Medical diagnostic systems

(Orvosbiológiai képalkotó rendszerek)

Ultrasound velocimetry

(Ultrahang sebességmérés)

Miklós Gyöngy

Diagnosis based on human body dynamics

Motion type	Typical speed (mm/s)	Measurement method of choice
Muscoskeletal movement		
external visible motion	50-5000	optical
muscle contraction		
[Deffieux *et al.* 2006; Jarvis *et al.* 1997]	5 (transverse),500 (axial)	servomotor (invasive), **ultrasound**
Organ wall motion (e.g. heart, vessels)		**ultrasound**
Fluidic		
lymphatic		
[Fischer *et al.* 1996; Havas *et al*. 1997]	0.1	scintigraphy
respiratory system		peak flow meter
urinary, digestive, reproductive, mammary		production rate (of interest): ? excretion: optical
amniotic fluid [Kinga Gyöngy]		**ultrasound**
cerebrospinal fluid [Lee *et al.* 2004]	40	MRI, **ultrasound**
blood circulation [Cobbold 2007, p. 620]	**peak 1 m/s**	**ultrasound**

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Overview of this lecture

- Cardiovascular system
- Doppler effect and its relevance to blood
- Doppler velocimetry of blood flow (and solid structures)
- Other US-based motion analysis methods

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The cardiovascular system

- Carrying oxygen from the lungs to the body (cells) for metabolism
- Major determinant of health
  - How much flow is there? How well is organ supplied with nutrients? (stenosis/thrombosis)
  - Is there regurgitation of blood? Backflow can be indicator of ill-health
  - What is the flow pattern with time?

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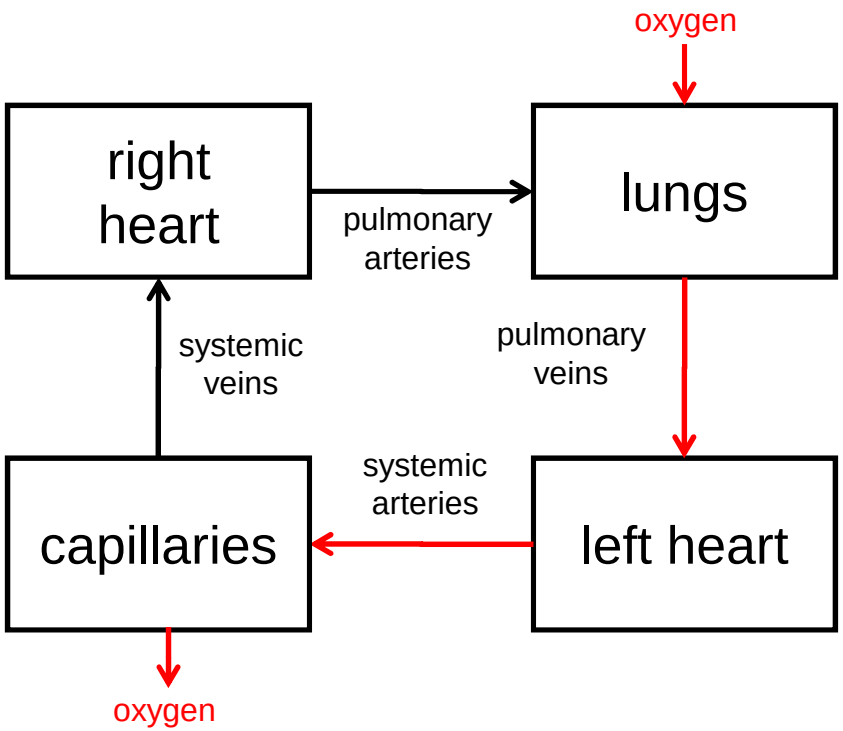
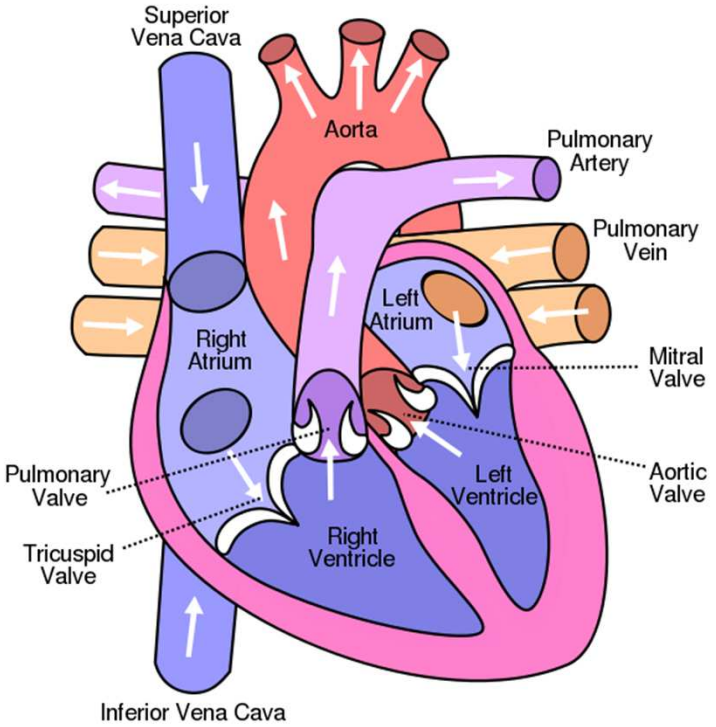
The heart – a double pump





