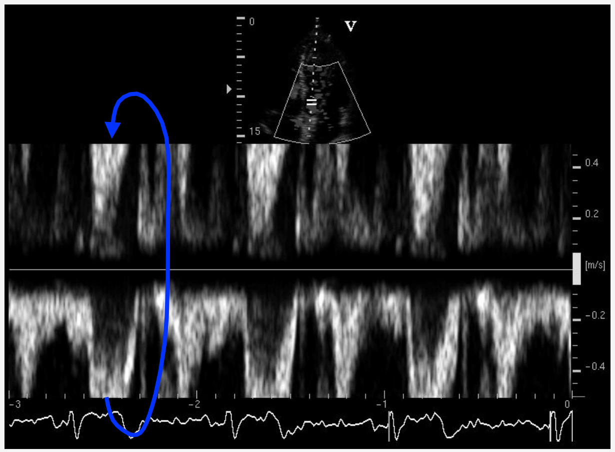
PW systems



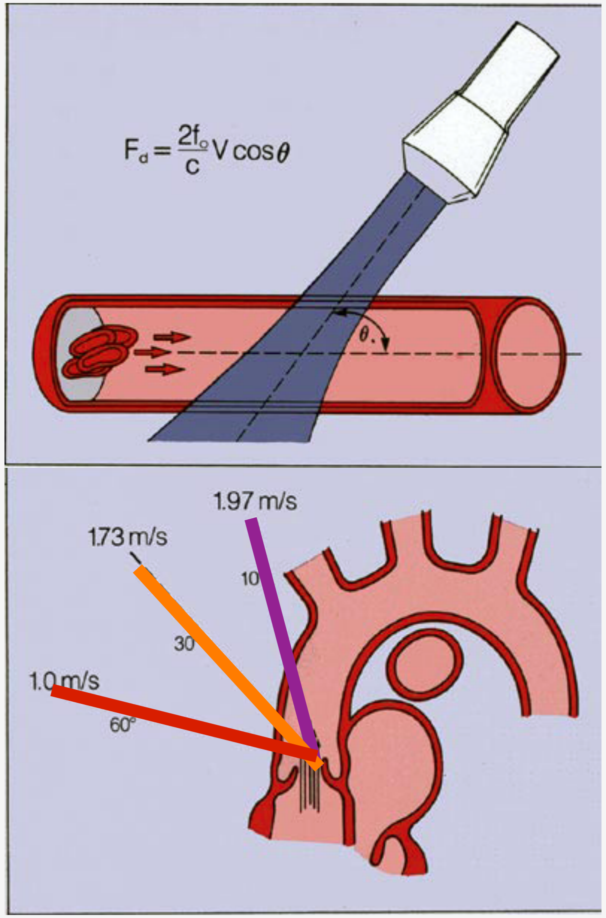
- Spatial information
- Aliasing !
  - PRF as high as possible to detect high velocities and avoid aliasing
  - but limited by depth: time to travel back
  - velocities are digitized into a limited number of bits: typical 8 bit = 256 values try to optimize resolution = highest velocity is highest value

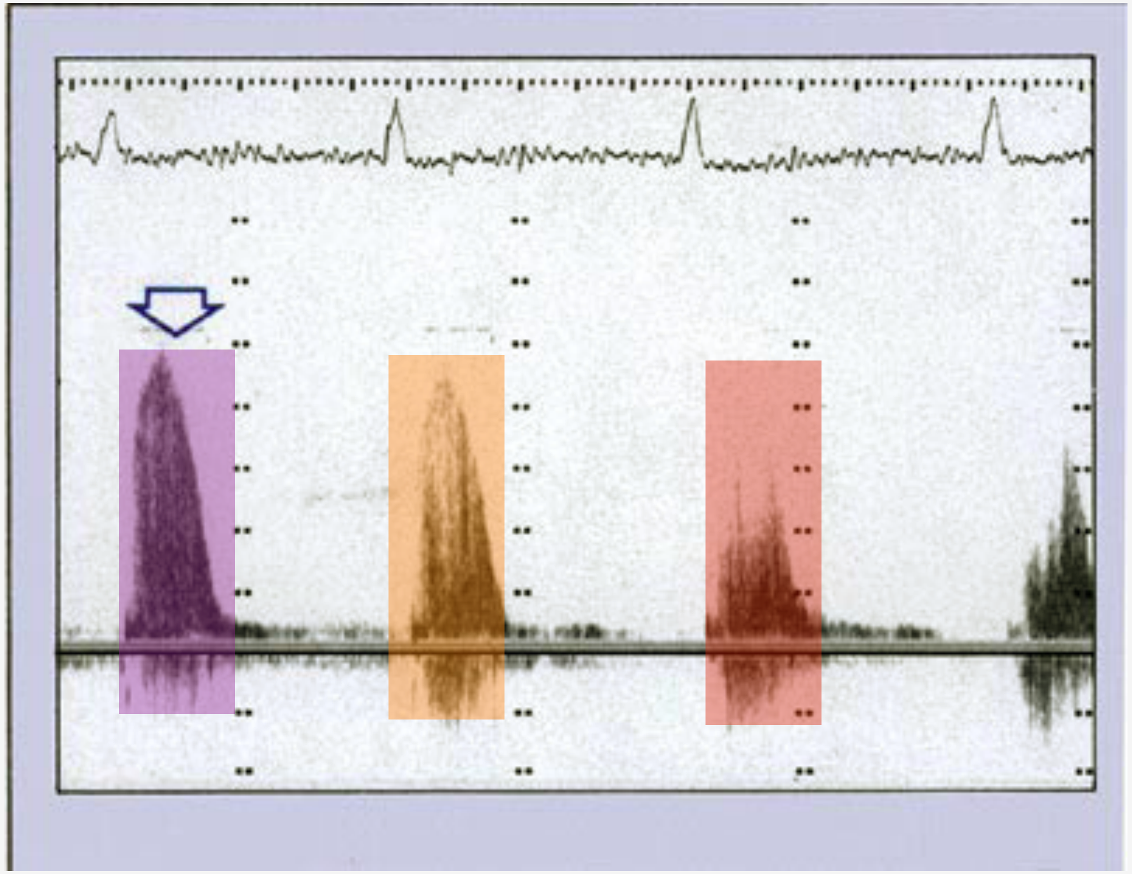
⇒ choose PRF as low as possible to just avoid aliasing



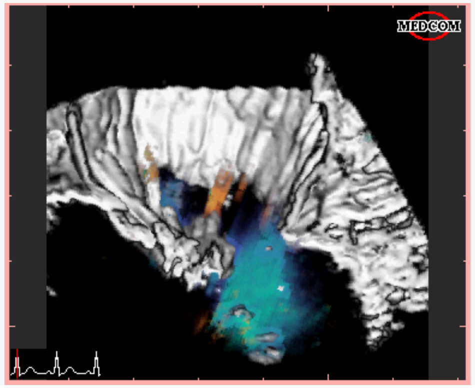


Doppler velocities: Angle dependency





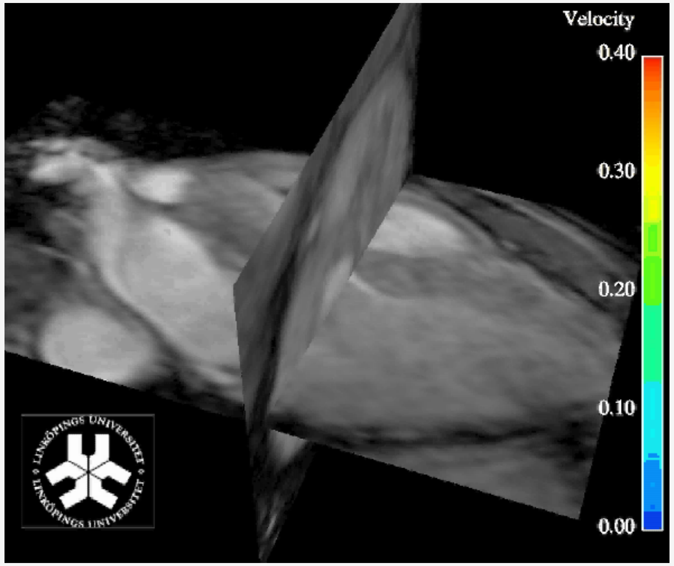
www.echoincontext.com: Kisslo & Adams



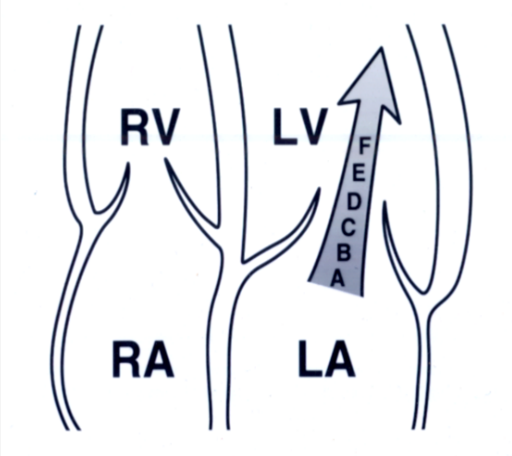
H. Kühl, Univ. Hosp. Aachen

Align the ultrasound beam with the direction of the jet angle dependency has dramatic effects…

