Imaging macroscopic flow

Quantitative and Functional Imaging

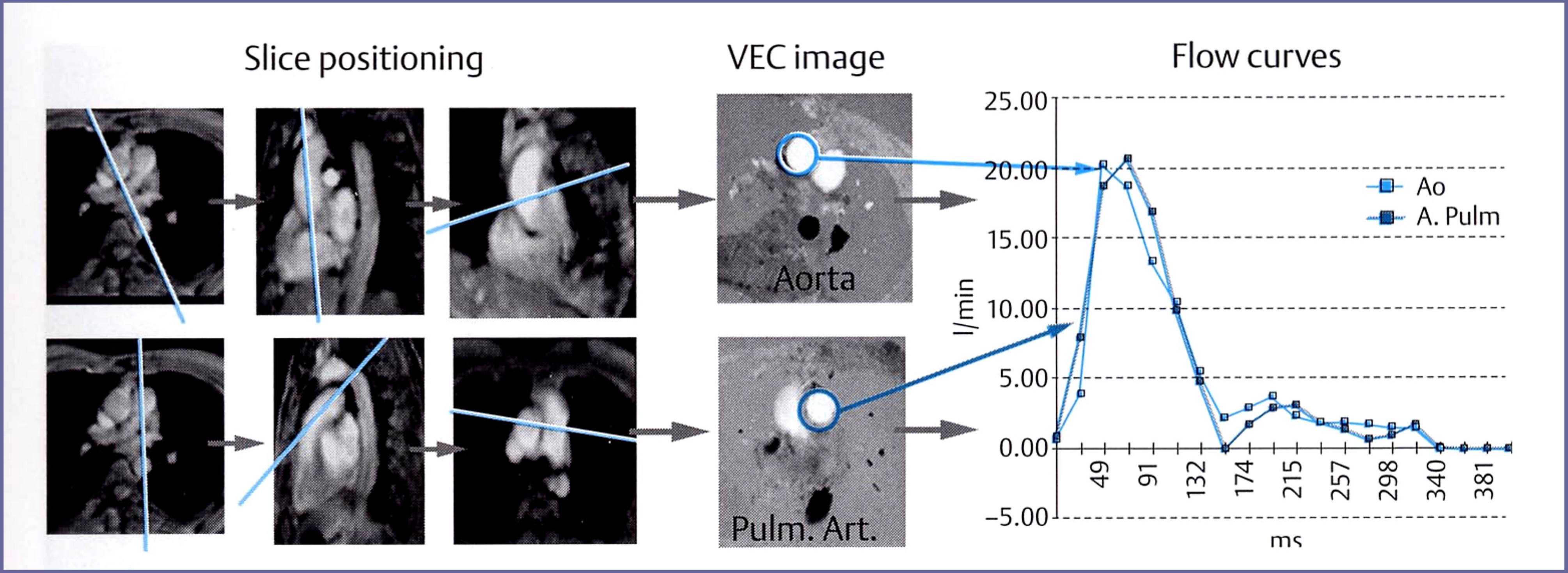
BME 4420/7450

Fall 2022

Image-based measurements

- Tissue properties
- Volume and shape
- Motion
  - Random (diffusion)
  - Microscopic flow (perfusion)
  - Macroscopic flow
- Metabolism
- Molecular imaging

Flow measurements of cardiac function



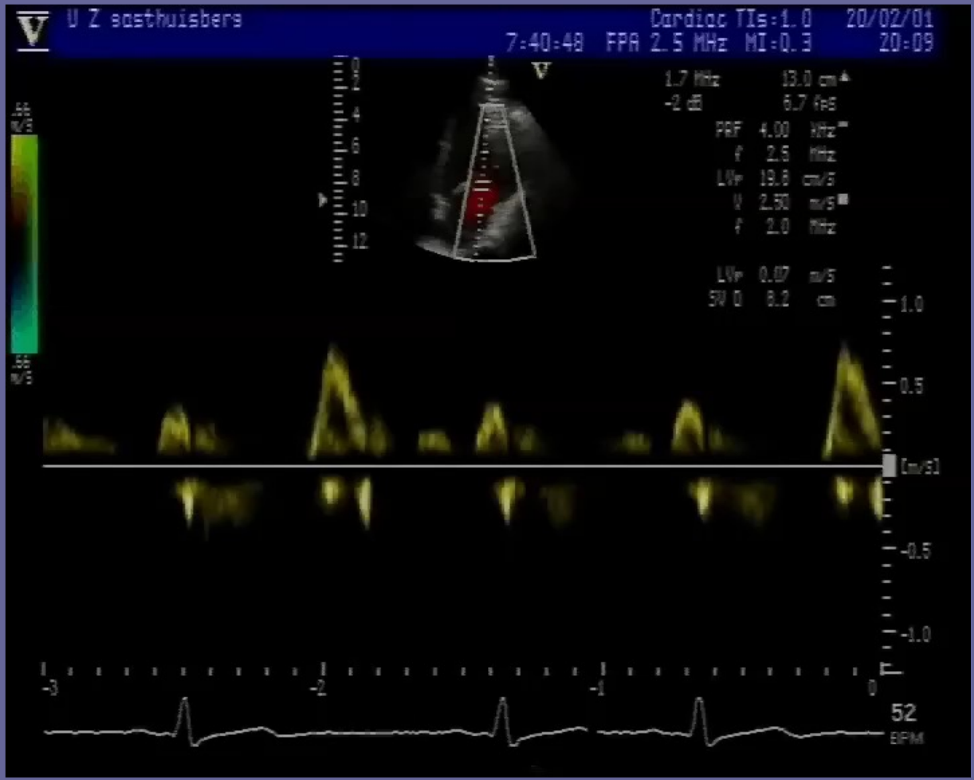
Didier (2003)

Topics

- Why image the vascular system?
- Doppler ultrasound
- CT angiography
- MRI blood velocity measurements
- Applications of cardiac MRI

Blood flow measured with Doppler ultrasound

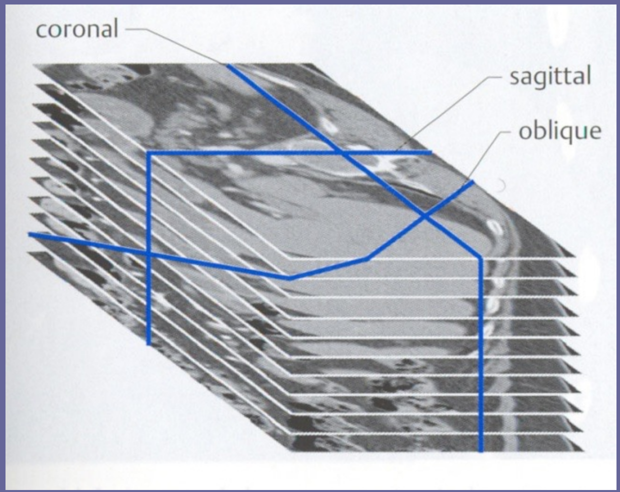
- Localized measurements of blood flow
  - Based on changes in pulse frequency/delay
- Example: cardiac valve function



Suetens (2002)

CT angiography

- Viewing the vascular lumen
  - Relies on contrast agent injection
- Viewing options
  - Slice by slice
  - Multiplanar reformatting
  - Maximum intensity projection
  - Curved planar reformatting

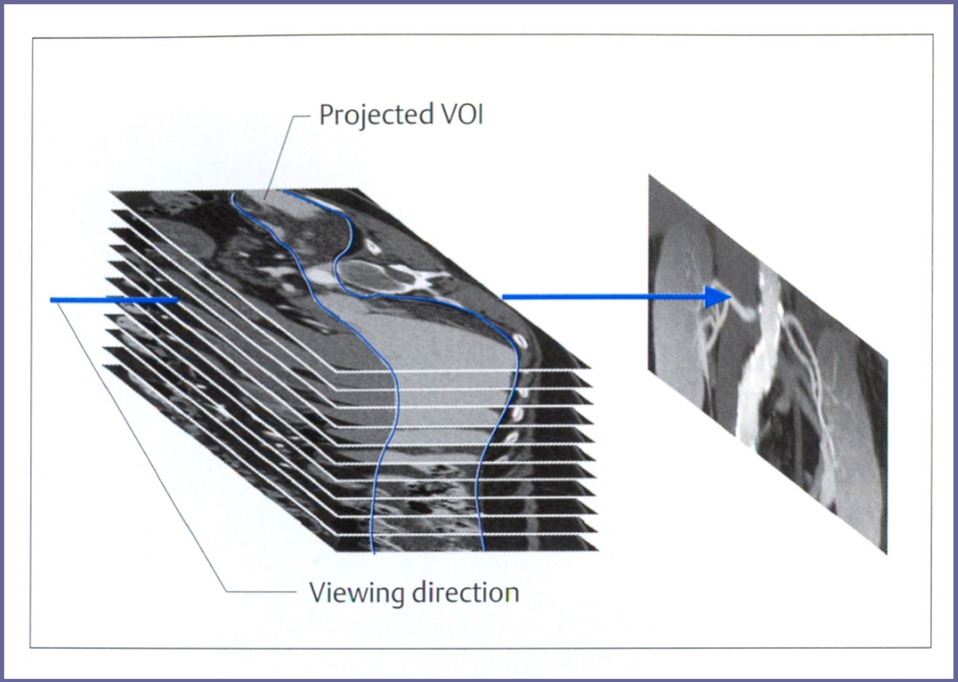


Propkop (2003)

Multiplanar reformating
of multiple axial images

Maximum intensity projection (MIP)

- Image of maximum intensity encountered along the viewing direction
- Simple method to view 3D structure

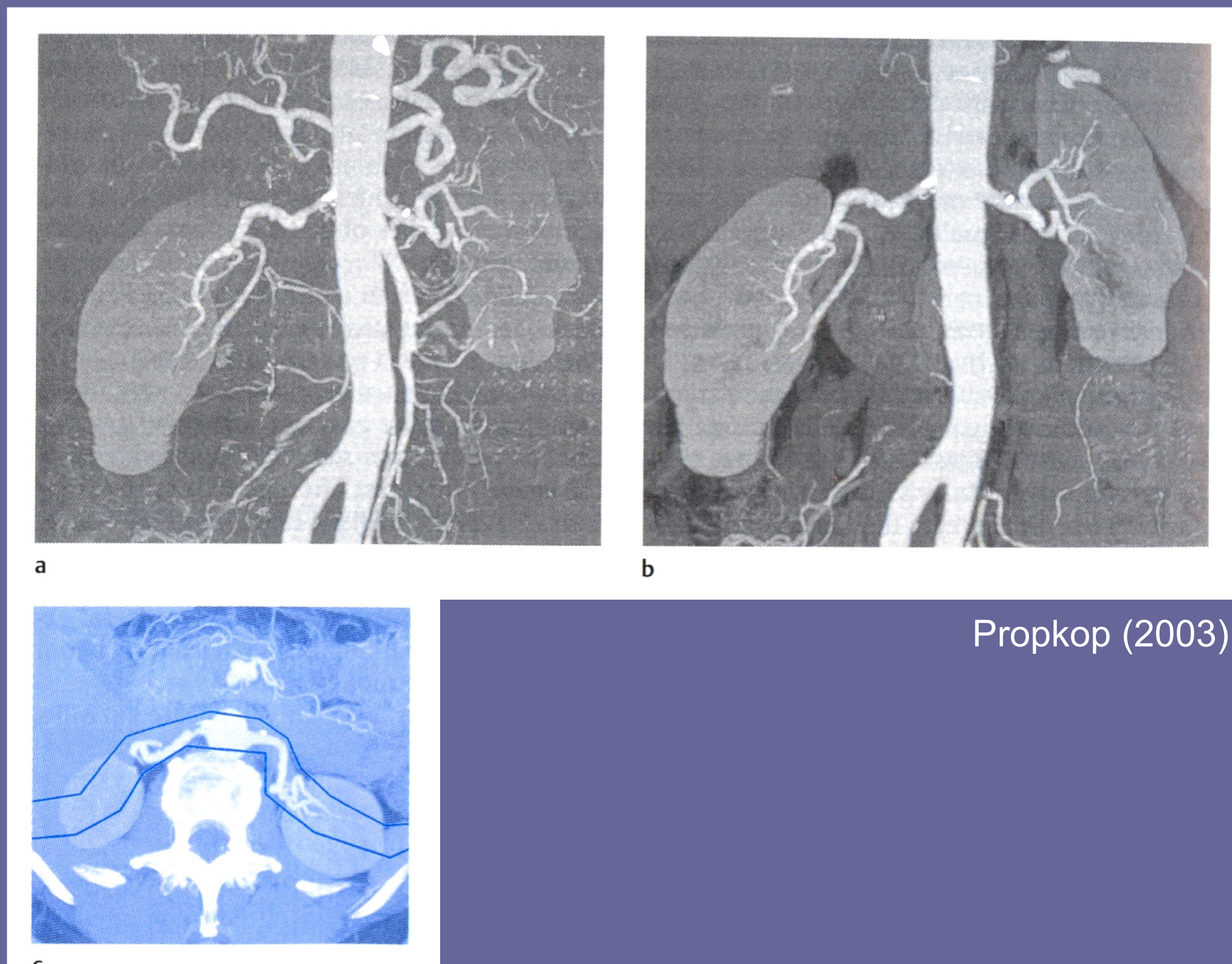


Propkop (2003)

Edit out structures that are not of interest

Bone edited out

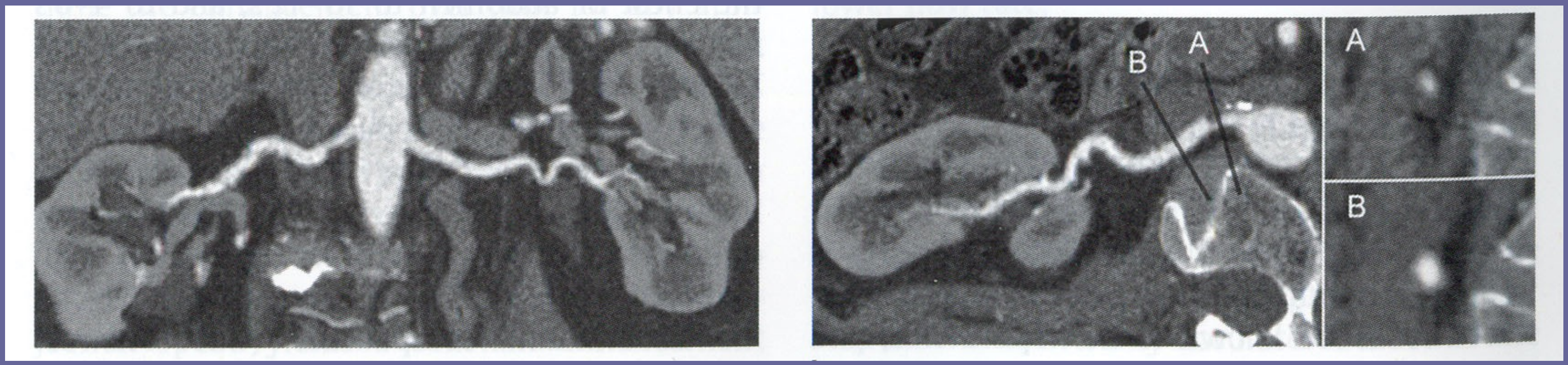
Bone and enteric arties edited out



Propkop (2003)