the human heart
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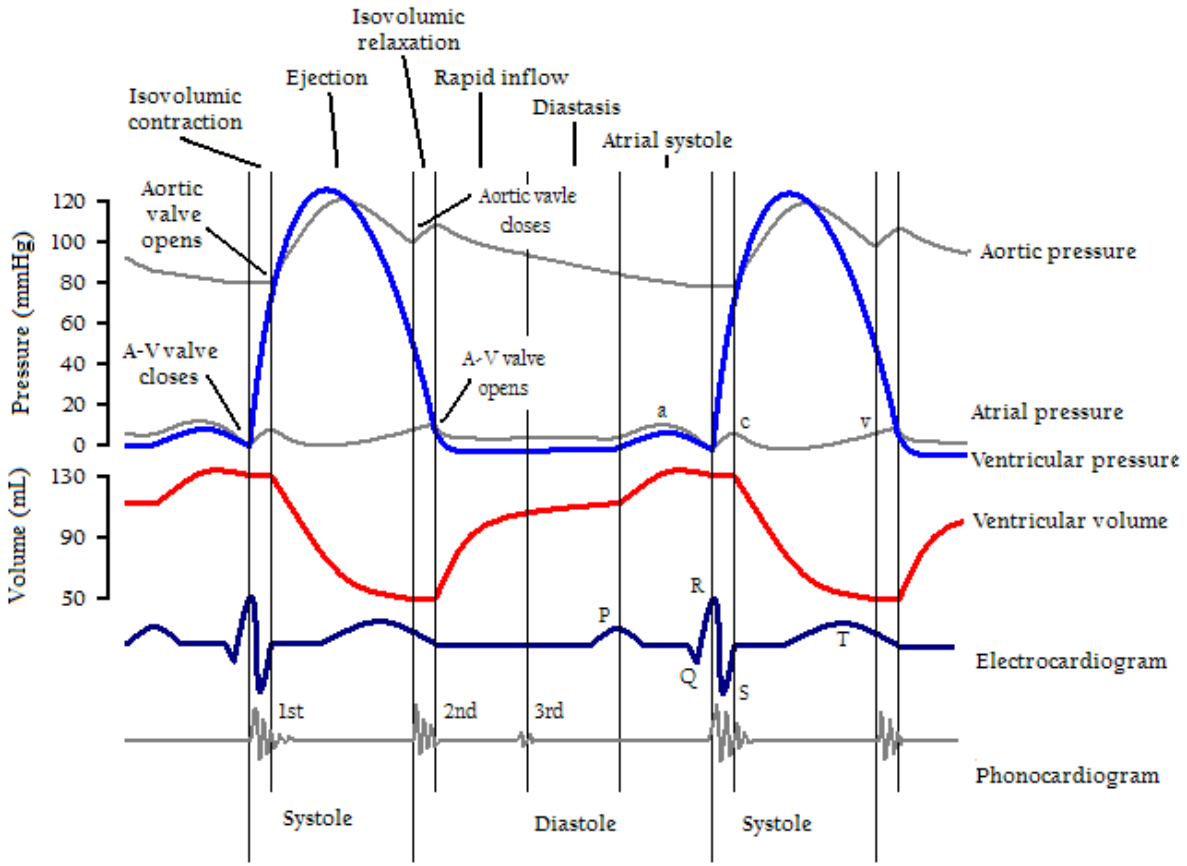
Medical diagnostic systems – Ultrasound velocimetry