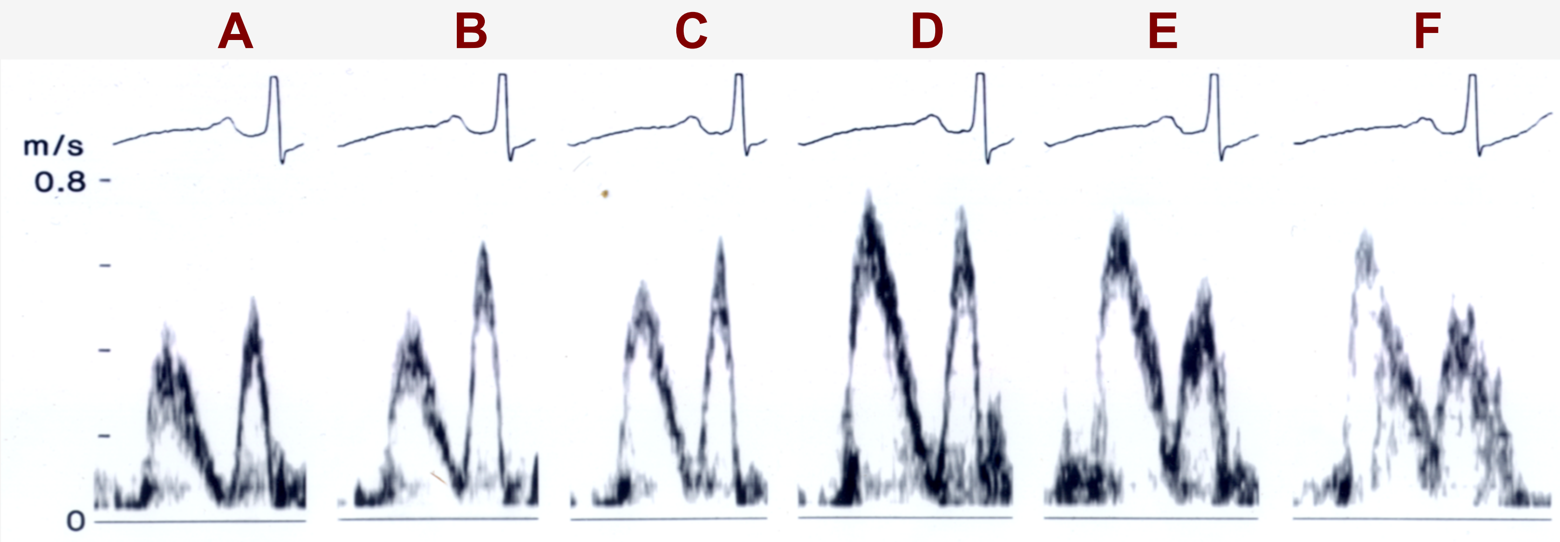
Doppler velocities: measurement position



Effect of sample volume position



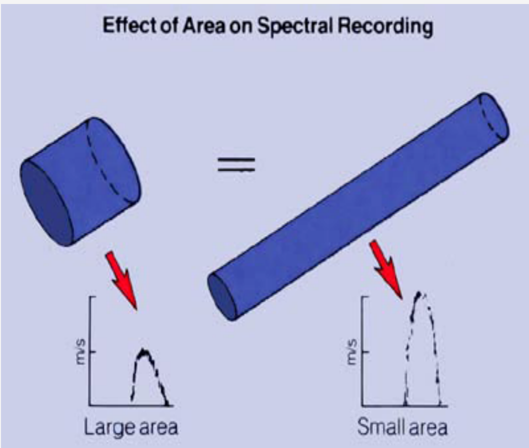
Appleton, JASE 1997

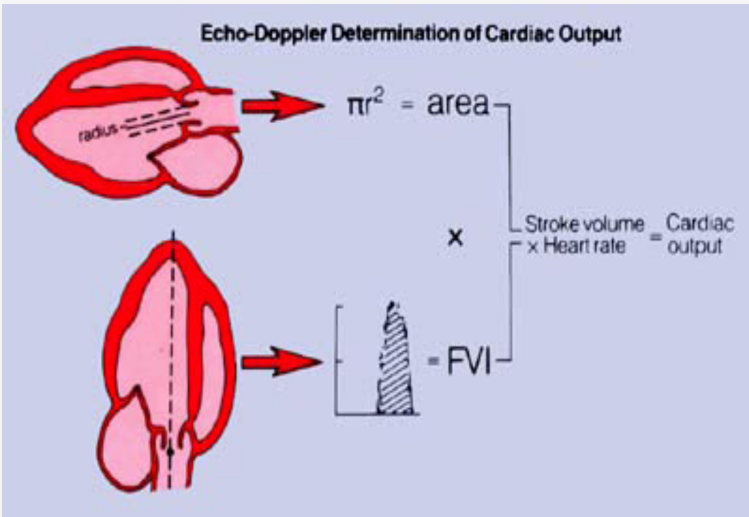


Mitral inflow pattern

Haemodynamics: Volumes and volume changes

- Volume flow rate = cross sectional area x velocity = $A \times v$
  - In cardiovascular applications: velocity is time and spatially variant !
    - Measure a spatially averaged velocity: Doppler sample volume
    - Include temporal variation and time: tracing of the spectrum = FVI
- Volume = volume flow × time
- Area from diameter: $A = \pi \times (D/2)^2 = \pi/4 \times D^2 = 0.785 \times D^2$
- FVI (flow velocity integral): trace the Doppler spectrum (units: $v \times t \rightarrow m/s \times s = m$)
- Stroke volume = $A \times FVI$
- Cardiac output: $CO = SV \times HR$ (heart rate)
- Cardiac index: $CI = CO/BSA$



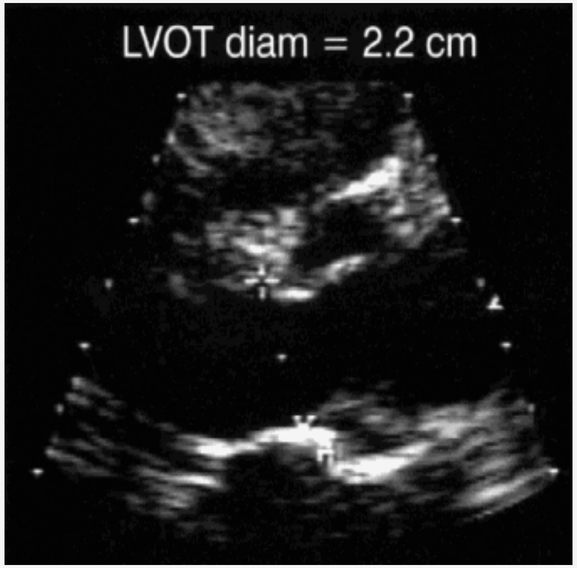


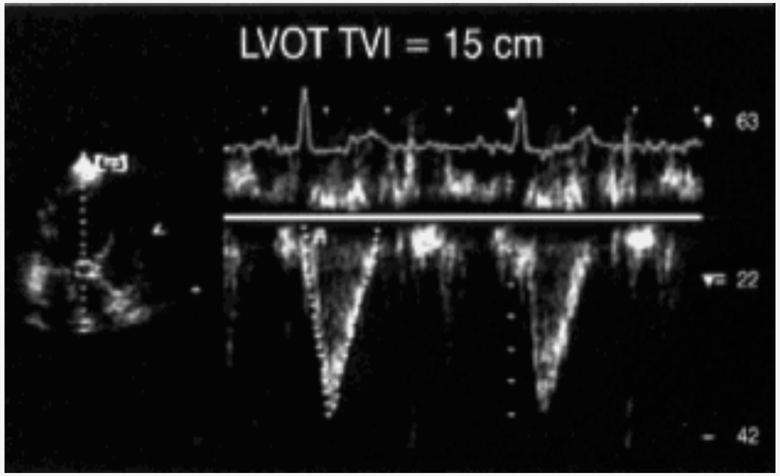
Note terminology
TVI : time velocity integral
VTI: velocity time integral
FVI: flow velocity integral