Curved planar reformatting

- Reconstruct image on a curved surface that follows the structure of interest
- Facilitates placement of regions of interest for measurement



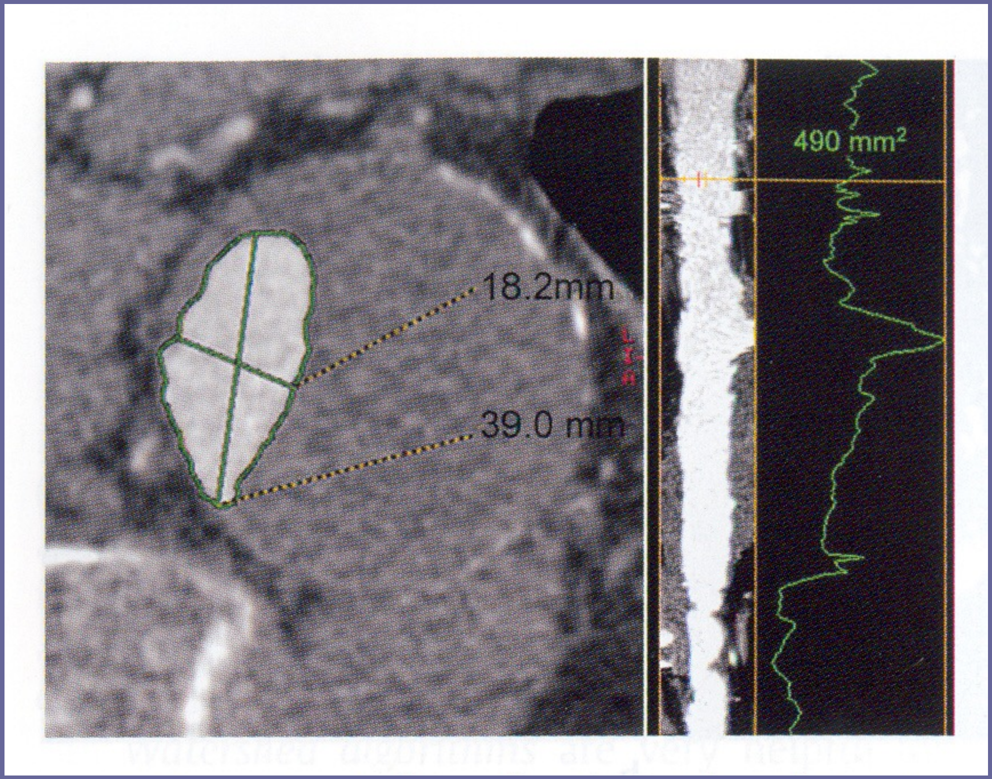
Propkop (2003)

Anteroposterior curved surface

Caudocranial curved surface
with cross-sectional view of stenosis

Automated vessel analysis with CT

- Vessel tracking
- Curved sheet reconstruction
- Cross-sectional area estimation
- Continuous assessment of vessel lumen



Propkop (2003)

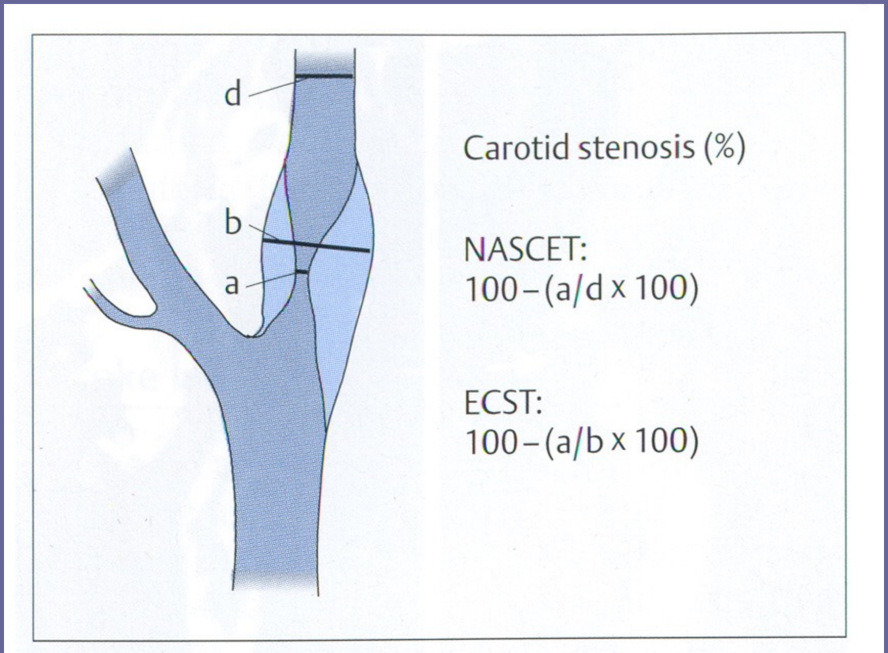
Carotid stenosis

- Complication of atherosclerosis
- Increased risk of stroke
  - Plaques rupture
  - Form thromboemboli
- Stroke is the 3rd leading cause of death in most industrialized countries
- Patients benefit from surgery
  - Endarterectomy
  - Halves the risk of stroke
- Quantify stenosis to answer
  - Which patients are at greatest risk of stroke?
  - Which patients benefit from treatment?
  - What aspects of a stenosis have the greatest predictive power?

Propkop (2003)

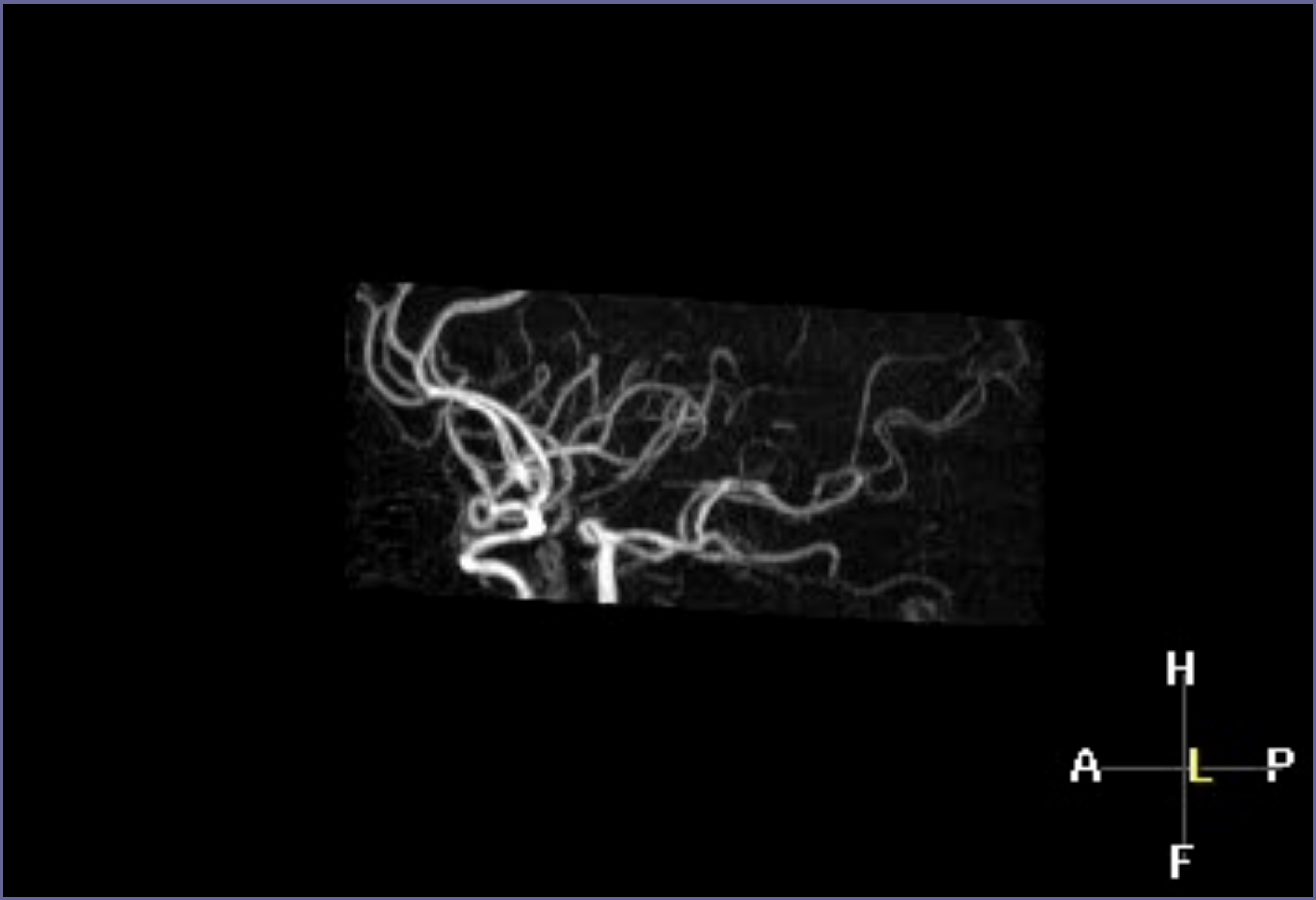
Quantifying carotid stenosis

- 70% stenosis is clinically significant
- Even 50% stenosis (NASCET criteria) benefits from surgery



Propkop (2003)

Imaging flow with MRI

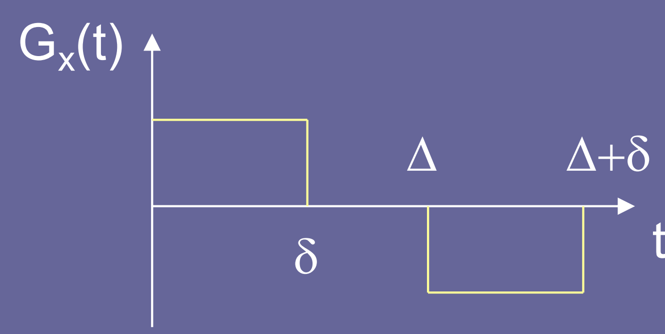


Suetens (2002)

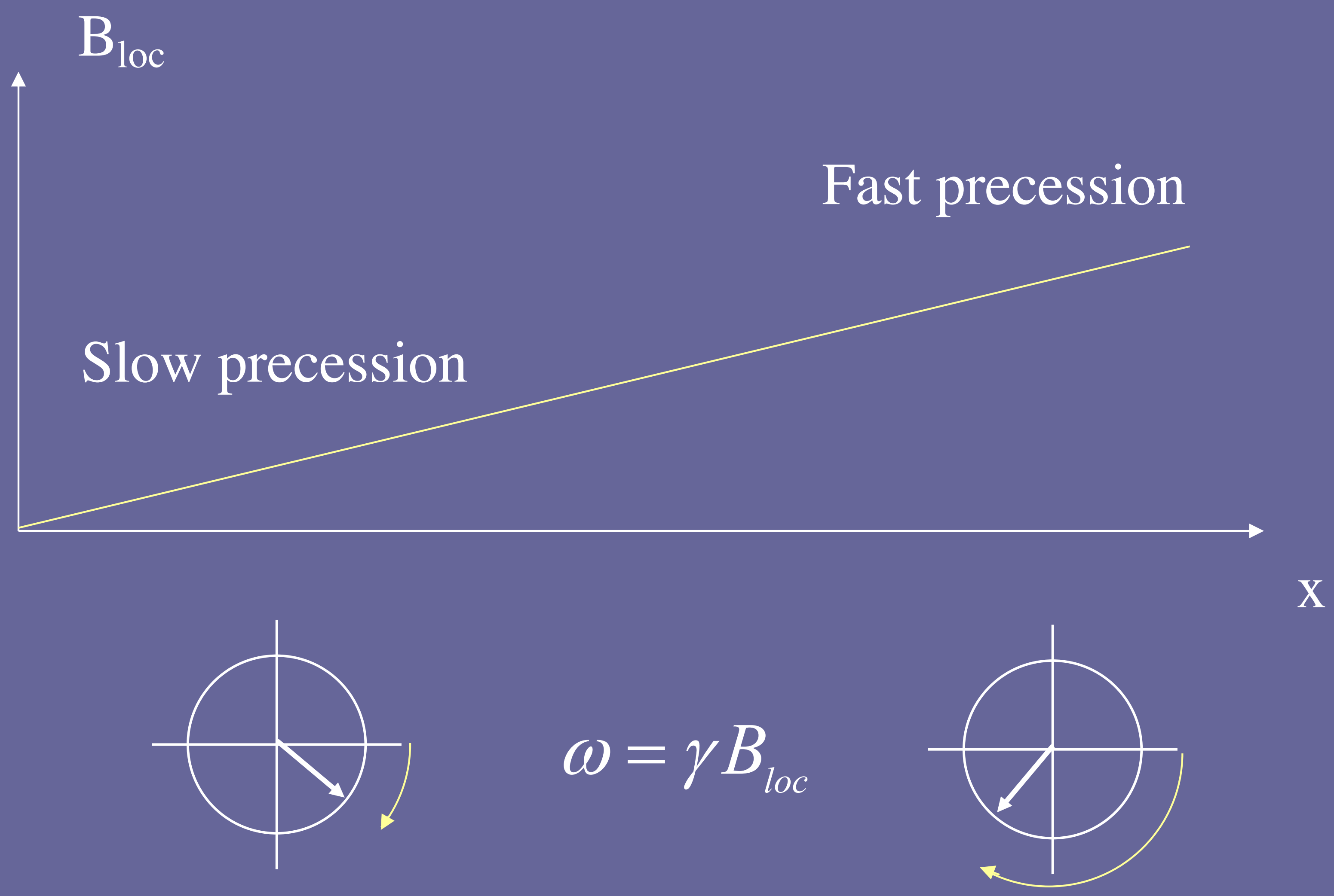
Phase contrast MRI

- Suppose spins move along x with constant velocity, v_x
- At t=0, the spin phase is zero
- Field gradient is applied to the spins