the cardiac cycle

http://en.wikipedia.org/wiki/File:Cardiac_Cycle_Left_Ventricle.PNG

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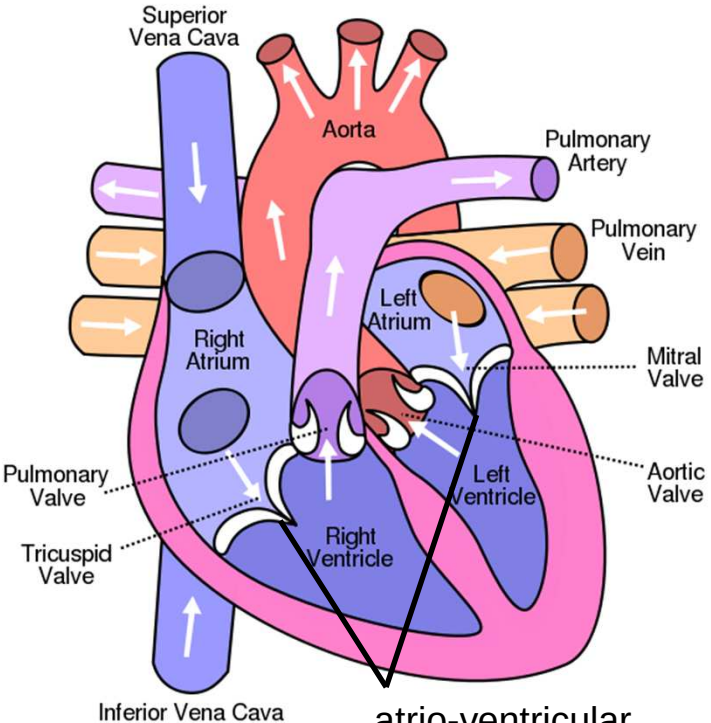

atrio-ventricular (AV) valves

the human heart

http://commons.wikimedia.org/wiki/File:Diagram_of_the_human_heart_%28cropped%29.svg

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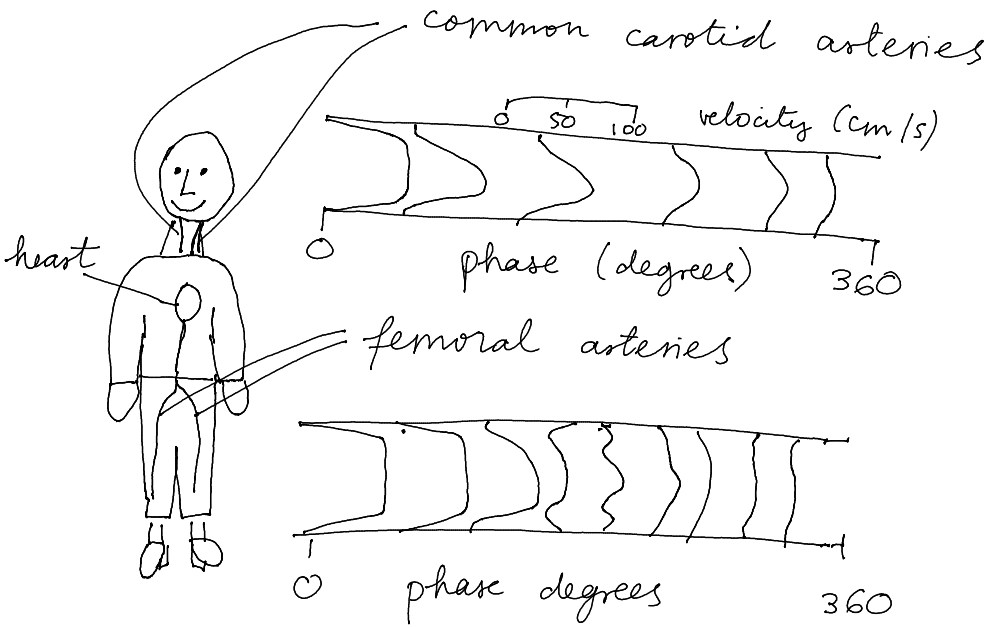
Blood velocity profiles [Gijsen *et al.* 1999]