www.echoincontext.com: Kisslo & Adams

Example: CO measurement

- CO = SV × HR = A × FVI × HR
- LVOT area:
  - Parasternal long axis view: D = 2,2 cm
  - $A = 0.785 \times 2.2^2 = 3.8\ cm^2$
- Apical view: tracing FVI = 15 cm
- $SV = area \times VI = 3{,}8\ cm^2 \times 15\ cm = 57\ cm^3 = 57\ ml$
- CO = 57 ml × 80 bpm = 4.6 l/min





The Echo Manual, J. Oh, J. Seward, A. Tajik

Regurgitant volumes

- Approach:

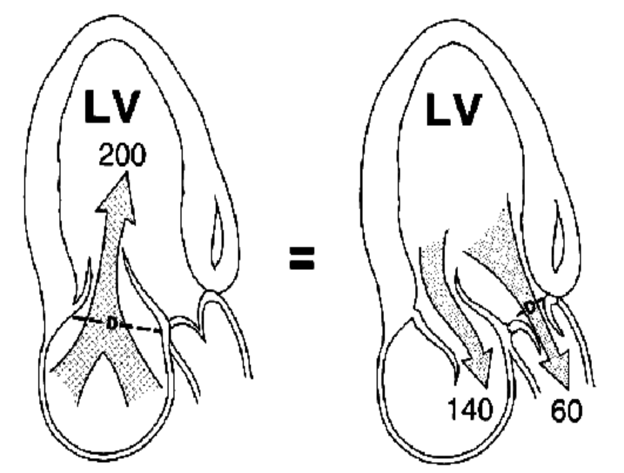
  1. Direct measurement of regurgitant volume based on **SV = A × FVI**

     needs the effective valve area !

  2. Indirect measurement by making the volume balance of the ventricle

     $V_{tot} = V_{stroke} + V_{regurg}$

- $V_{tot} = V_{stroke} + V_{regurg} \rightarrow V_{regurg} = V_{tot} - V_{stroke}$
- V_{tot} = mitral inflow = $A_{mitral} \times FVI_{mitral}$
- V_{stroke} = aortic outflow = $A_{LVOT} \times FVI_{LVOT}$
- $V_{regurg} = A_{mitral} \times FVI_{mitral} - A_{LVOT} \times FVI_{LVOT}$



- Regurgitant fraction = $V_{regurg}/V_{tot} \times 100\%$

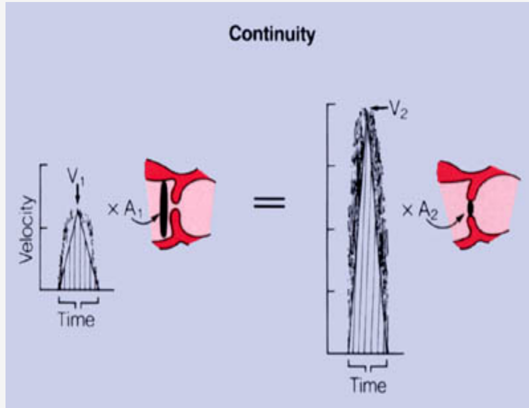
The Echo Manual, J. Oh, J. Seward, A. Tajik

Haemodynamics: Effective valve area

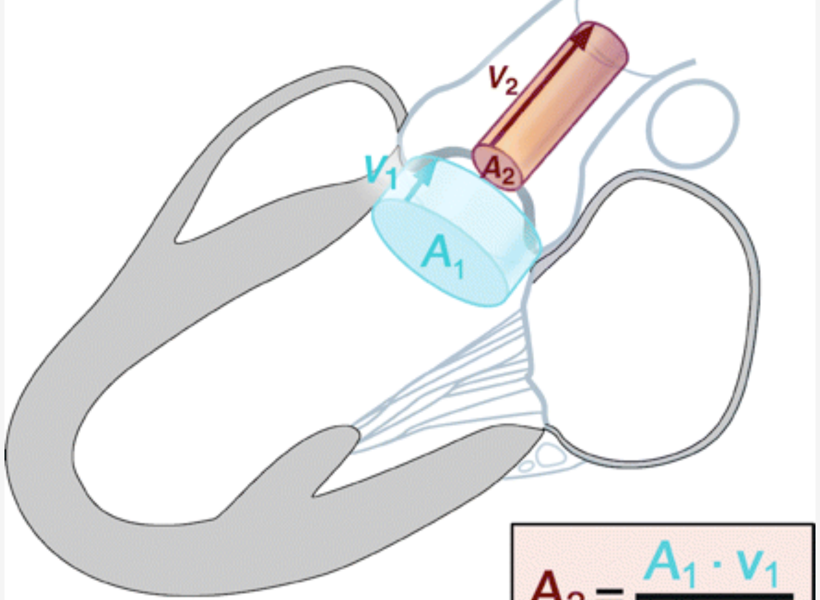
- Use ?
  - Direct regurgitant volume measurements: $V_{regurg} = A \times FVI_{regurg}$
  - Direct evaluation of stenosis/regurgitation valve area
- Methods to determine effective valve A ?
  - Continuity equation
  - PISA
  - Pressure half time

Valve area: continuity equation

- Blood = incompressible & no extra shunts/regurgitation present
- Conservation of volume:
  - *what passes before the valve has to pass trough the valve*
  - *what passes trough the MV has to pass trough the AV*



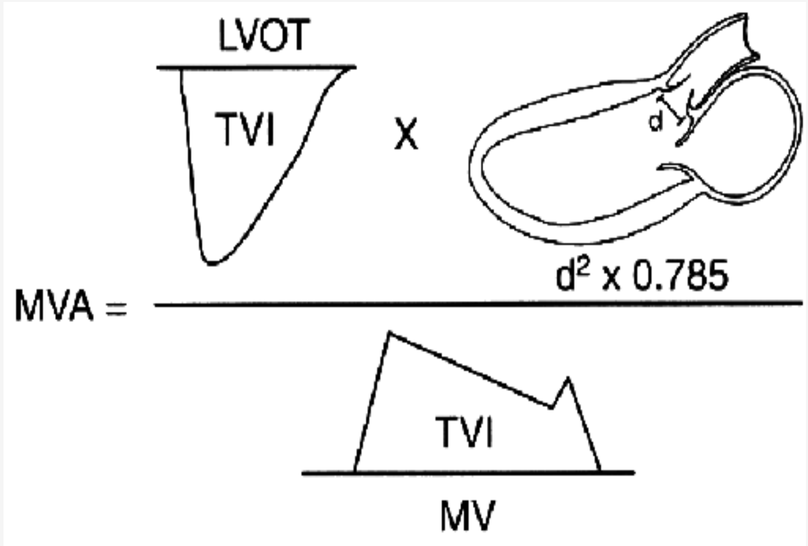
Before & after a valve



$$A_2 = \frac{A_1 \cdot v_1}{v_2}$$

EAE/ASE recommendations AS
Eur J Echocard 2009

Mitral inflow vs aortic outflow



Caveat: no regurgitations & arrhythmias!!