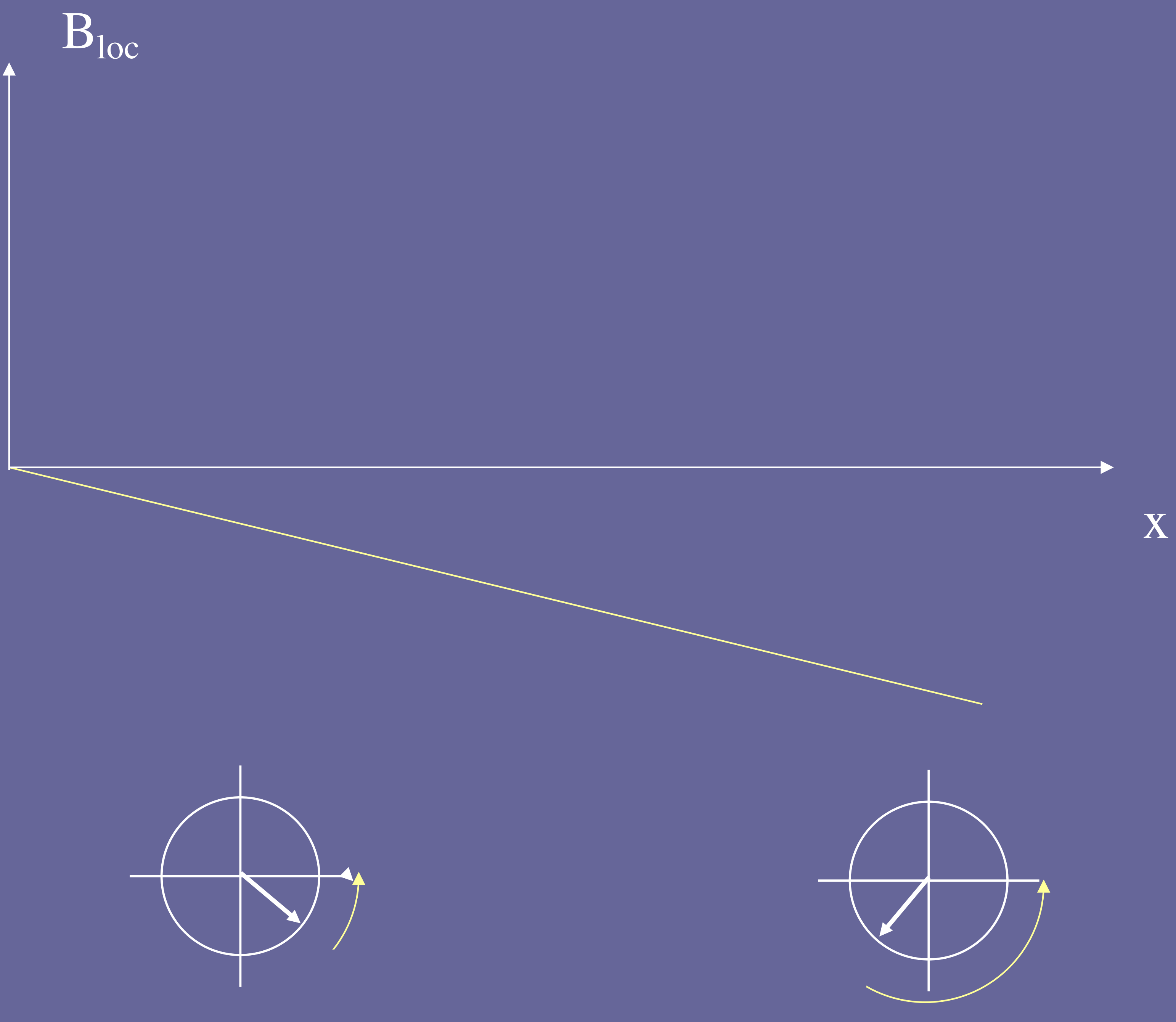
$$G_x(t) = \begin{cases} G_0, & 0 < t \le \delta \\ 0, & \delta < t \le \Delta \\ -G_0, & \Delta < t \le \Delta + \delta \end{cases}$$



Effect of a field gradient

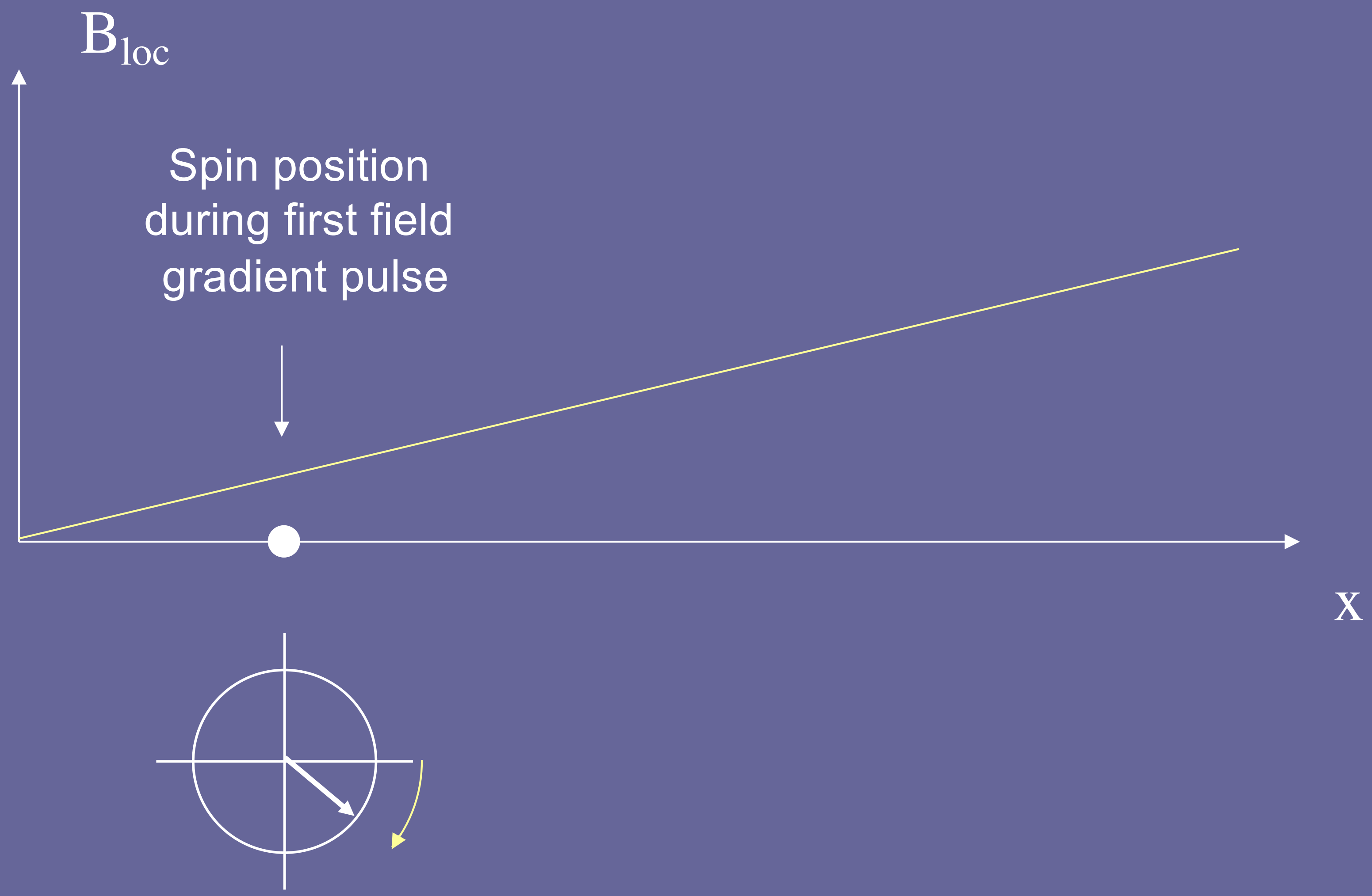


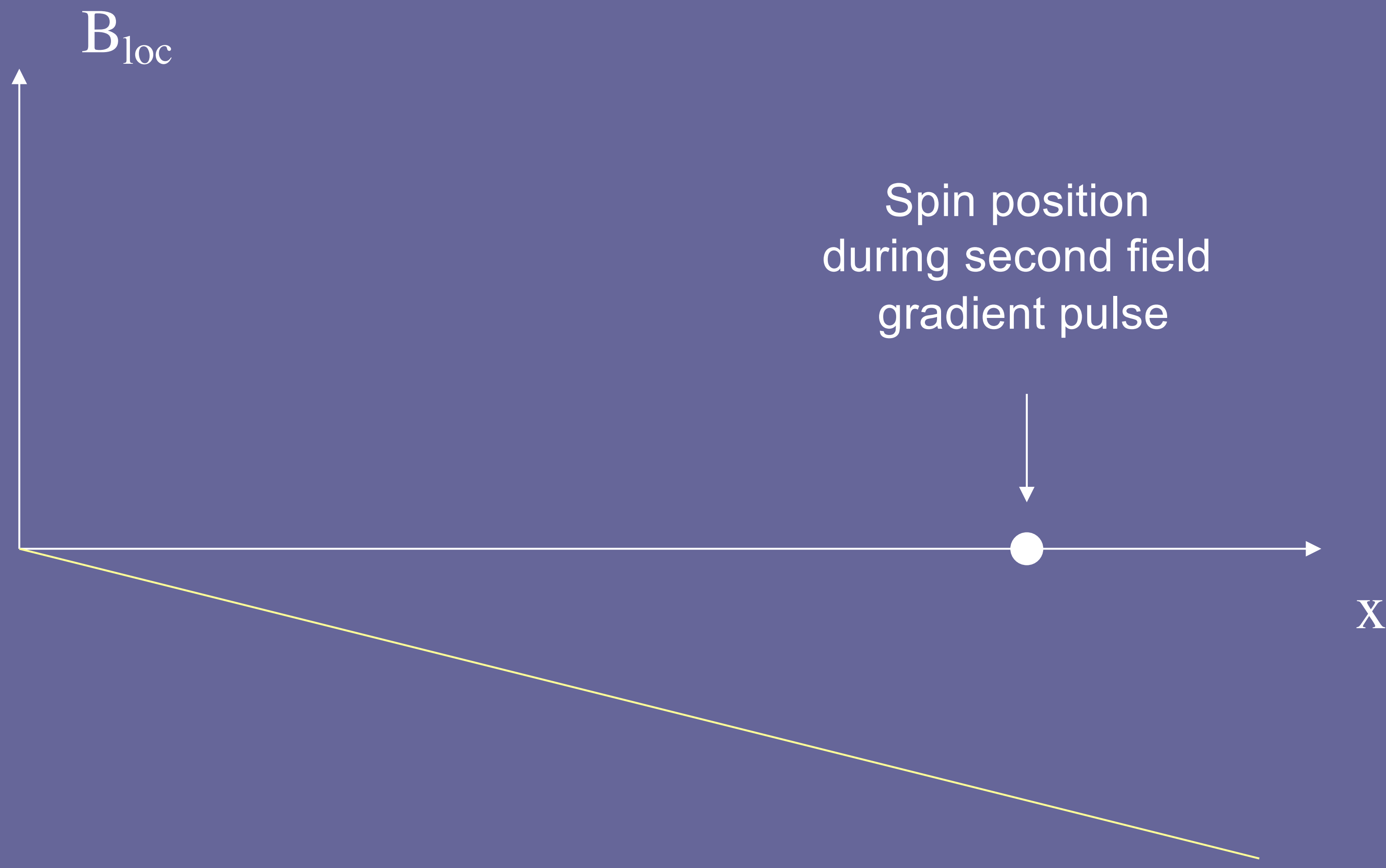
$$\omega = \gamma B_{loc}$$



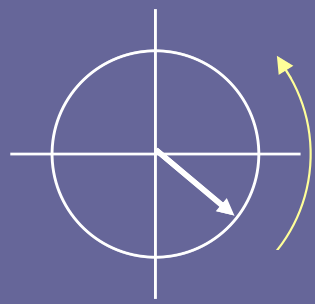
Stationary spins are rephased by reversing the field gradient

What about a moving spin?





=>Residual phase is proportional to displacement



- If the spin position is

$$x(t) = x_0 + v_x t$$

then its phase is

$$\varphi = \int \omega_z \cdot dt = -\gamma \int B_{loc}(t) \cdot dt$$

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$$= -\gamma \cdot \int_0^{\delta} G_0 \cdot \left(x_0 + v_x t\right) dt - \gamma \cdot \int_{\Delta}^{\Delta+\delta} \left(-G_0\right) \cdot \left(x_0 + v_x t\right) dt$$

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$$= -\gamma G_0 v_x \cdot \left\{ \left. \frac{t^2}{2} \right|_0^{\delta} - \left. \frac{t^2}{2} \right|_{\Delta}^{\Delta+\delta} \right\} = \left(\gamma G_0 \Delta \cdot \delta\right) \cdot v_x$$

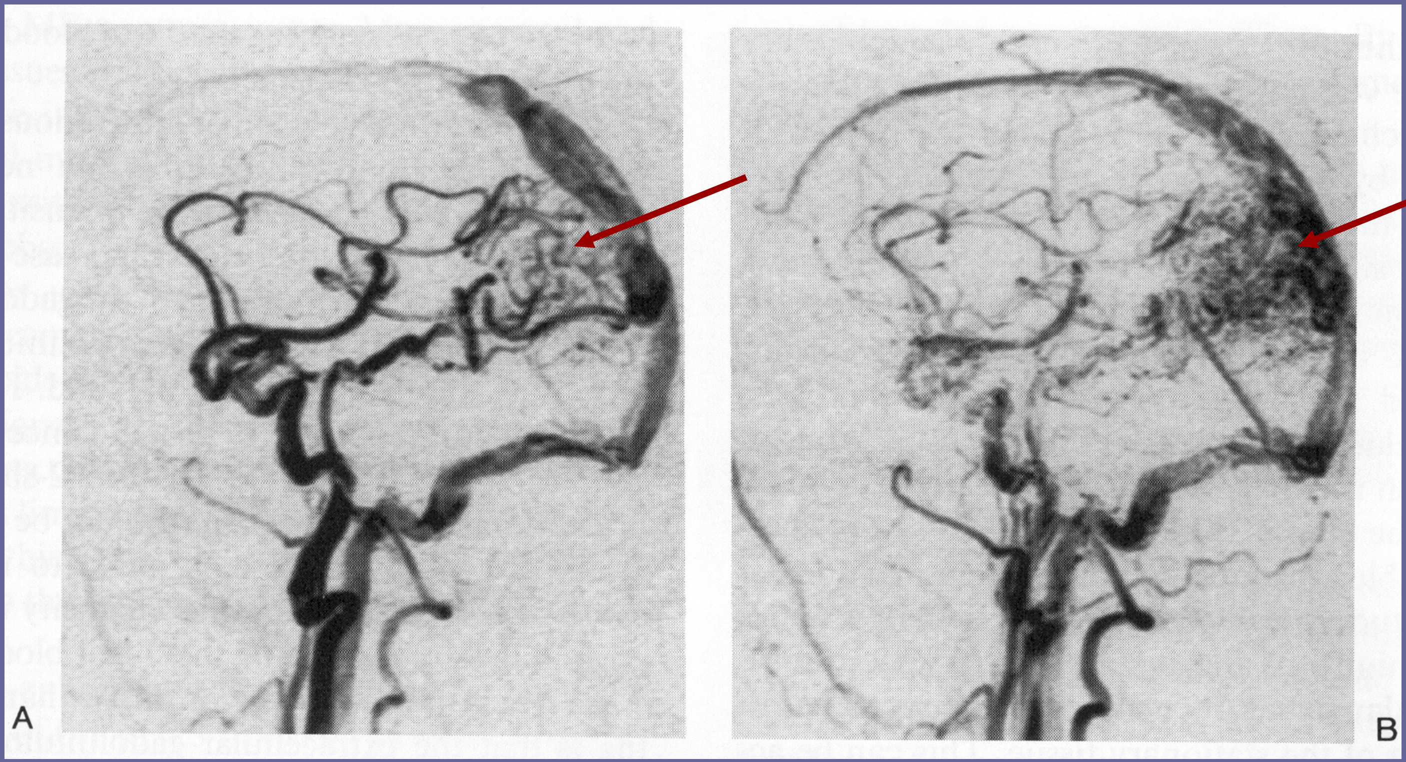
=> Residual phase is proportional to velocity

Phase maps

- Spin phase depends on
  - Velocity
  - Static B_0 field errors
- How can these be distinguished?