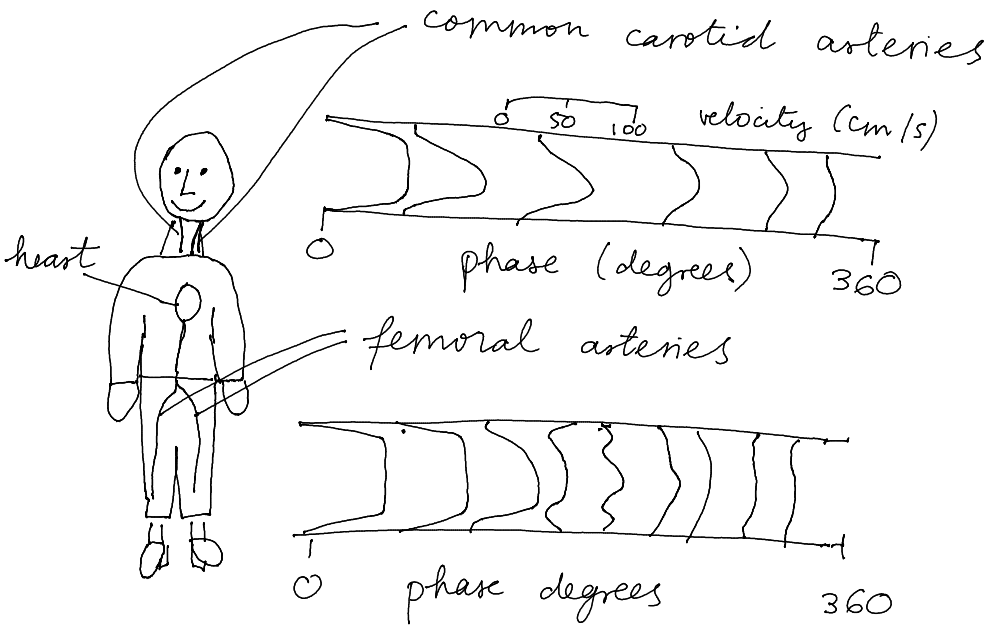
- Newtonian liquid: shear stress proportional to velocity gradient
- In contrast, blood is non-Newtonian and exhibits shear thinning (viscosity decreases at higher shear stresses – imagine ketchup)
- Newtonian liquid: fully developed flow profile in circular tube (vessel) is parabolic
- In contrast, shear thinning fluid causes flattening of velocity profile
- Note also: vessel wall is elastic!



Adapted from [Cobbold 2007, p. 629]

Blood velocity profiles [Shehada *et al.* 1993]

- Period=0.85 s; 0º: systole
- Assuming fully developed flow, [Shehada *et al.* 1993] modelled flow profiles of common carotid artery and femoral artery
- Even assuming Newtonian fluid, pulsatile nature of flow creates non-parabolic profile and even backflow
- Despite same order of magnitude parameters for common carotid and femoral arteries (diameter, viscosity, mean flow, peak flow, Womersley number), substantial difference in velocity profiles is observed

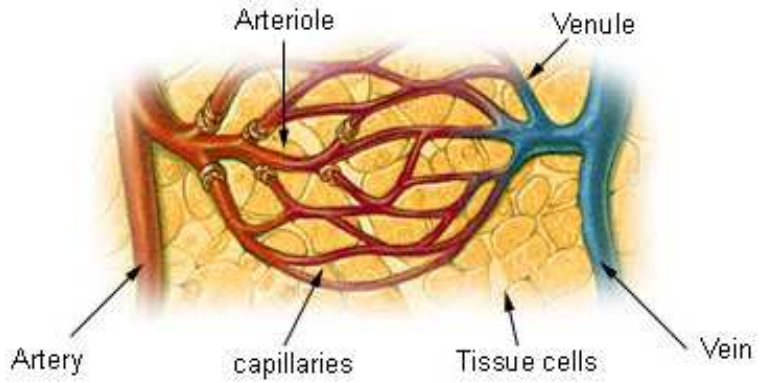


Adapted from [Cobbold 2007, p. 629]

Vascular blood perfusion

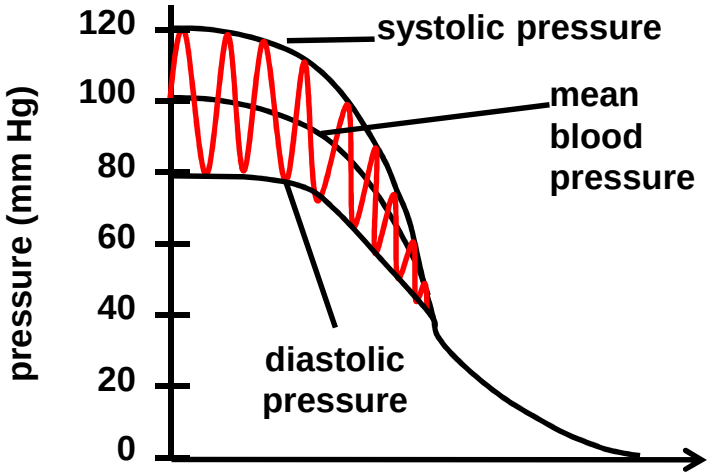
[Uzwiak 2010]