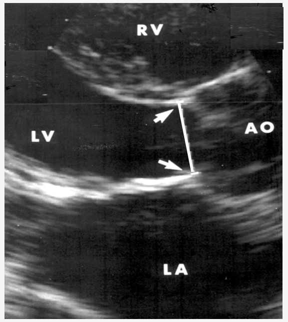
Example: continuity mitral-aortic

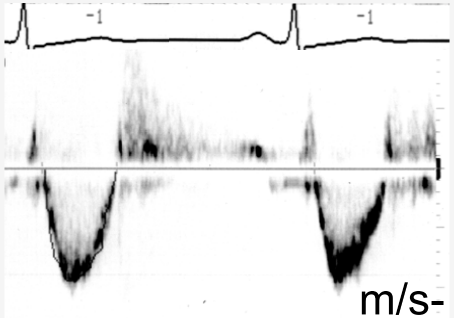
Advantage

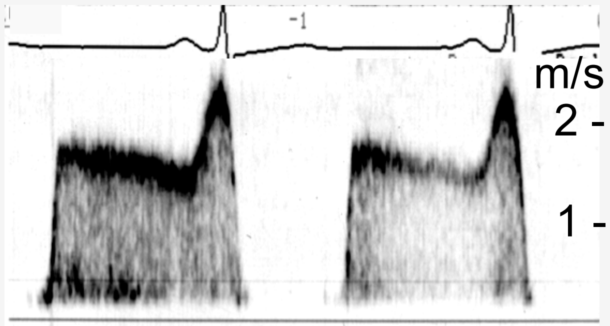
- Functional area
- Best correlation with cath. area

Problems

- Only with no or minor MR and AR
- With AR, RVOT SV - more difficult
- Atrial fibrillation







$A_{LVOT} = 2.54\ cm^2$

$FVI_{LVOT} = 16.5\ cm$

$\Rightarrow SV_{LVOT} = 42\ ml$

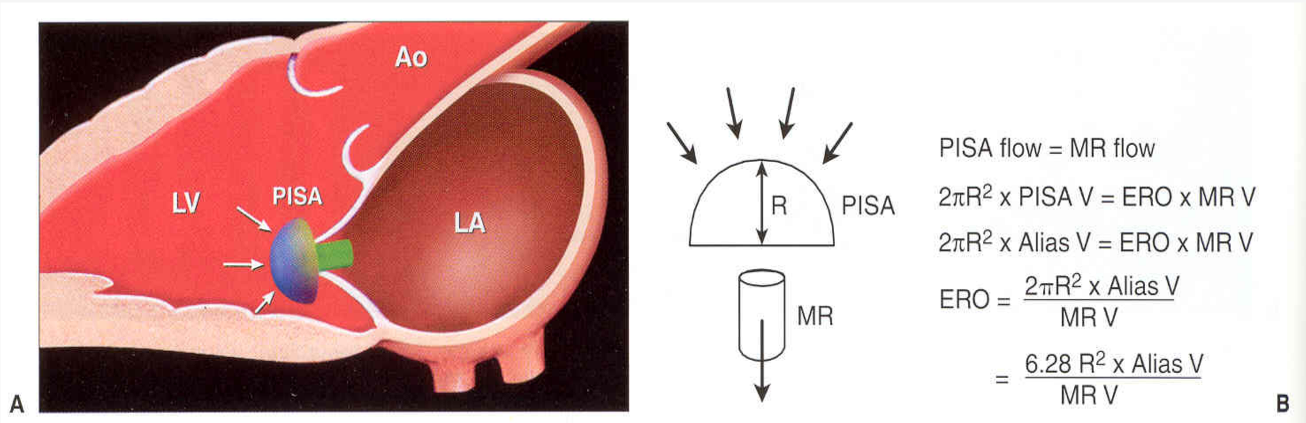
$FVI_{mitral} = 102\ cm$

$$A_{mitral} = \frac{FVI_{mitral}}{SV_{LVOT}} = \frac{42\ ml}{102\ cm} = 0.4\ cm^2$$

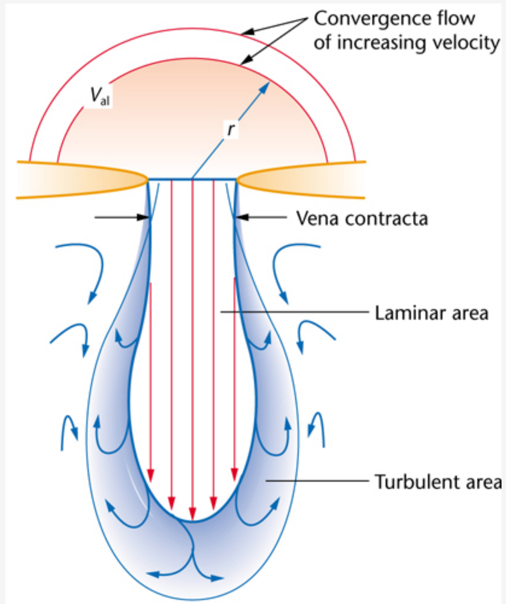
Hatle 98

PISA for determining valve orifice area / regurgitant volume

- Based on continuity equation between valve orifice and a distance from it
- PISA: Proximal Isovelocity Surface Area
  - Flow converges hemispherical towards the orifice
  - Detect isovelocity surface V_{PISA} using aliasing of velocities: blue-red color change change baseline and velocity scale.
  - Determine area of the isovelocity surface (assume half sphere: $2\pi R^2$)
  - Continuity: $2\pi R^2 \times V_{PISA} = A_{orifice} \times V_{orifice} \Rightarrow A_{orifice} = 2\pi R^2 \times V_{PISA} / V_{orifice}$
- $V_{regurg} = A_{orifice} \times FVI_{orifice}$

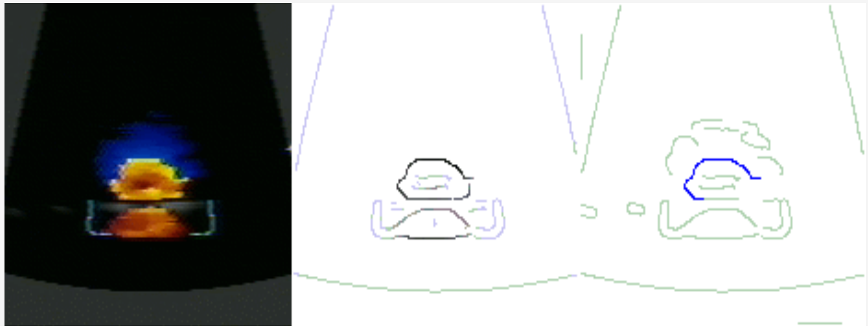


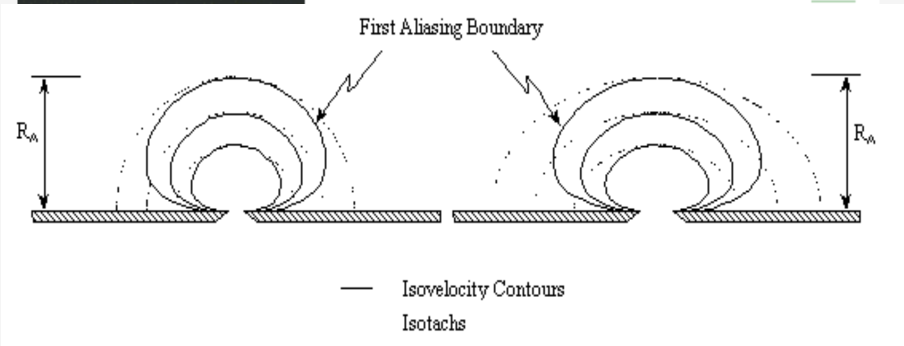
The Echo Manual, J. Oh, J. Seward, A. Tajik