Phase contrast angiography

- Velocity can be measured from image intensity
- Velocity selective angiography is possible:



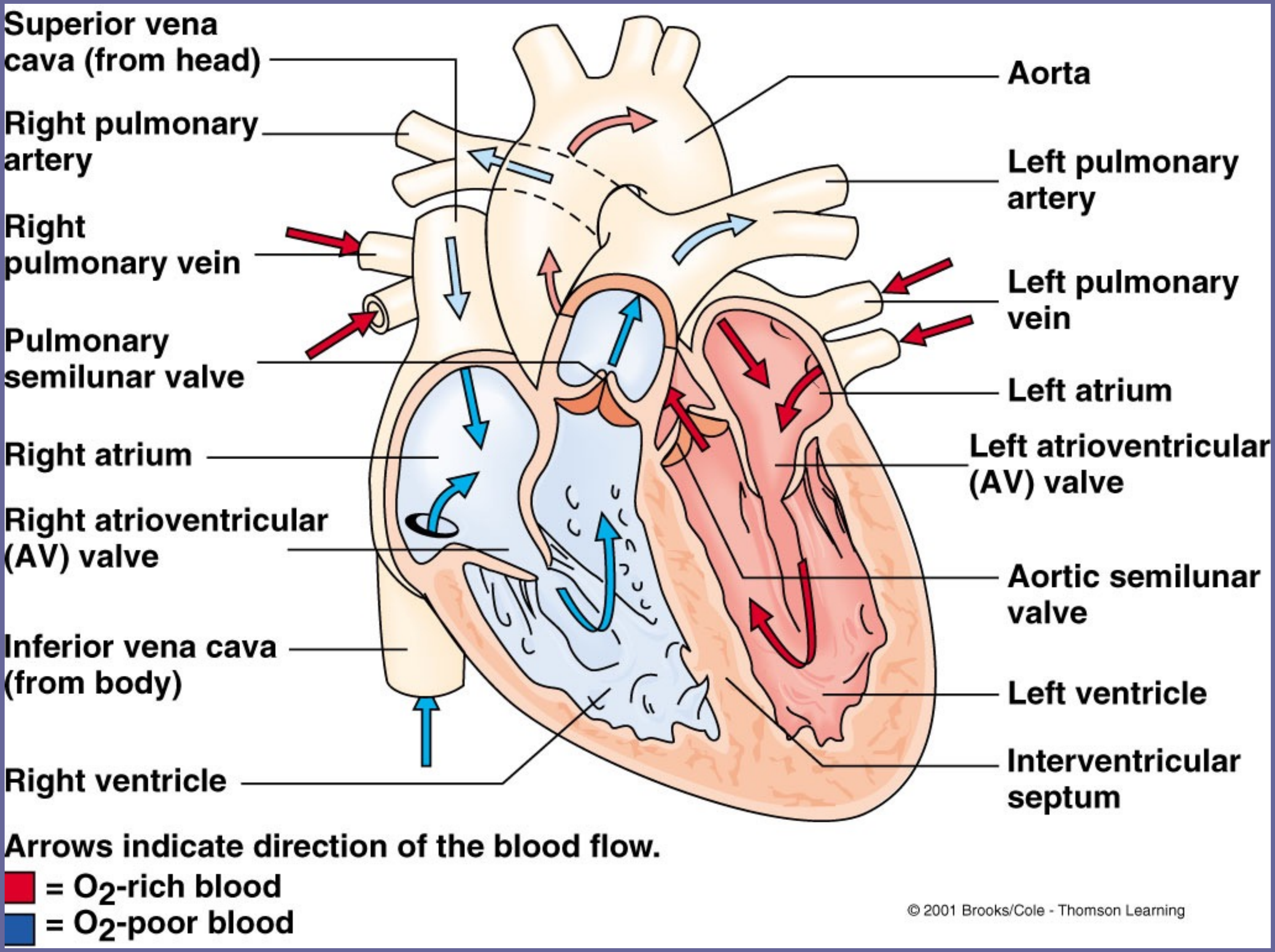
Arteriovenous Malformation (AVM)

Anderson, et al (1993)

Arterial (rapid) flow

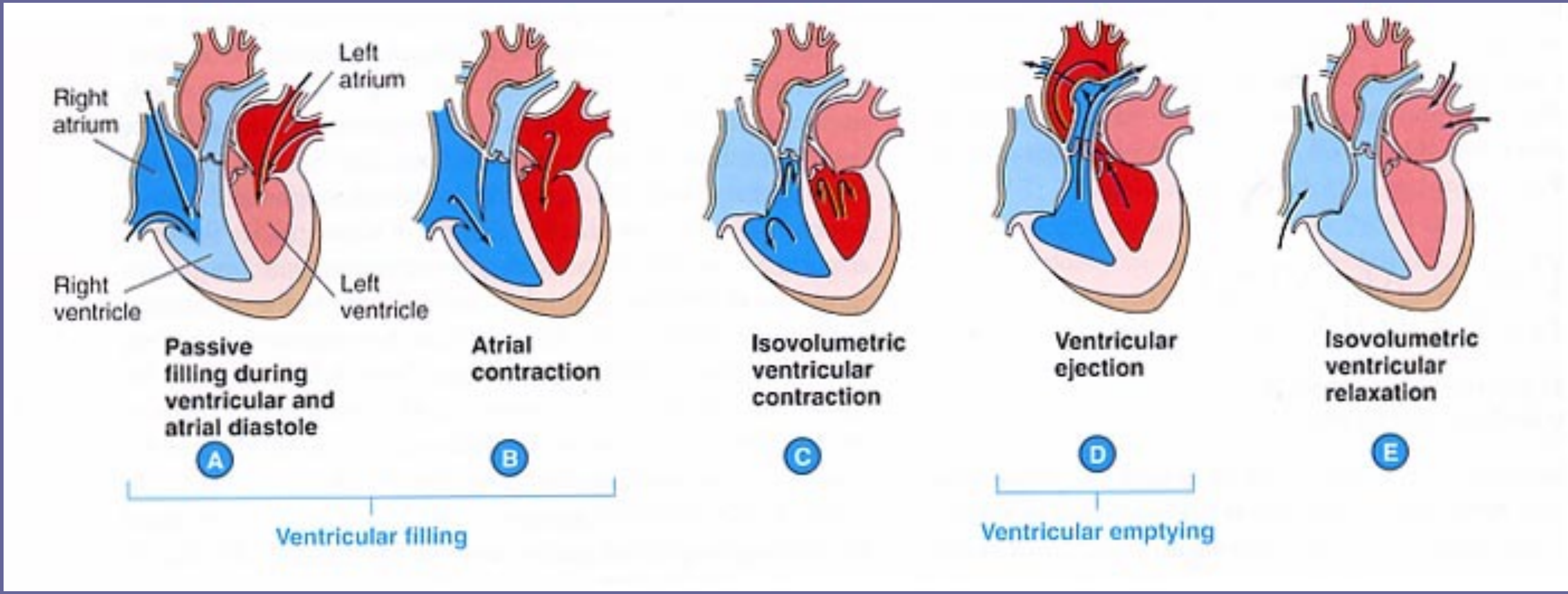
Venous (slow) flow

Application to cardiac imaging



Sherwood (2001)

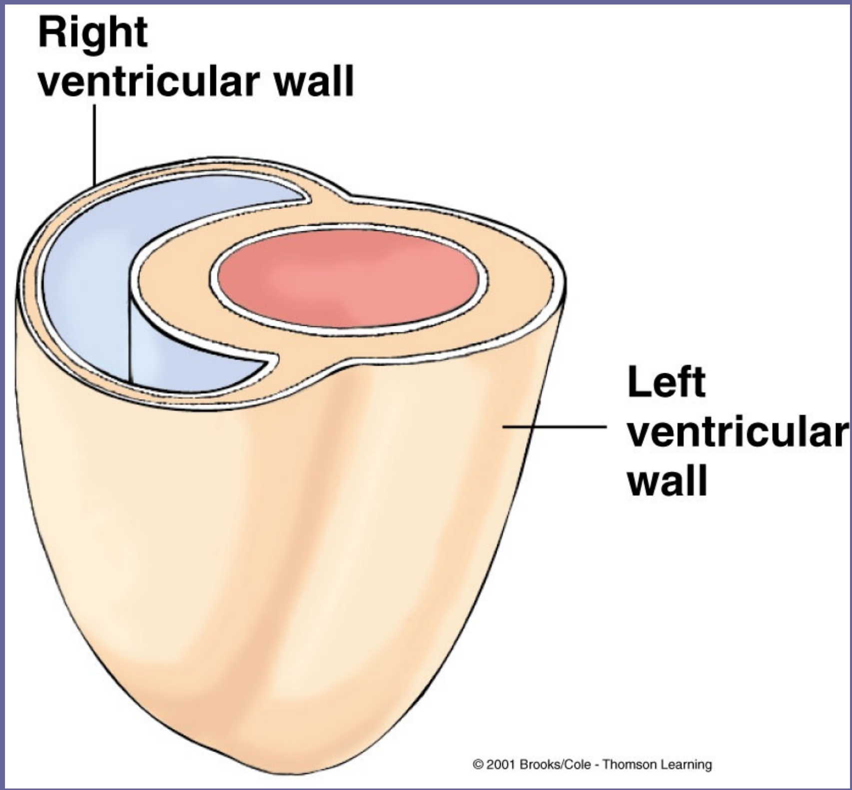
The cardiac cycle



Sherwood (2001)

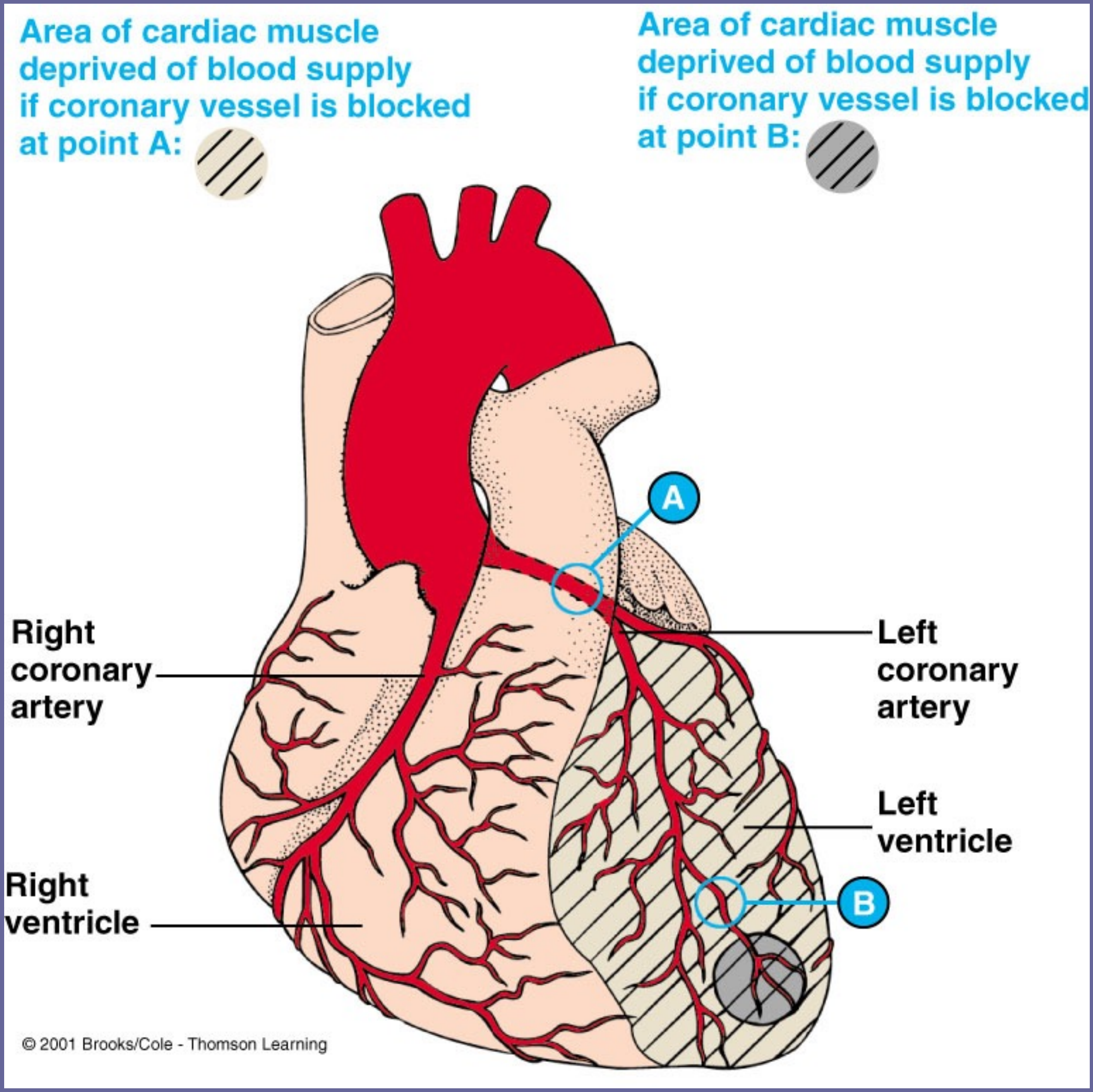
Ventricular anatomy

- Right ventricle pumps blood through the lungs
- Left ventricle pumps blood through the systemic circulation
- Most work is done by the left ventricle



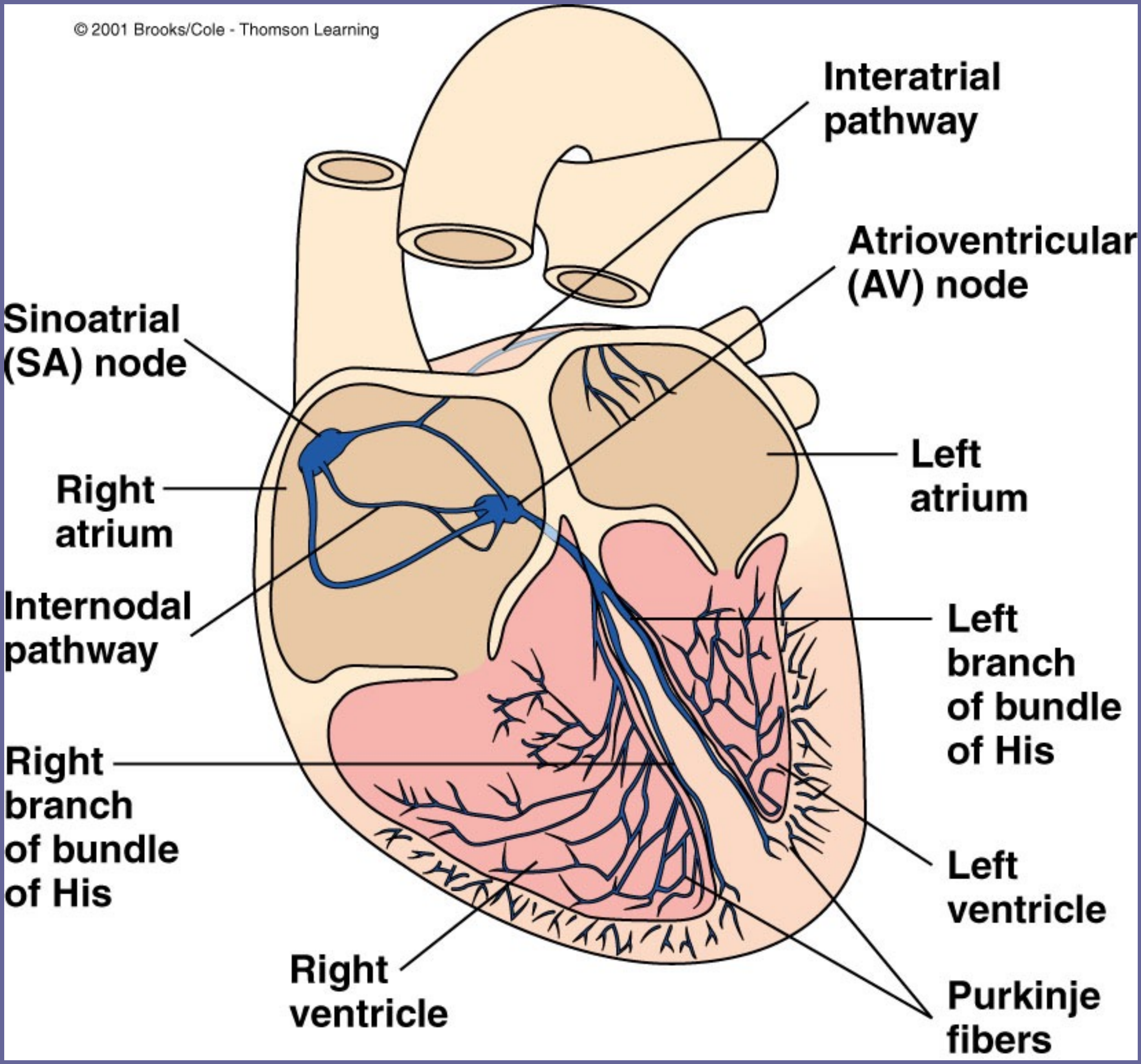
Sherwood (2001)