- flow due to pressure gradient
- mass conservation
  - total flow rate constant
  - 90 % of blood returns via veins
  - surface area ↑ velocity ↓
- surface area greatest at capillaries
  - 40-50 cm/s at arteries
  - 0.03 cm/s at capillaries
  - speed again rises towards veins but does not reach arterial blood velociy due to blood loss at capillary bed (collected by lymphatic vessels)



Vessel branching at the capillaries

Public domain: http://commons.wikimedia.org/wiki/File:Illu_capillary.jpg



adapted from [Uzwiak 2010]

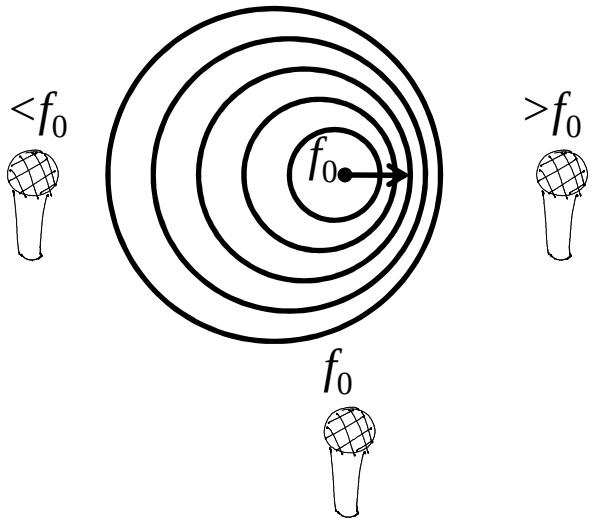
The Doppler effect

- Source approaching stationary observer: observed frequency increases
- Same effect if observer approaching stationary source (relative velocity)

Examples:

- Ambulance siren
- Galaxies (blue-shift/red-shift)
- Running towards water surface waves (perhaps best illustration of effect, since one clearly observes *meeting* crests of waves more often)

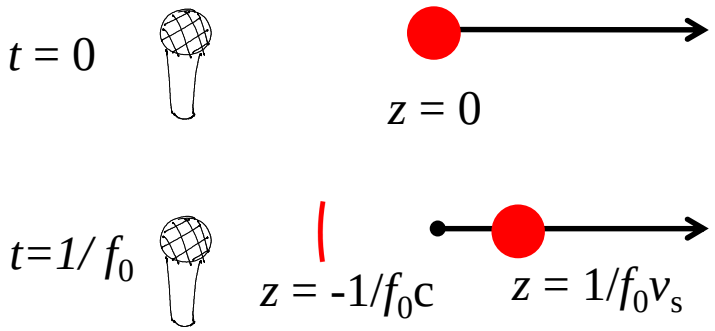
- What scatters in blood?
- Are blood scatterers the running observers or running sources? Both...!



adapted from [Szabo2004, p. 339]

Doppler effect quantified

- Source frequency f_0, velocity v_s away from receiver
- Peak transmitted at $t=0$, $z=0$
- A period later ($t=1/f_0$), another peak transmitted
- By this time
  - (left portion of) $t=0$ emission moved to $z=-1/f_0c$
  - source moved to $z=1/f_0v_s$
  - wavelength between pulses $\lambda = 1/f_0(1/v_s + 1/c) = (v_s + c)/v_scf_0$



$$f = \frac{c}{\lambda} = \left(\frac{c}{c + v_s}\right) f_0$$

Doppler effect quantified

source frequency

wave velocity

received frequency

$$f = \left(\frac{c}{c + v_s}\right) f_0$$

source velocity (away from observer)

$$\frac{c}{c + v_s} = 1 - \frac{v_s}{c + v_s} \approx 1 - \frac{v_s}{c} \quad (v_s \ll c)$$

$$f \approx \left(1 - \frac{v_s}{c}\right) f_0 \quad (v_s \ll c)$$

Doppler frequency $f_D = f - f_0 \approx -\frac{v_s}{c} f_0 \quad (v_s \ll c)$

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The Doppler effect – a moving scatterer

[Szabo 2004, p. 342; Cobbold 2007, pp. 617-618]