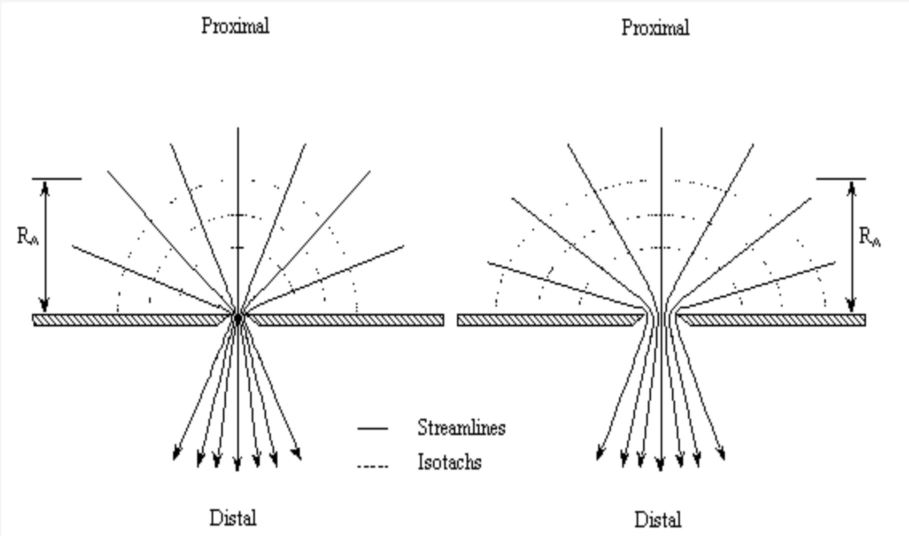


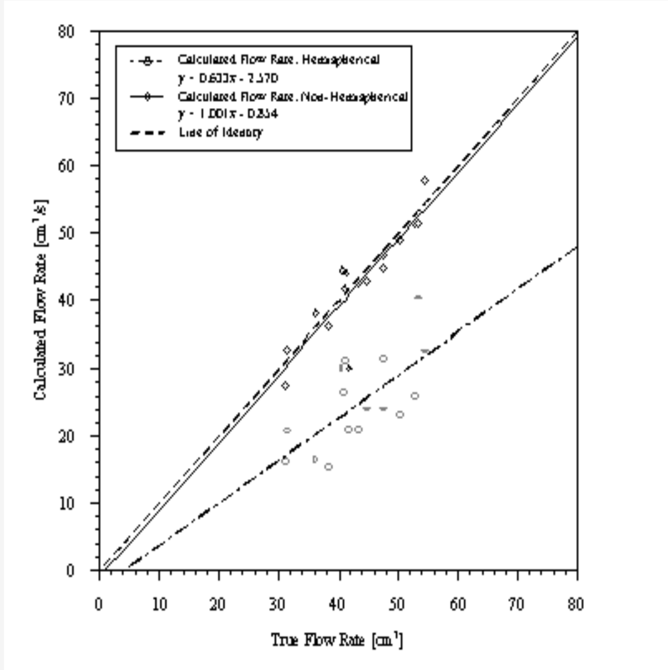
ESC Texbook of Cardiovasc. Med, 2006

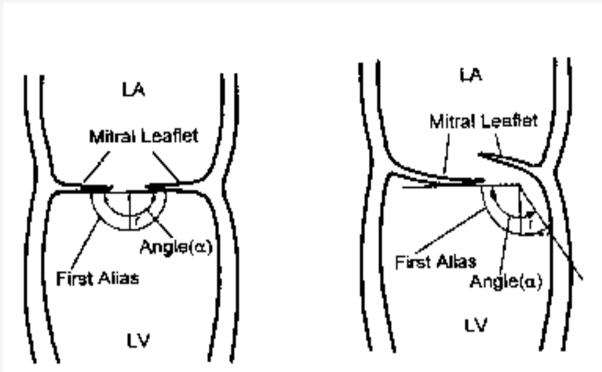
PISA problems: non-hemisperical convergence





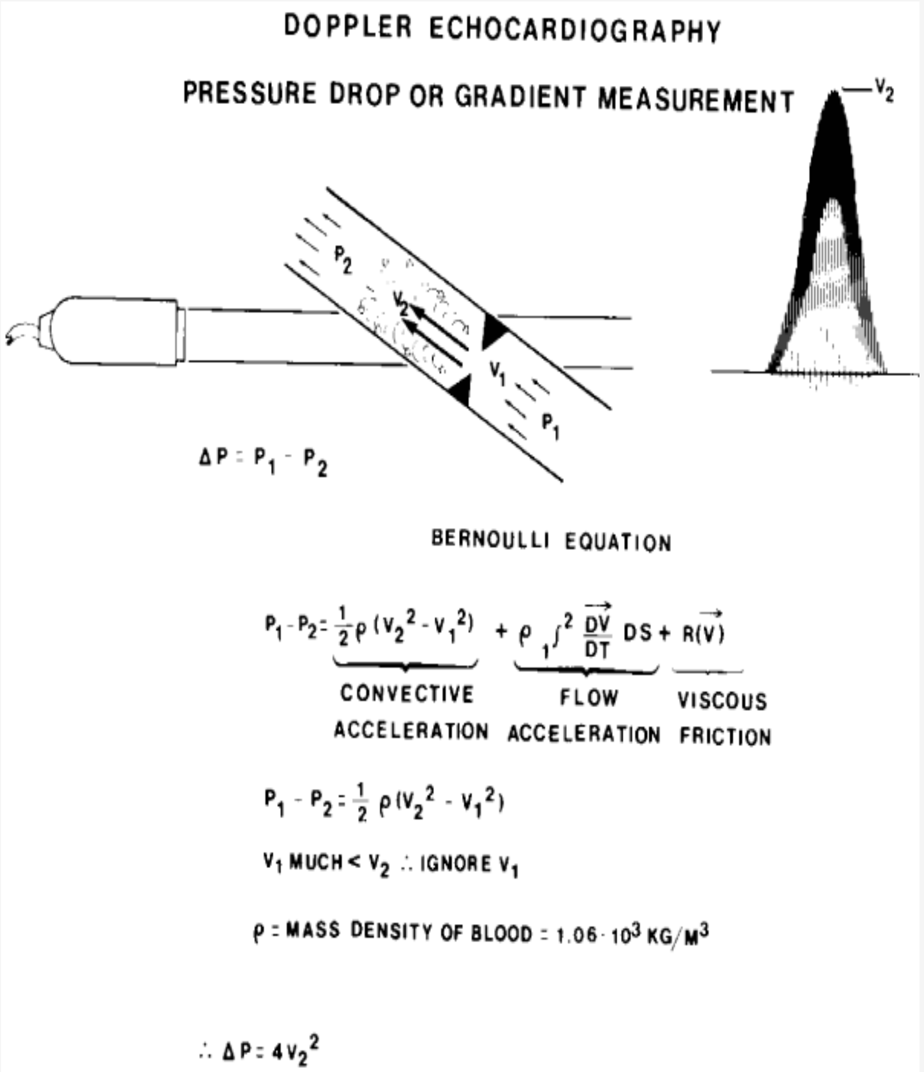






http://me.queensu.ca/people/sellens/research/sprayFlow/

Haemodynamics: pressure (gradients)



Feigenbaum, Echocardiography

- Bernoulli: *relation between pressures and velocities for fluid flow*
- Simplified Bernoulli (in mmHg):

  $\Delta P = 4 \times v^2$

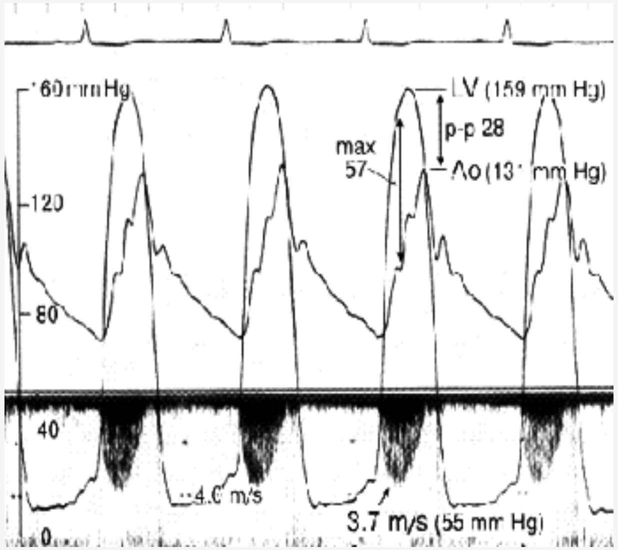
- Can be used in all cases where a *velocity gradient* is present
  - Stenosis
  - Regurgitation
  - Abnormal connection (VSD,…)
- Simplified !!
  - $v_1 < v_2 \rightarrow$ not valid for high LVOT flow (complex stenosis, AI)
  - $dv/dt = 0 \rightarrow$ no acceleration, only valid at velocity reversal = peak velocity
  - viscous forces $= 0 \rightarrow$ normal blood properties, low velocities