Extent of myocardial damage depends on size of occluded vessel



Sherwood (2001)

Conduction system of the heart



Sherwood (2001)

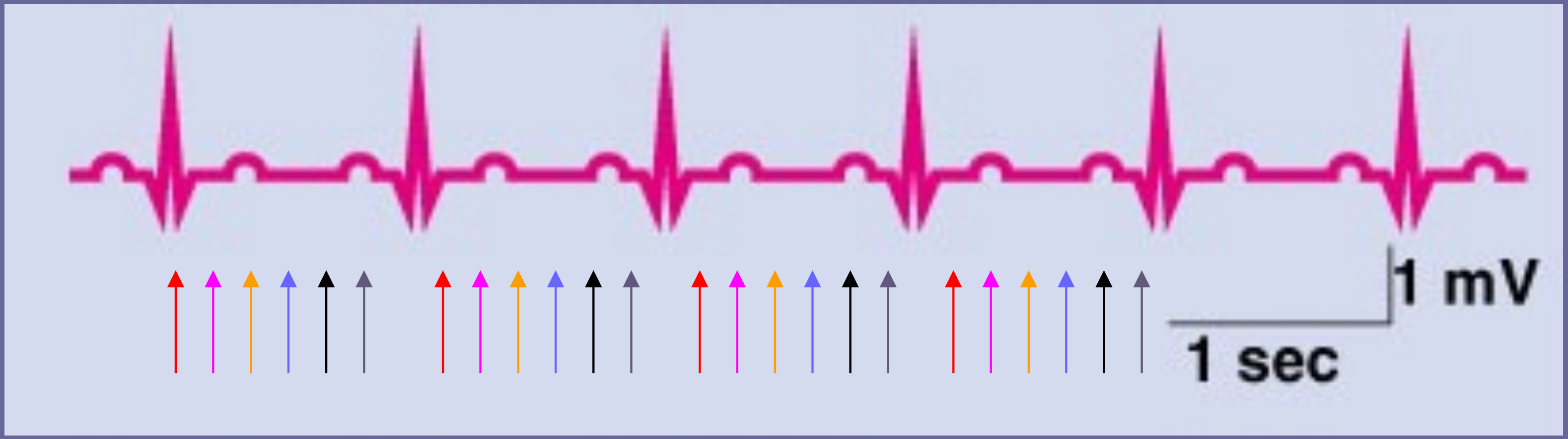
Measures of cardiac function?

Measures of cardiac function

- Stroke volume
- Blood flow velocities
- Heart wall motion
- Heart wall thickening
- Myocardial perfusion

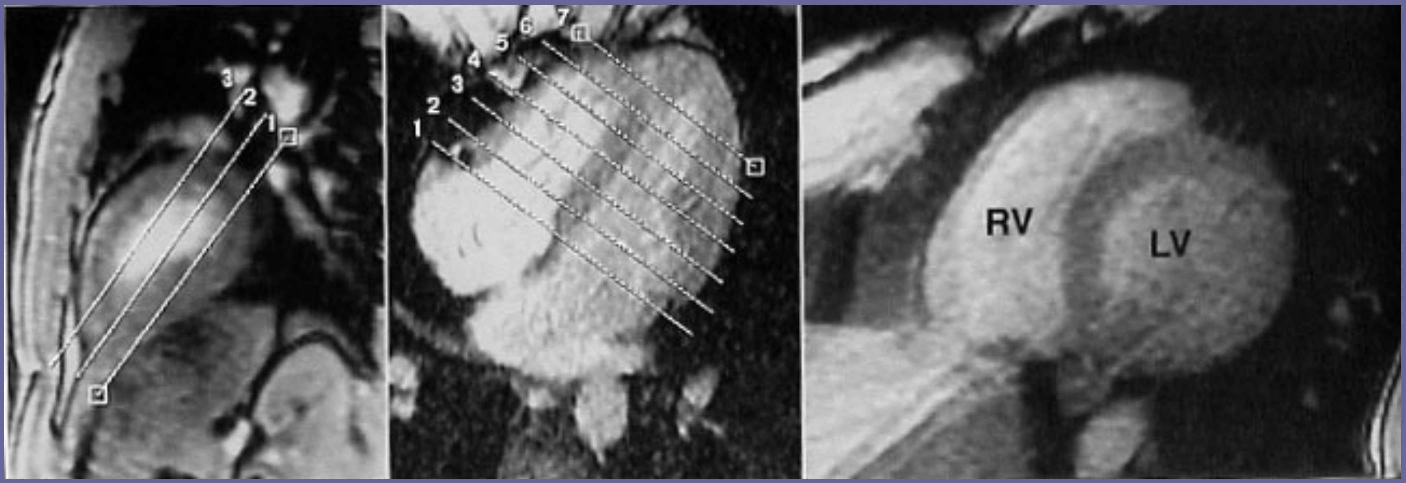
Cardiac gating

- Data acquisition for an image takes ~1 minute normally
- 60 or more heart beats in that time
- ‘Freeze’ motion by triggering acquisition in cardiac cycle



- Data captured at each red arrow contributes to 1 image, etc.

Short axis view of the heart

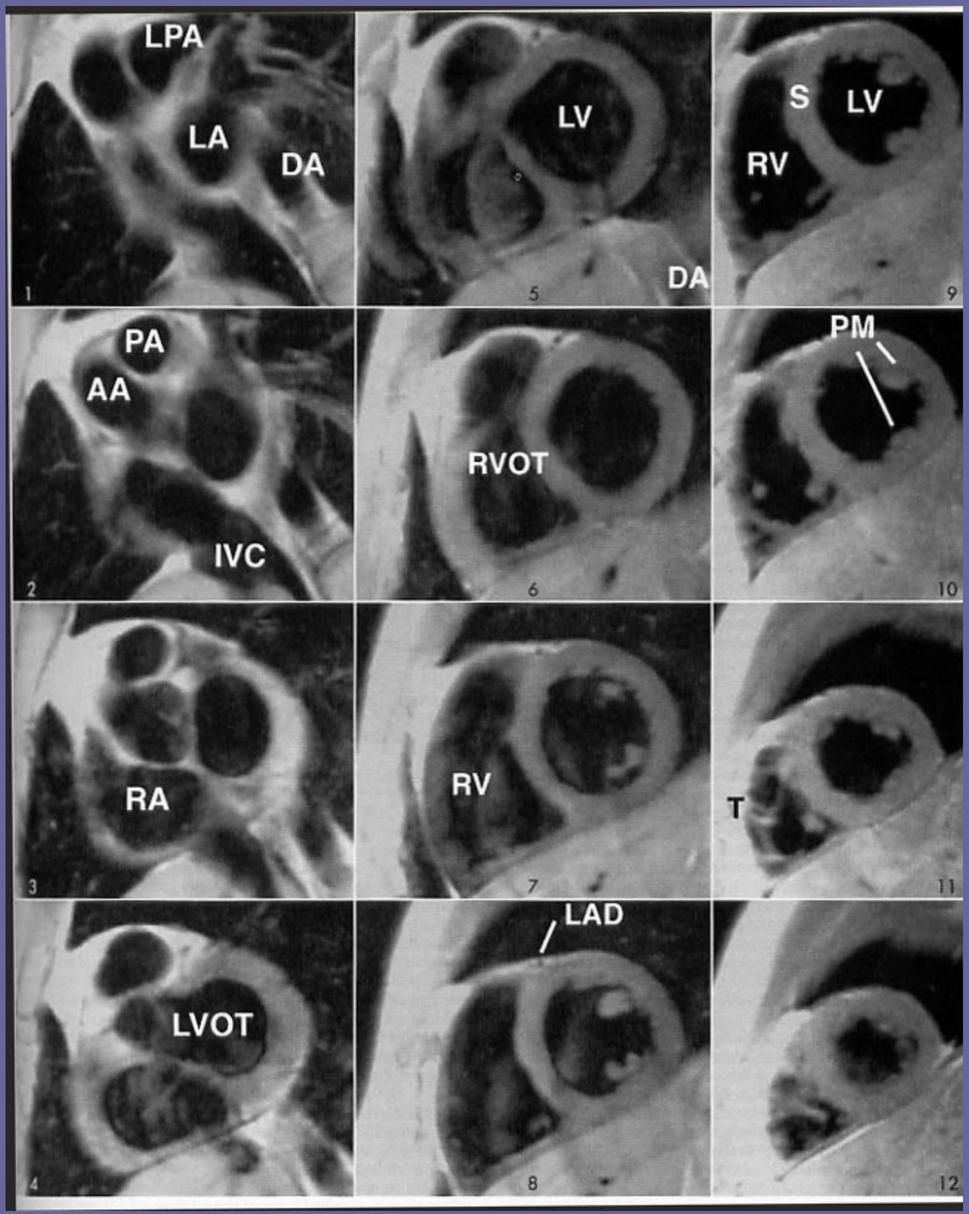


- The heart is rotated with respect to the body
- Easiest to analyze heart structure and motion in
  - Cross section (“short axis” view)
  - Longitudinal section (“long axis” view)

Normal cardiac anatomy

- LA: left atrium
- PA: pulmonary artery
- AA: ascending aorta
- IVC: inferior vena cava
- RA: right atrium
- LVOT: left ventricular outflow tract
- LV: left ventricle
- RVOT: right ventricular outflow tract
- RA: right ventricle
- S: septum

Superior



Inferior

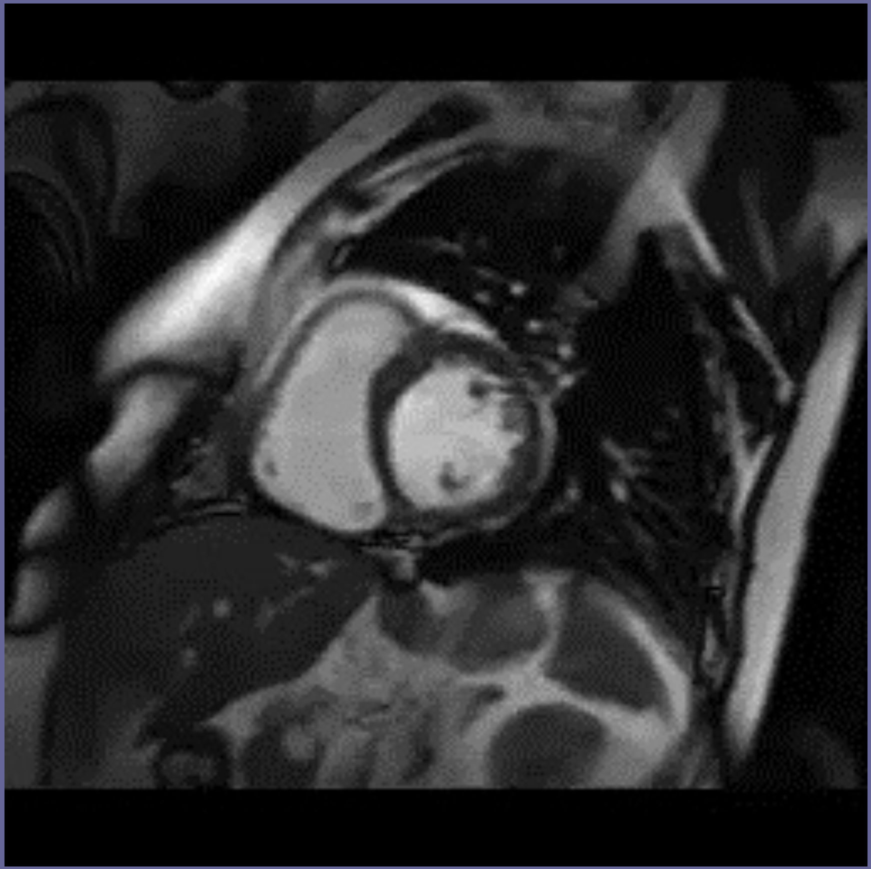
In-class exercise: Measurement of macroscopic flow

- What is the medical problem?
  - How is it related to flow?
- What is the quantity of interest?
- What would you look for in imaging data?

Cardiac valve function	Athero-sclerotic plaque
Stroke	Kidney failure
Aneurism	Fetal blood supply
Arterio-venous malformation	

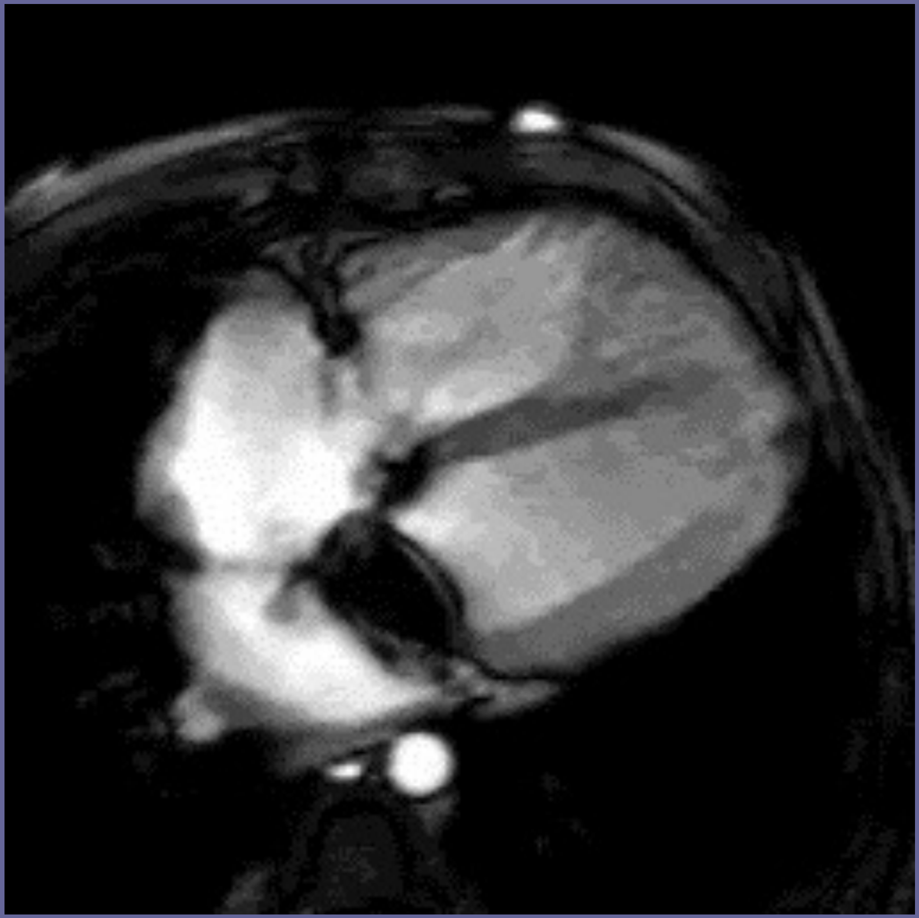
Cine loops

- Images acquired at distinct points in the cardiac cycle are assembled into a ‘movie’ loop
- Reveals dynamics



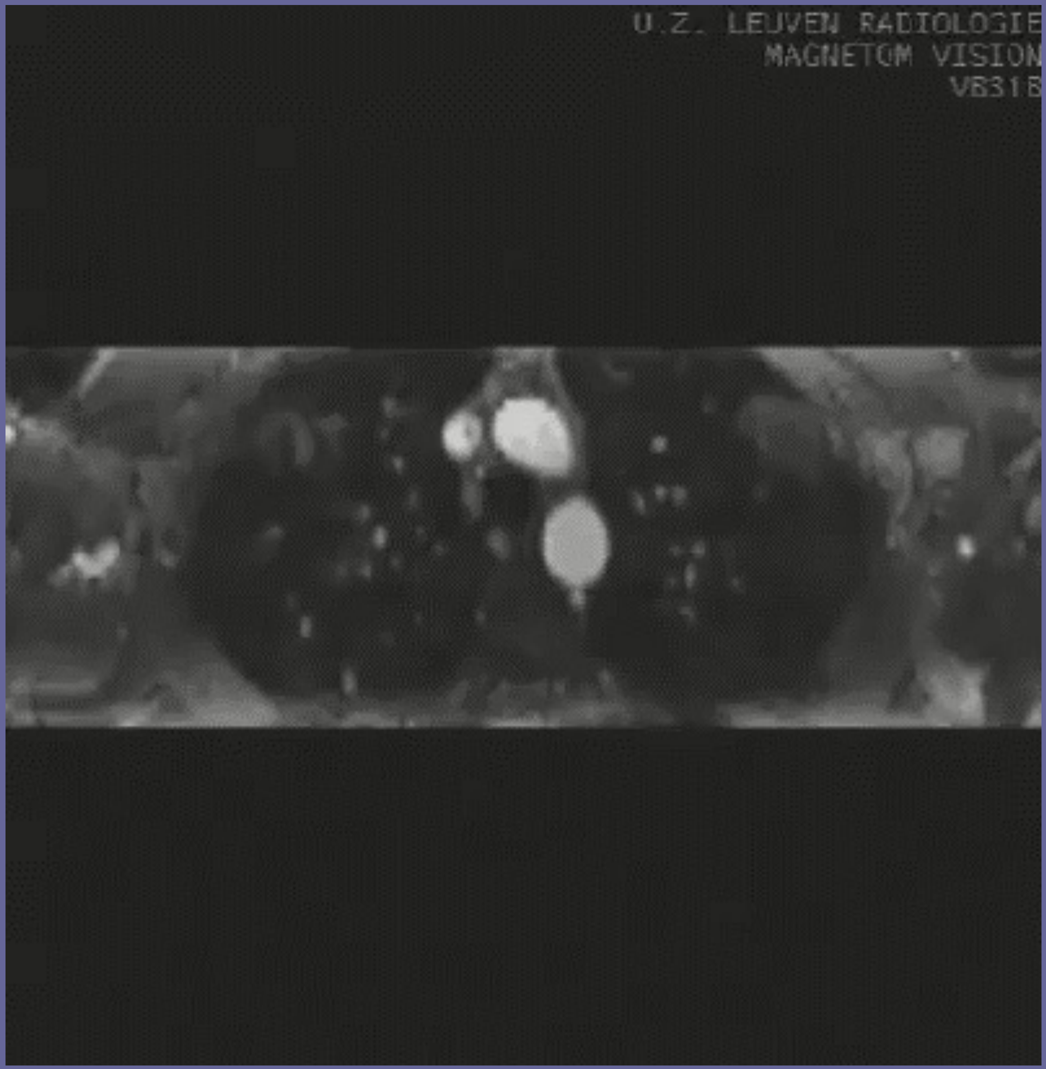
Suetens (2002)

Four chamber cine loop



Didier (2003)

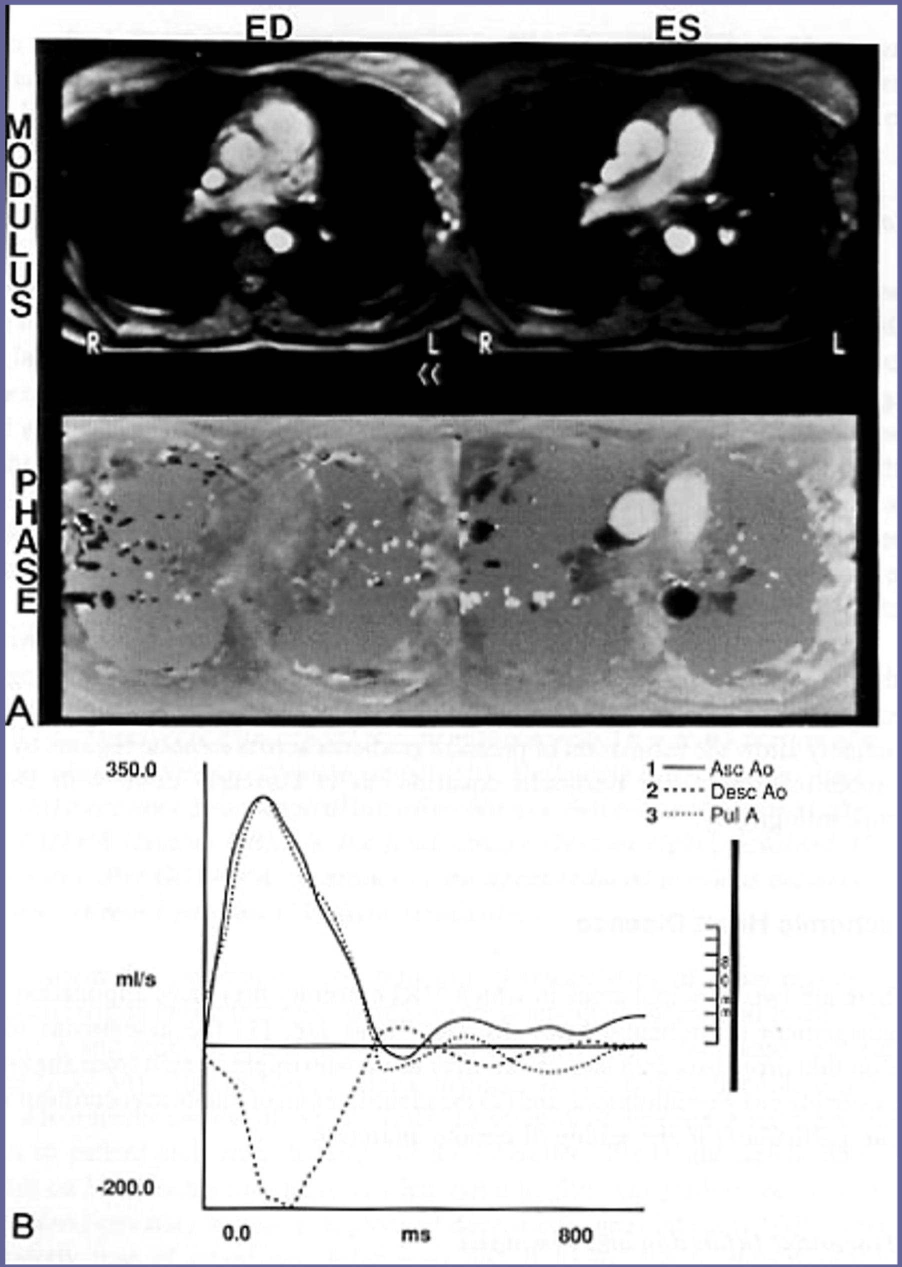
MR angiography



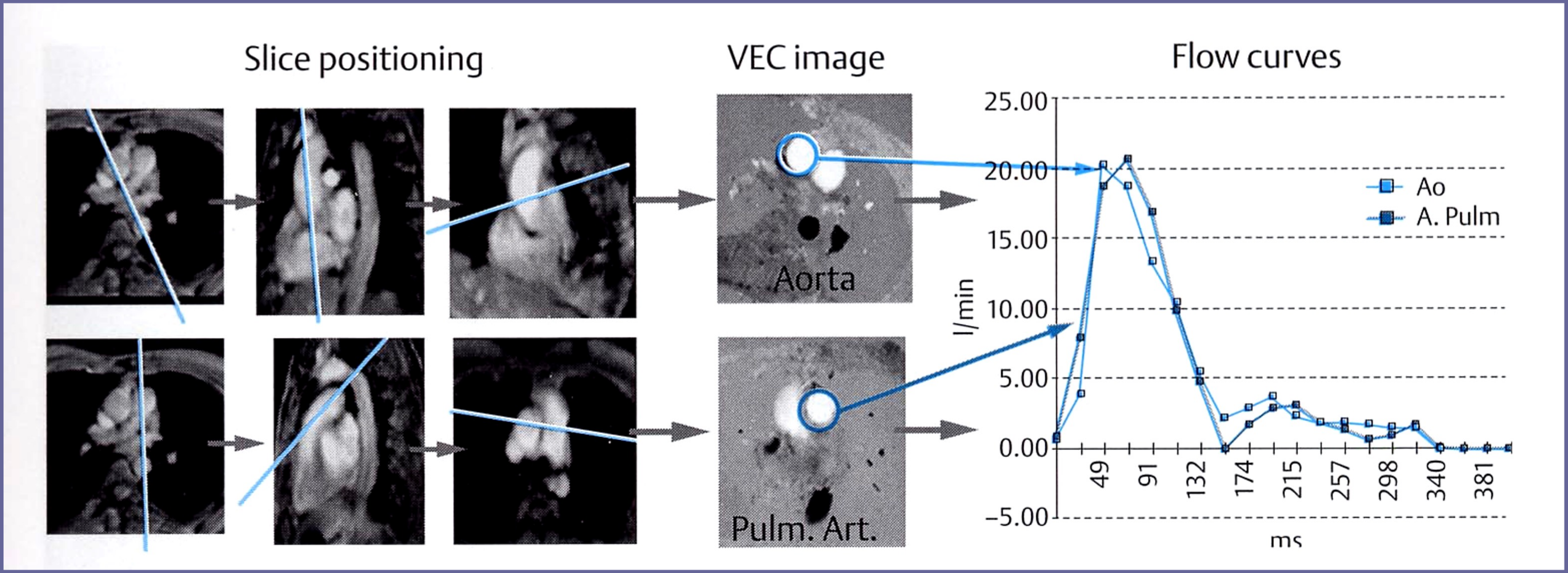
Suetens (2002)

Flow measurement

- Find blood velocity in major vessels
- Sum (velocity*area) over the cross section of vessel
- Determines flow at each point in cardiac cycle

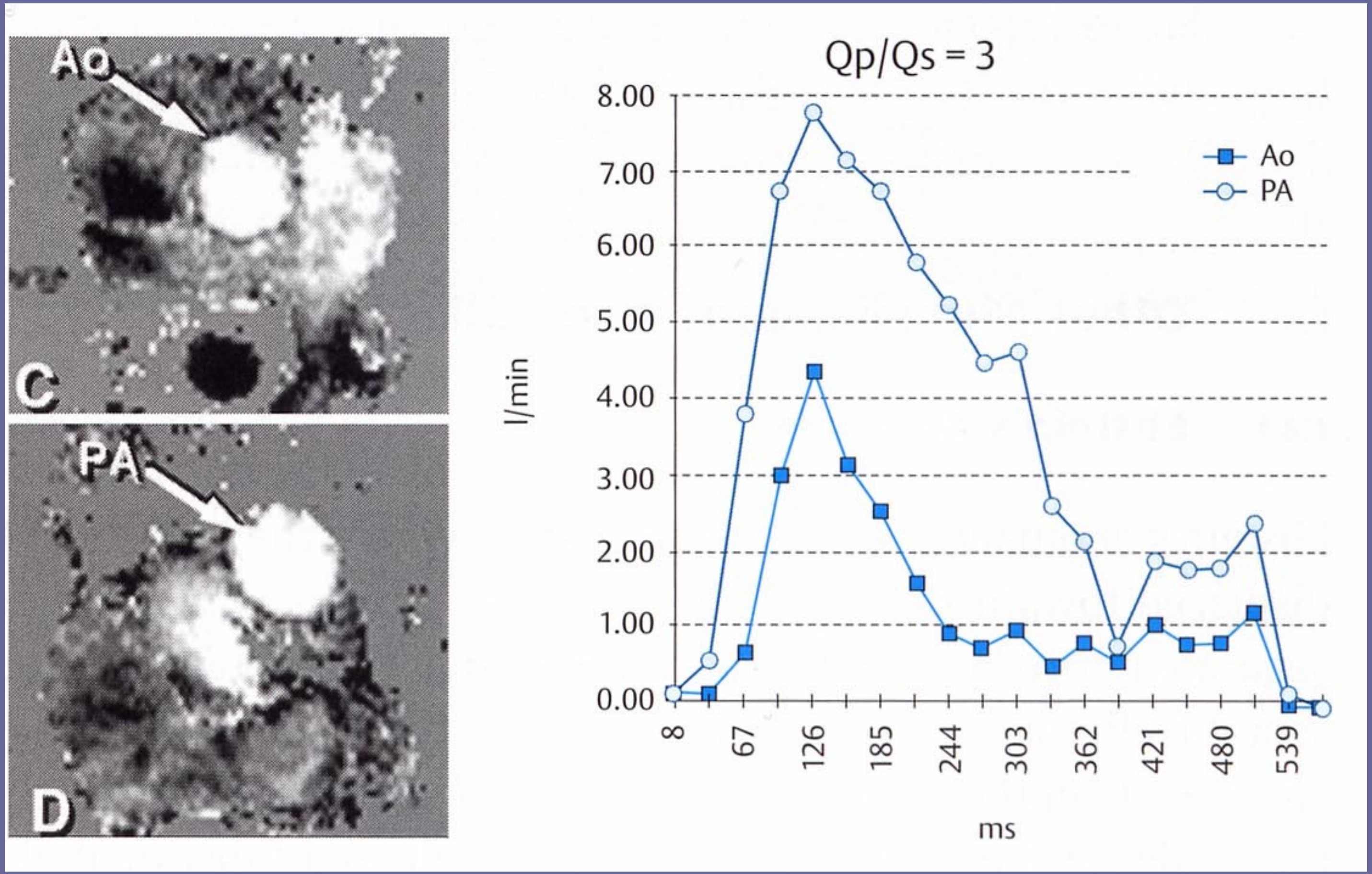


Measures of cardiac output



Didier (2003)

What’s wrong in this case?