Example: ΔP aortic stenosis

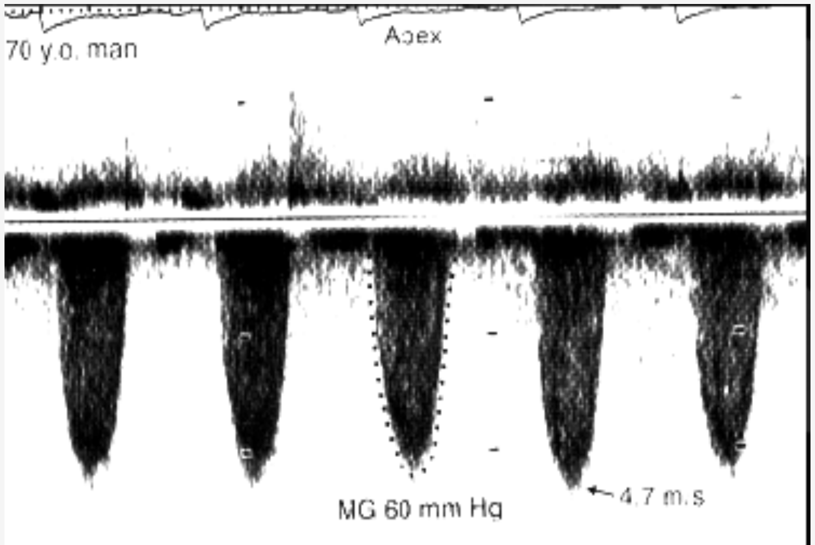
Velocities represent pressure *differences* ~ (p1 - p2)

Changes in velocity curves can be due to changes in p1 or p2 (or both)

- $\Delta P = 4\,v^2$
  $= 4 \times 3.7^2$ mmHg = 55 mmHg



- Mean gradient → mean velocity
  ⇒ tracing of the velocity signal



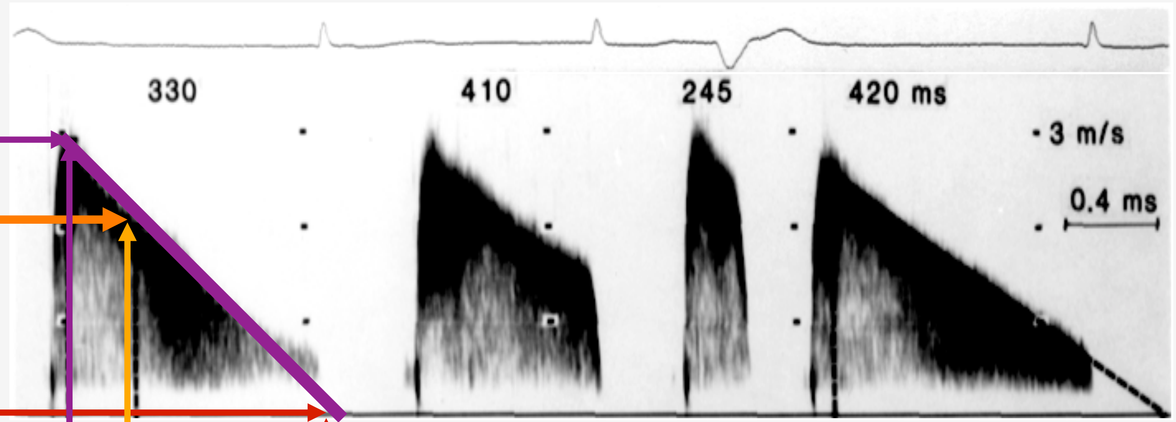
The Echo Manual, J. Oh, J. Seward, A. Tajik

Mitral Valve Area: Pressure half-time

P ~ v

P/2 ~ v/ √2 = .71*v

P = 0 ~ v = 0



t_A t_B

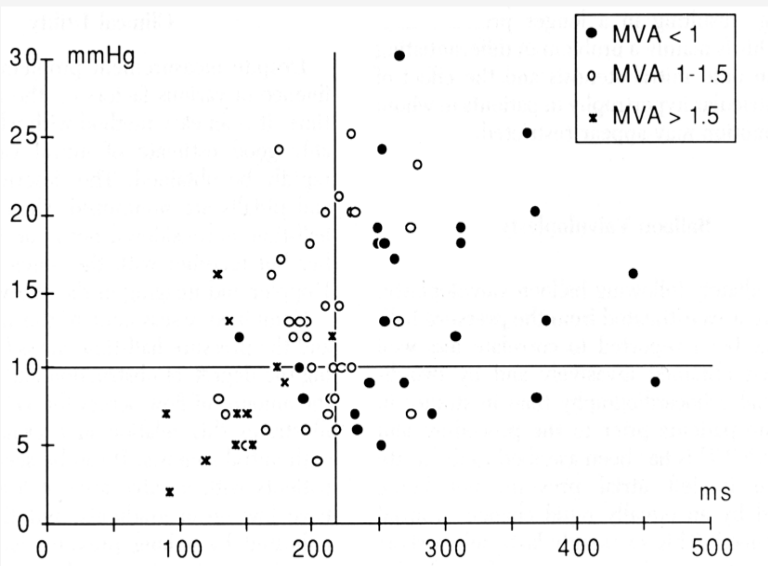
| basetime |

Pressure half-time

$= t_B - t_A$

$= 0.29 \times$ basetime

Mean Pressure Drop



Pressure ½ Time

$A_{mitral} = 220 / P_{half\text{-}time}$

LH 90

$P_{intracardiac}$ from valve regurgitation

Max. velocity of regurgitations

→ *pressure differences :*

AR – between aorta and LV in diastole

PR – between PA and RV in diastole

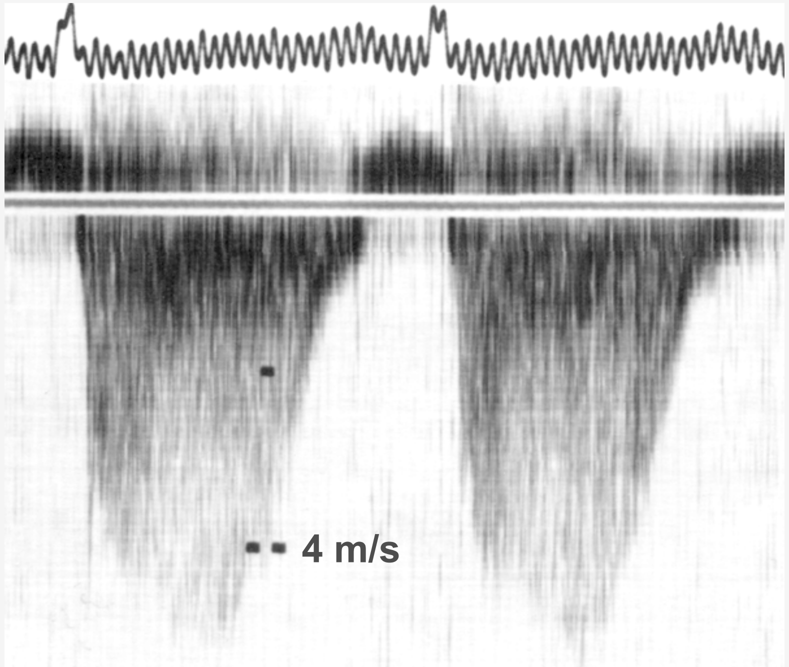
MR – between LV and LA in systole

TR – between RV and RA in systole

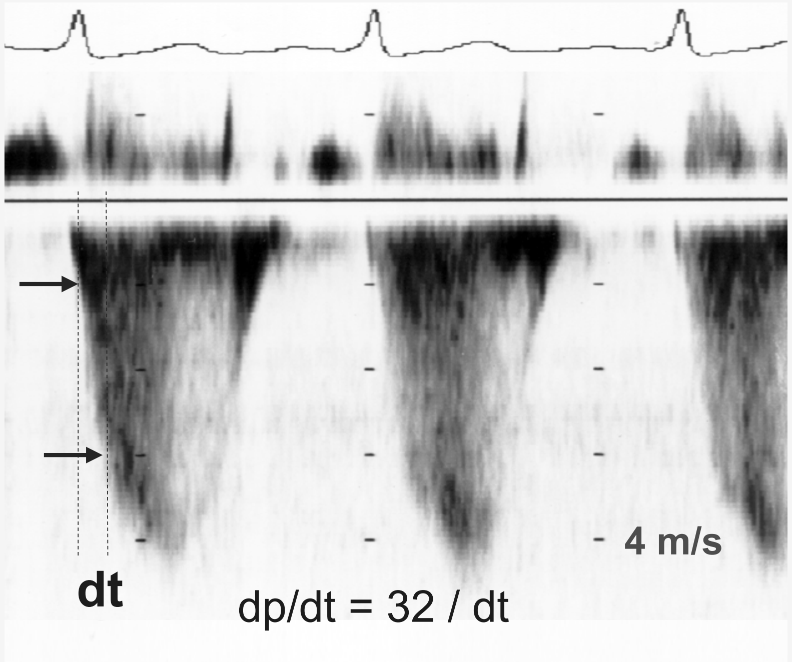
Ventricular performance: dP/dt from regurgitation velocity