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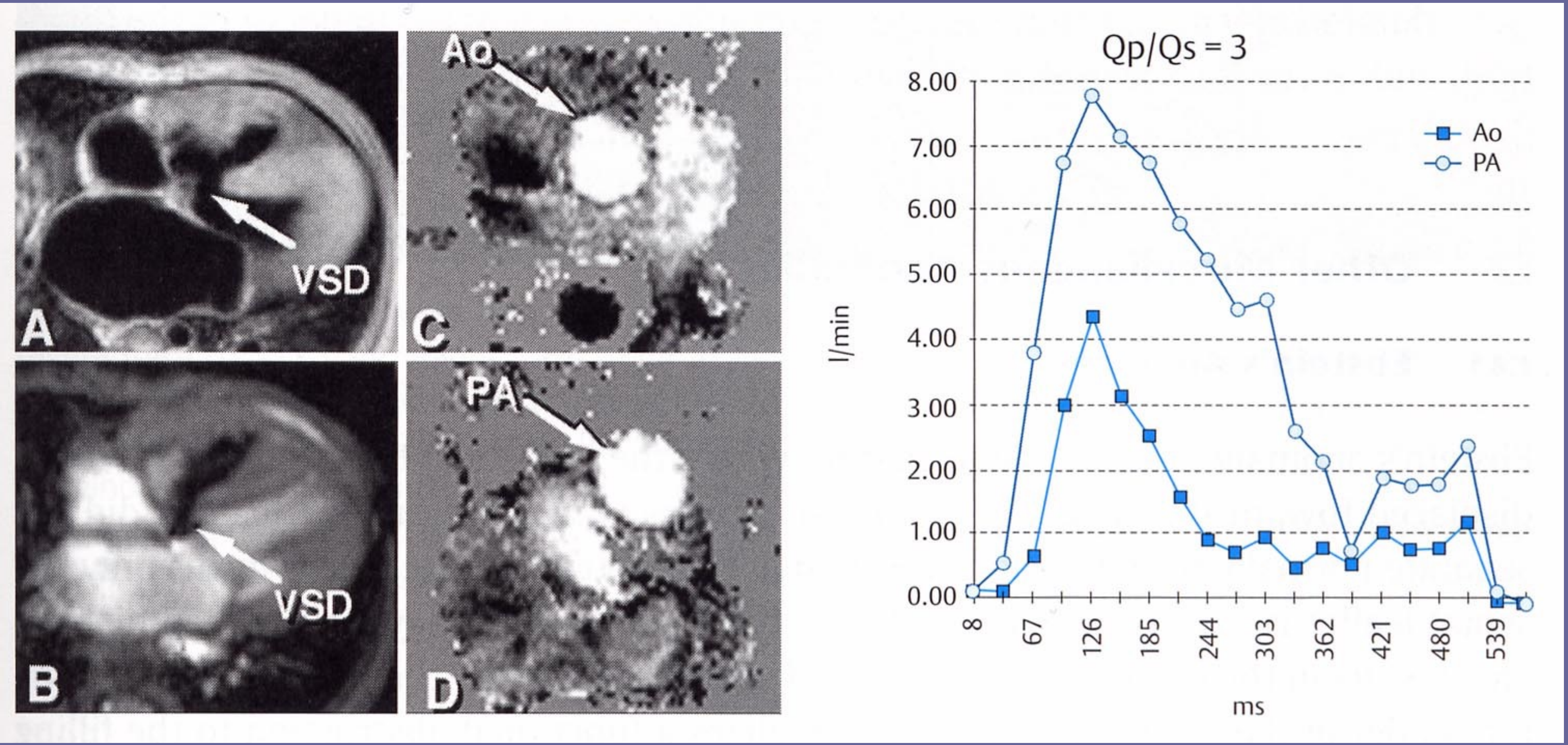
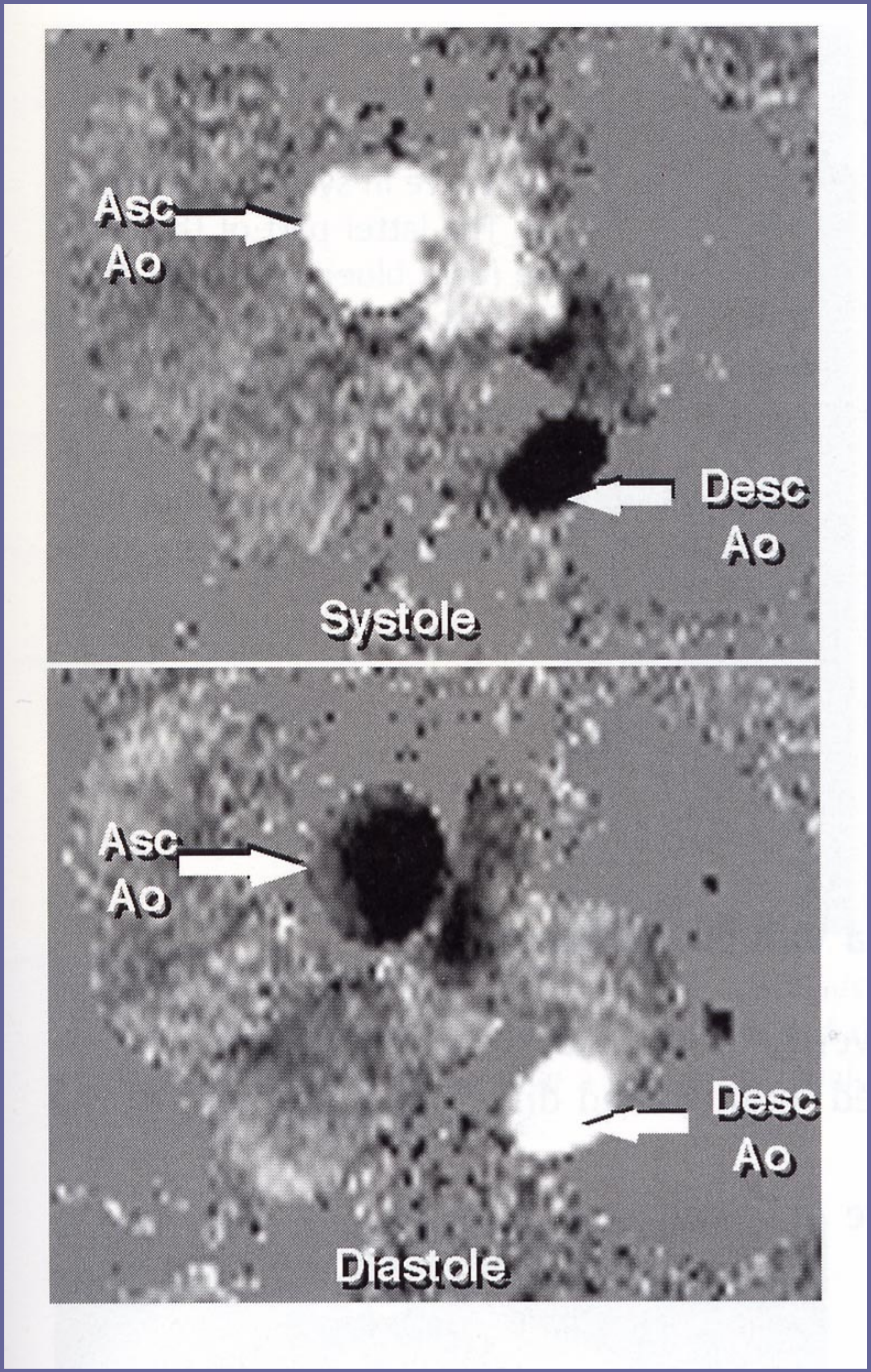


Ventricular septal defect

Didier (2003)

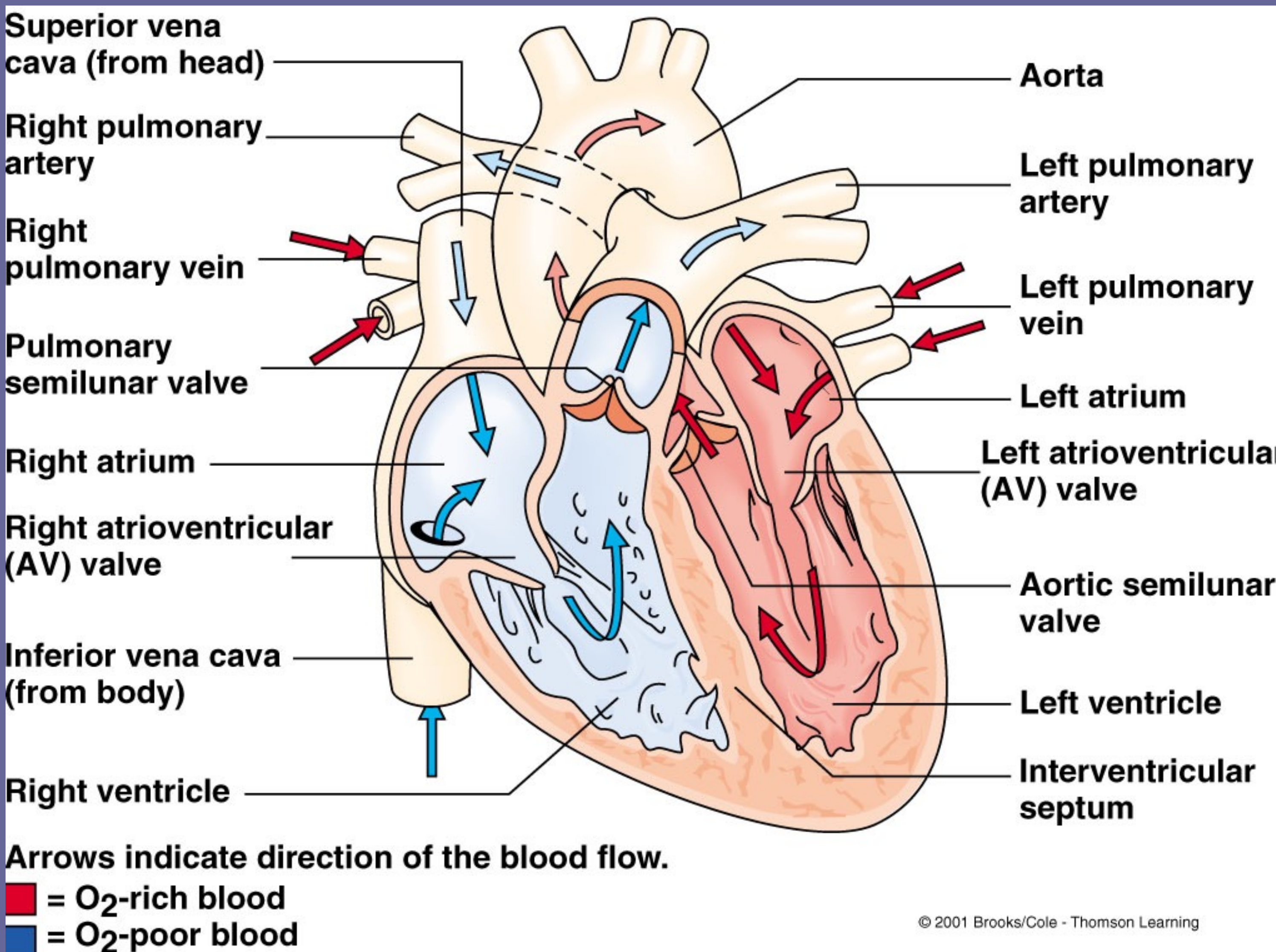
What’s wrong in this case?



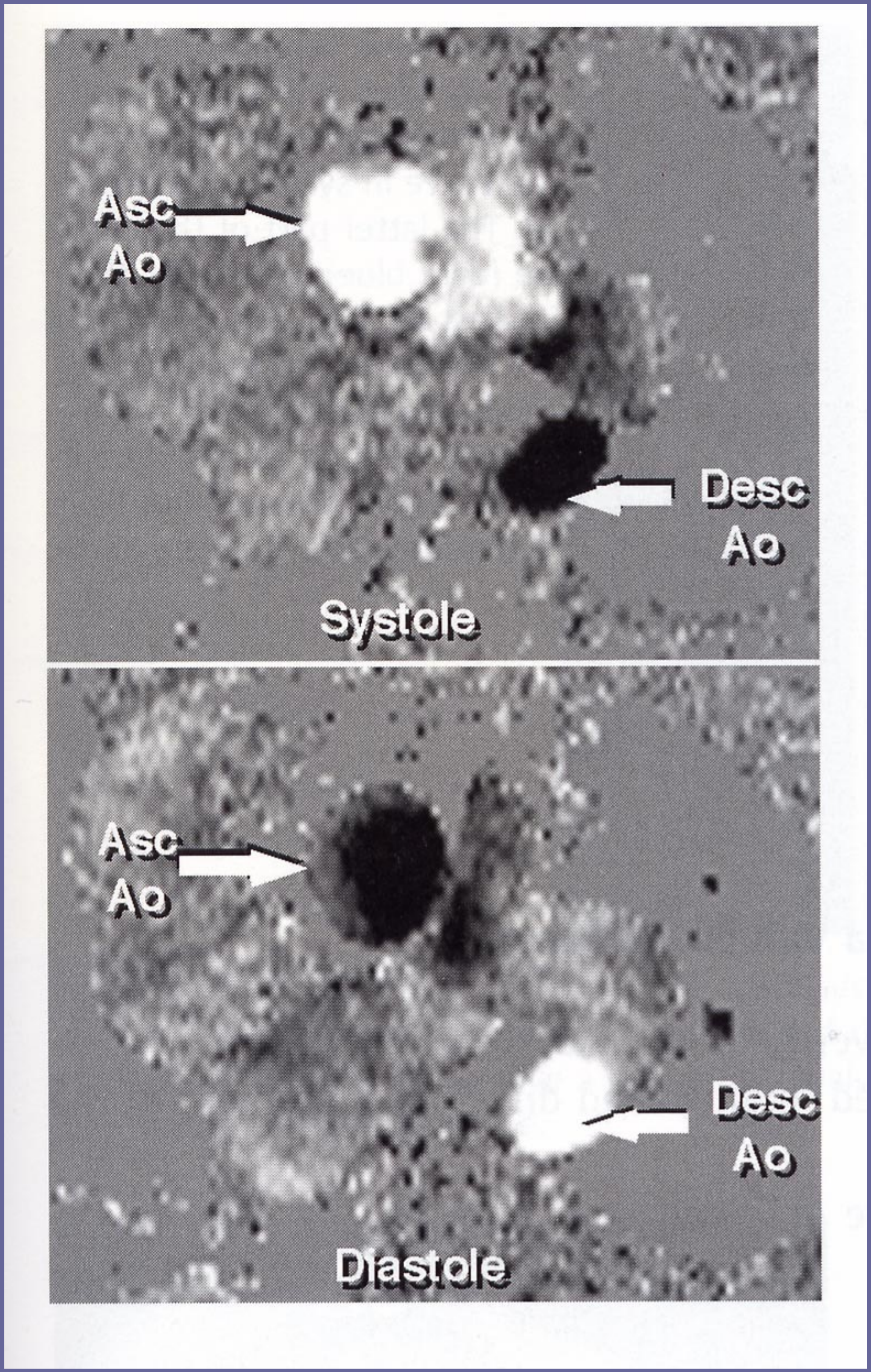
Bright -> flow toward head

Didier (2003)