$$dP/dt = (4 \times v_{3\ m/sec}^2 - 4 \times v_{1\ m/sec}^2) / dt \quad (dt\ in\ s)$$
$$= (4 \times 3^2 - 4 \times 1^2) / dt$$
$$= 32 / dt \quad (mmHg/s)$$

Example: RV function from tricuspid regurgitation



dp/dt – 1180 mm Hg/s

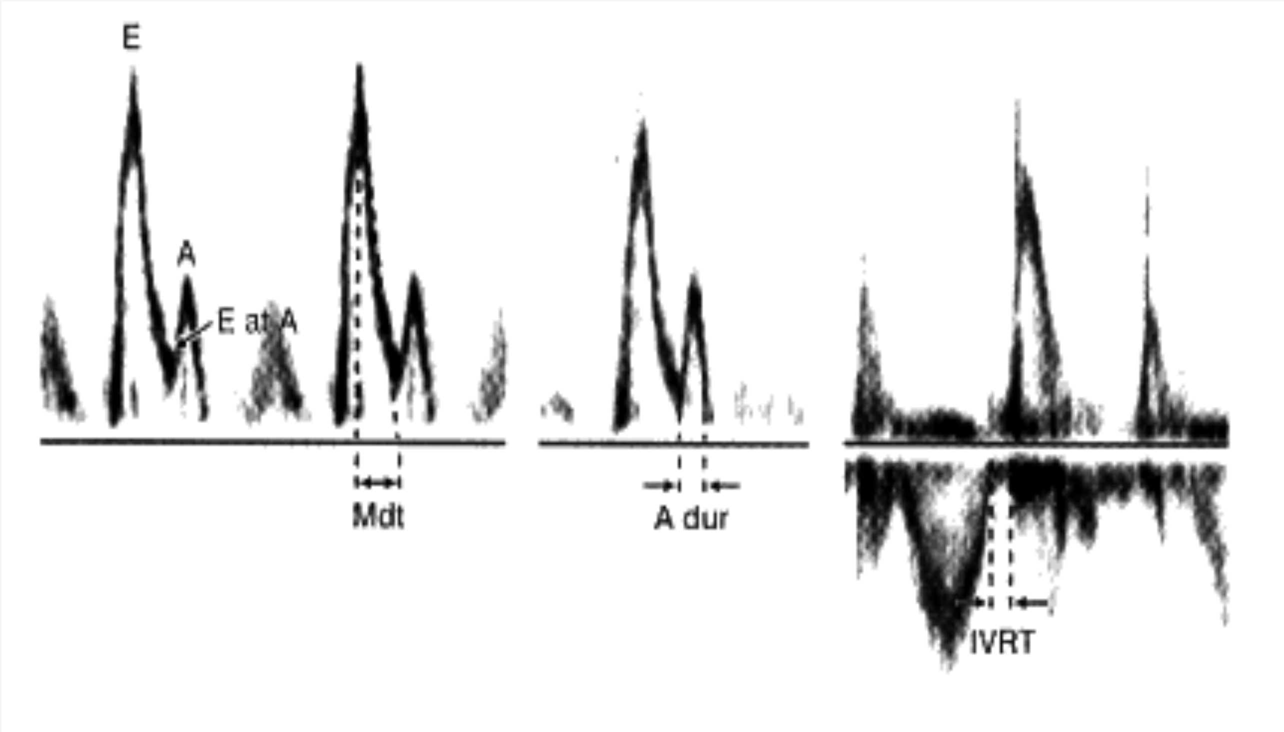


dp/dt – 680 mm Hg/s

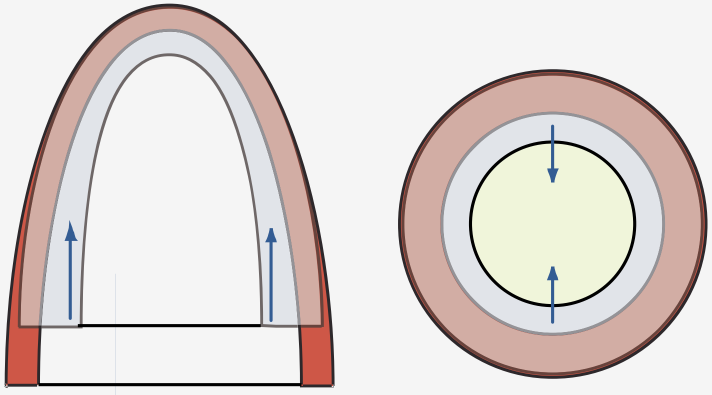
LH 98

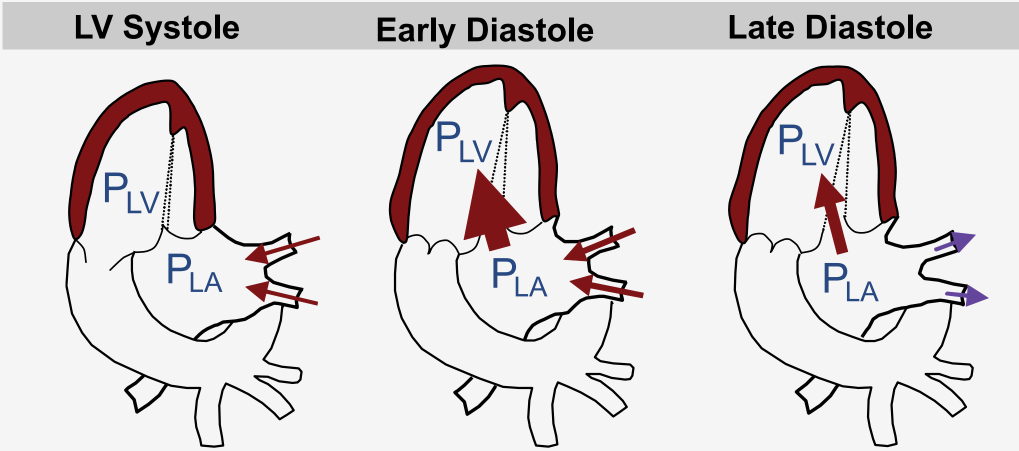
e.g. elevated $P_{left\ atrial}$: mitral inflow

- ΔP higher:
  - MV opens earlier: decreased IVRT
  - higher $V_{E\text{-}wave}$
- P_{LV} increases faster $\Rightarrow$ shorter deceleration time
- Higher LV P_{diast} $\Rightarrow$ lower A vel
- Increased pulmonary vein reversal flow