Application to cardiac imaging

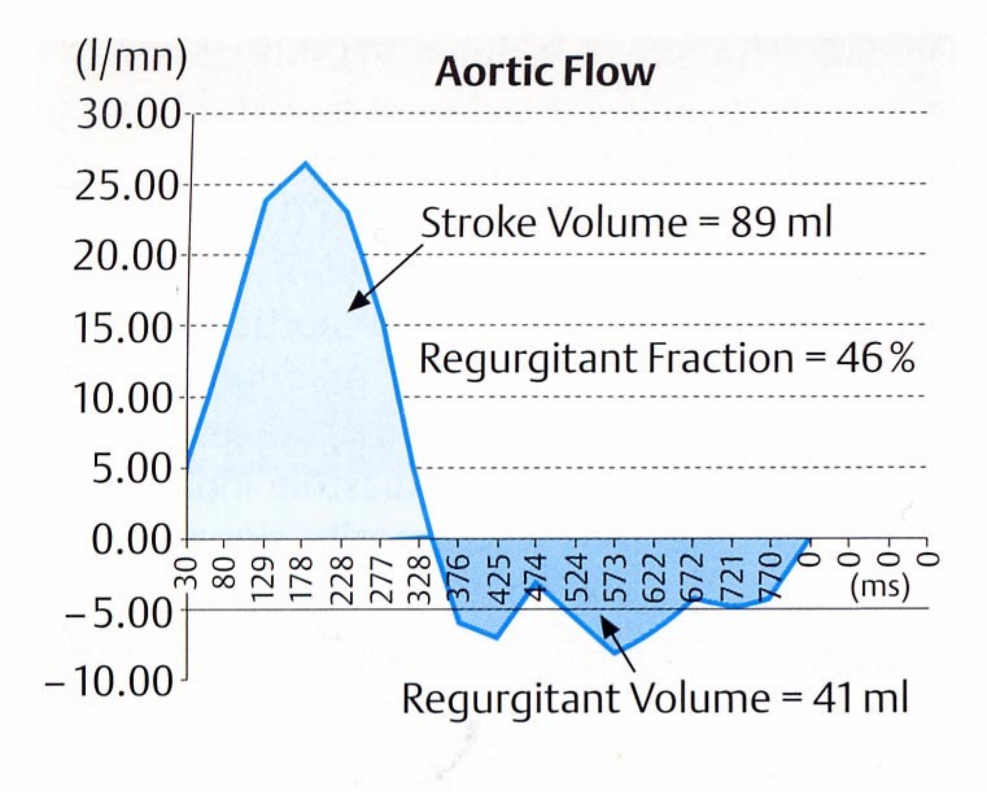


Sherwood (2001)



What's wrong in this case?

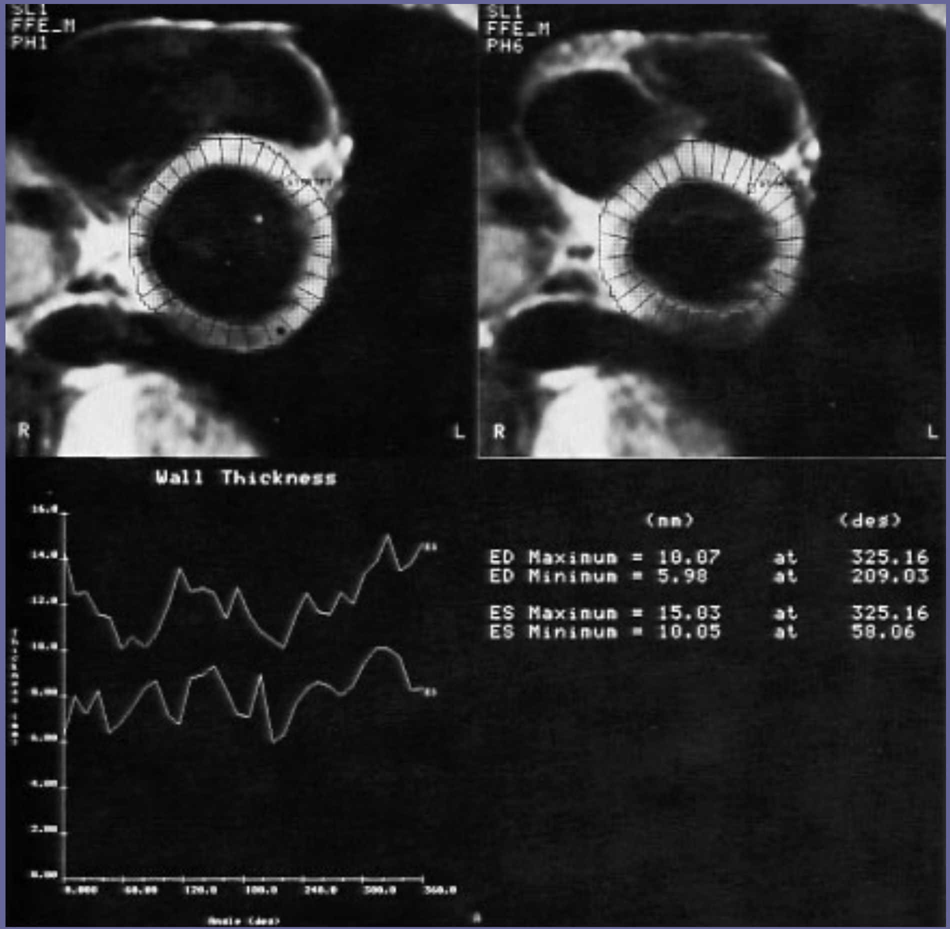
Aortic regurgitation



Didier (2003)

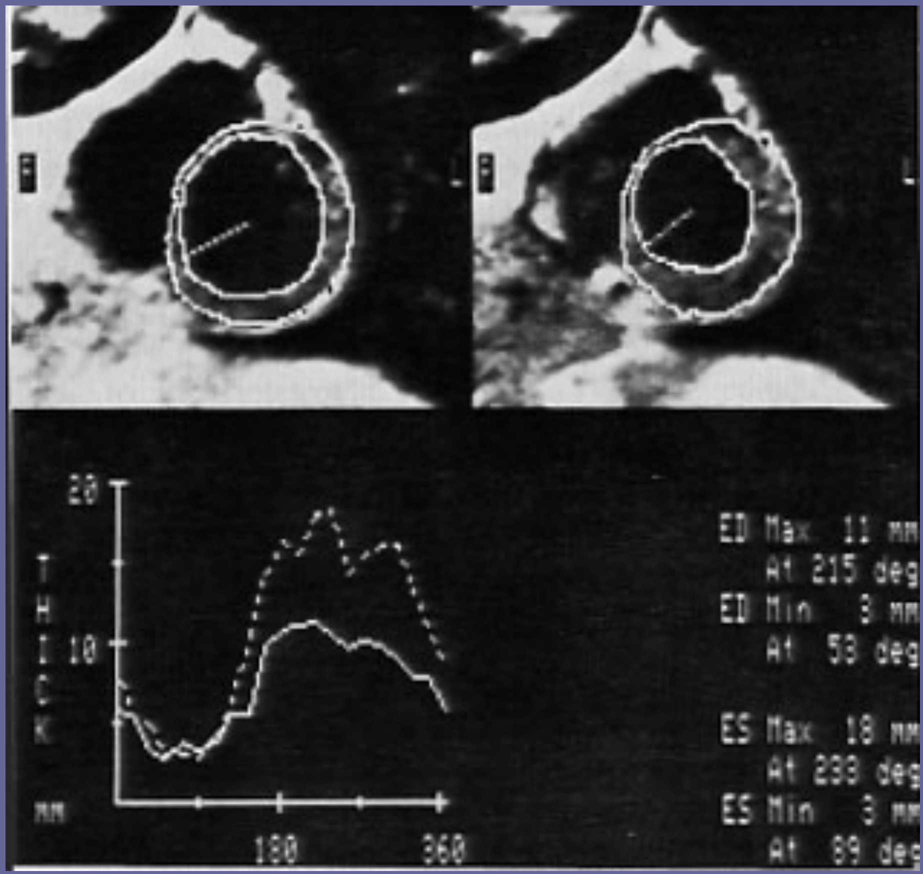
Systolic wall thickening

- Measure wall thickness at regular intervals around circumference
  - End diastolic
  - End systolic
- Plot thickening vs. angle
- Measures myocardial contractility



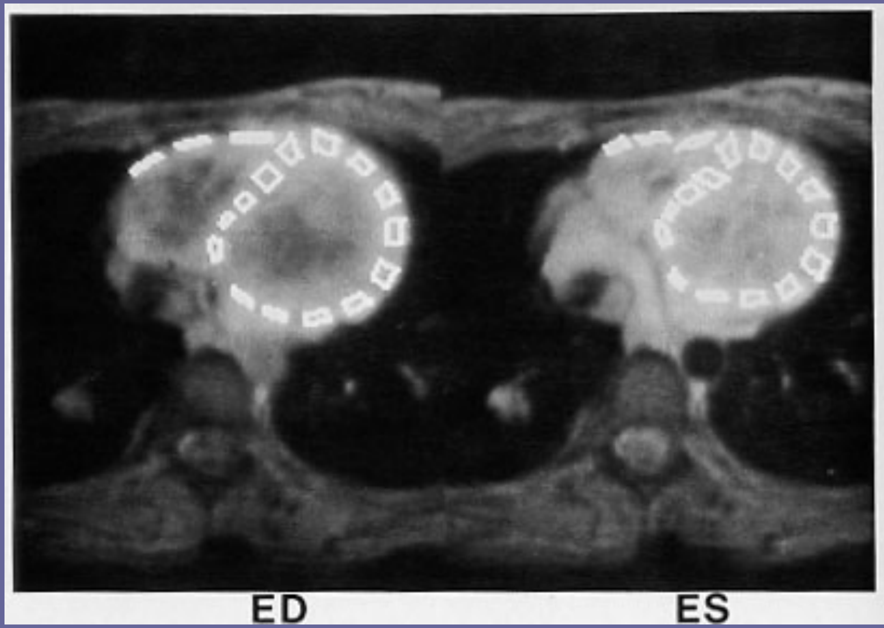
Myocardial scarring

- Septum is thinned in both diastole and systole
- Indicates infarction and scarring
- Opposite wall has normal diastolic thickness and systolic thickening
- Opposite wall is viable

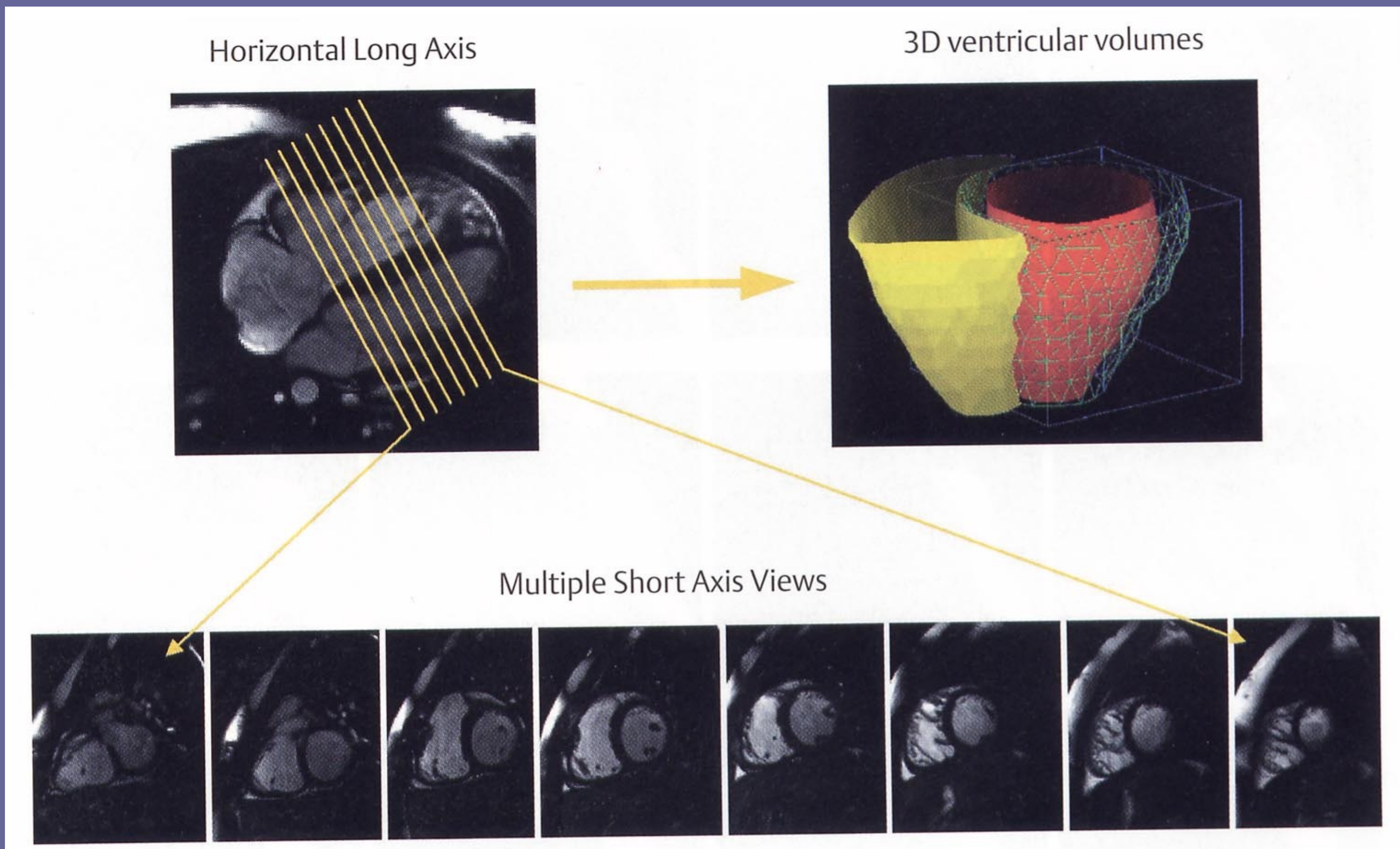


Myocardial strain

- Measure heart wall velocity at each point
- Plot local mechanical deformation during systole
- Reveals heart wall abnormalities



Construction of finite element models from contiguous images



Didier (2003)

Summary

- Ultrasound, CT, and MRI are all routinely used to image vascular disease
- Quantitative measures of vessel diameter and blood velocity can be made
- Cardiac MRI can assess
  - Flow in specific
    - Vessels
    - Valves
    - Shunts
  - Myocardial
    - Motion
    - Strain
    - Perfusion
    - Capillary wall integrity
  - Multiparametric exam

References

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