Mitral flow vs annular velocity

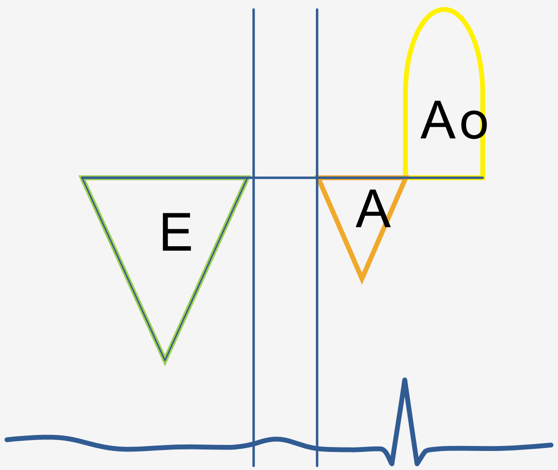




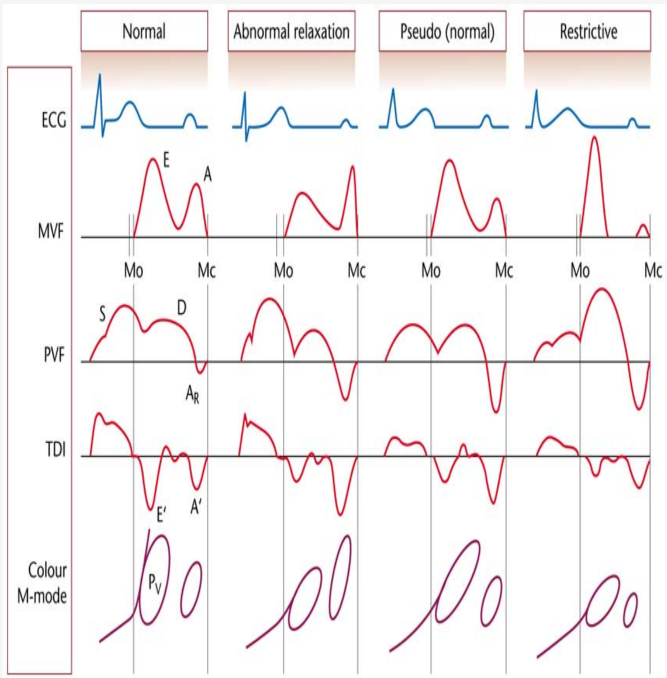
Vel mitral ~ $P_{LA} - P_{LV}$

annular vel ~ total deformation ~ ΔV

Mitral flow

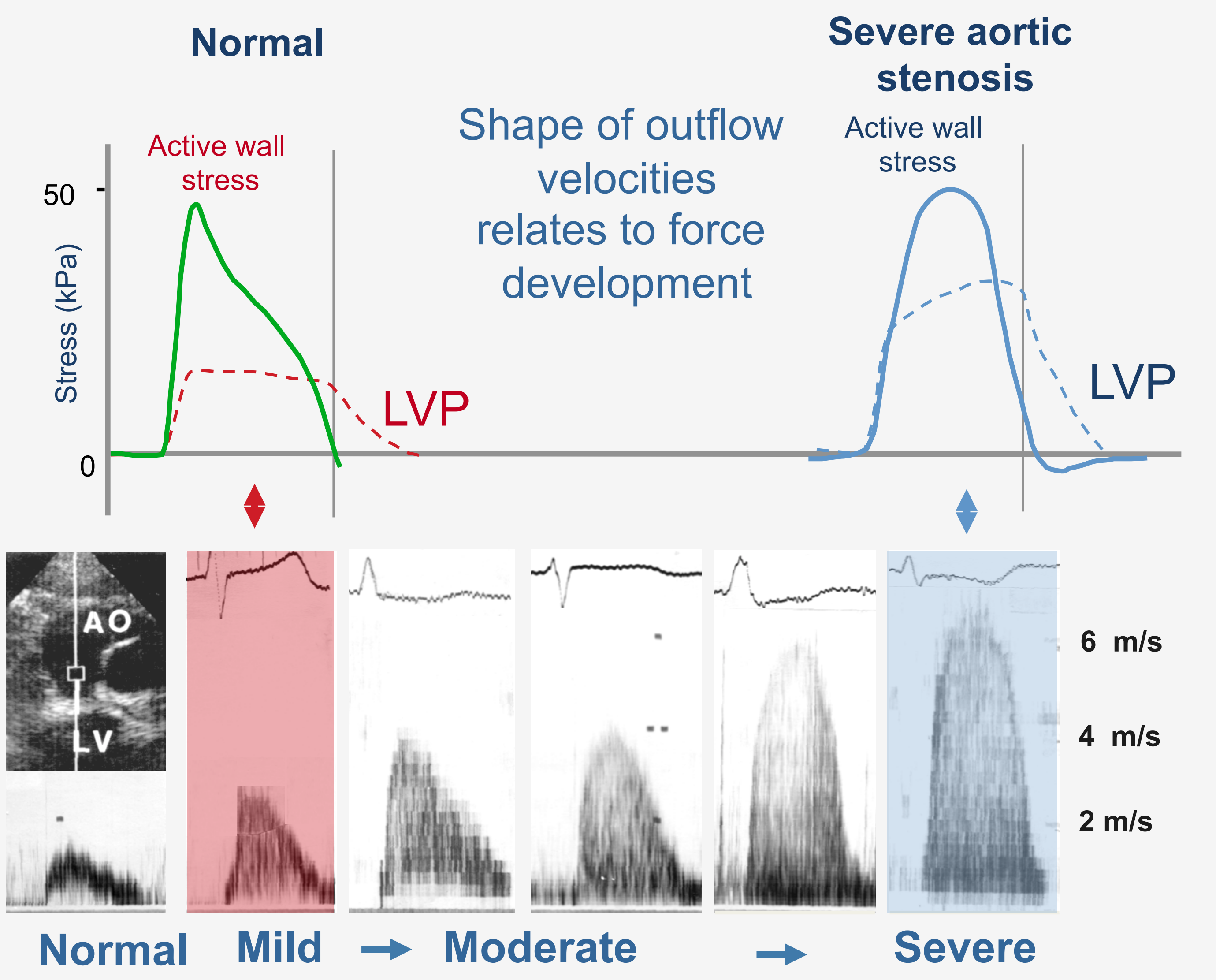


Annular velocity

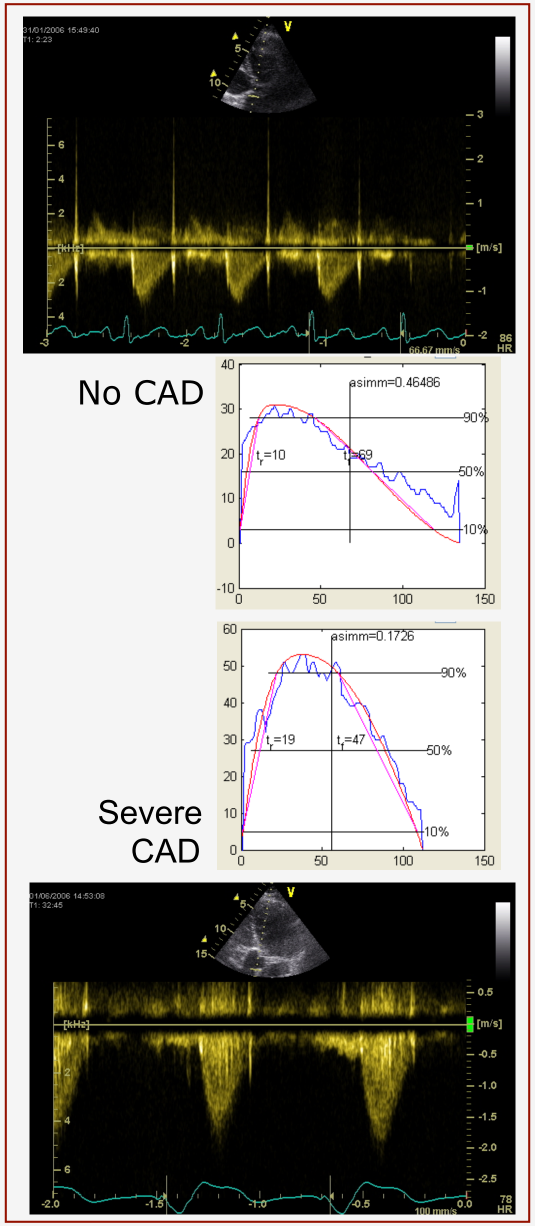


The ESC Texbook of Cardiovascular Medicine, 2006

Flow morphology ↔ force development



Liv Hatle /P. Claus



Conclusion

Doppler techniques are useful in the evaluation and quantification of cardiac haemodynamics and function

- Stroke and regurgitant Volumes
- Valve areas
- Pressure differences
- Pressure (force) development