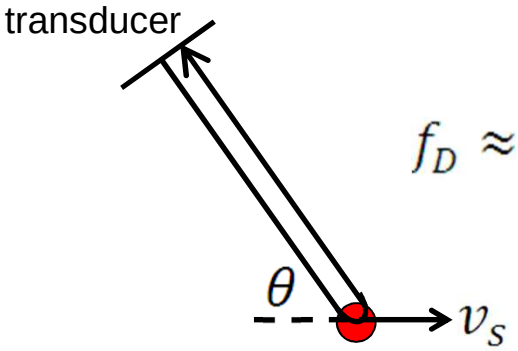
Doppler effect varies with angle

Doppler effect „doubles”

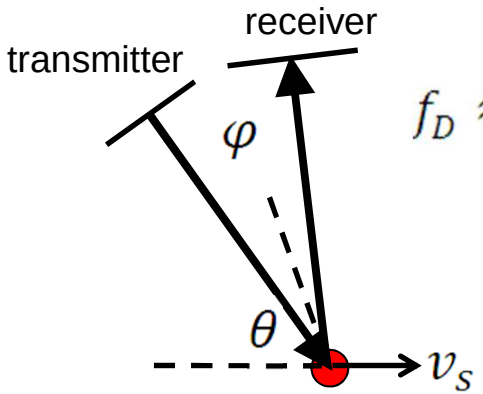
- frequency shift experienced by scatterer
- frequency shift experienced by receiver

Continuous Wave (CW) insonation:

- Array split into two subapertures



$$f_D \approx \left(-2\frac{v_s}{c}\cos\theta\right) f_0$$



$$f_D \approx \left(-2\frac{v_s}{c}\cos\theta\cos\frac{\varphi}{2}\right) f_0$$

Scattering by blood

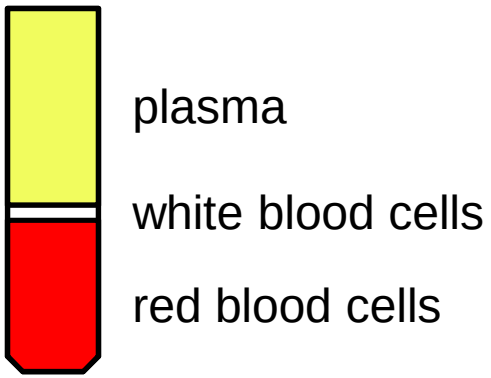
[Burns 2005; http://en.wikipedia.org/wiki/Hematocrit]

- Red blood cells (RBC) form ~38%(♀),48%(♂) of blood volume
- Proportion known as the hematocrit (Hct)
- Scattering dominated by RBC and dependent on Hct and RBC state (eg health, aggregation)
- 7 μm mean diameter

  $\rightarrow p_s \sim a^3 f^2$

(characteristic of sub-λ (Rayleigh) scatterers)

- increasing frequency increases scattering, but
- scattering still relatively weak



Test tube of blood after being placed in a centrifuge. Due to different densities, blood has fractionated into plasma (yellow), white and red blood cells. Red blood cells are the strongest sources of ultrasound scattering in blood.

Doppler velocimetry of blood flow

- continuous wave (CW)
- (single-gate) pulsed wave (PW)
  - Doppler effect? Depends on your definition.
- color flow imaging (CFI)
  - pulsed wave
  - power Doppler

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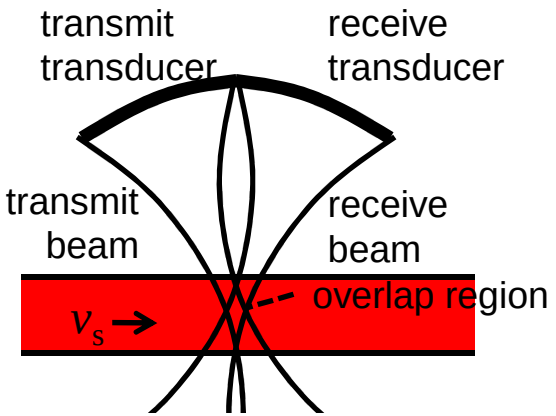
Continuous Wave (CW) Doppler

- Small frequency shifts better detectable over long integration times
- Thus, CW detects Doppler shift sensitively
- However, transducer cannot transmit and receive simultaneously (isolation of high power transmission and high sensitivity receive circuitry)
- Thus separate transducers needed (or else splitting of transducer into subapertures)
- Limited spatial resolution (overlap region of two beams)
- Thus, region of observation often encompasses several vessels



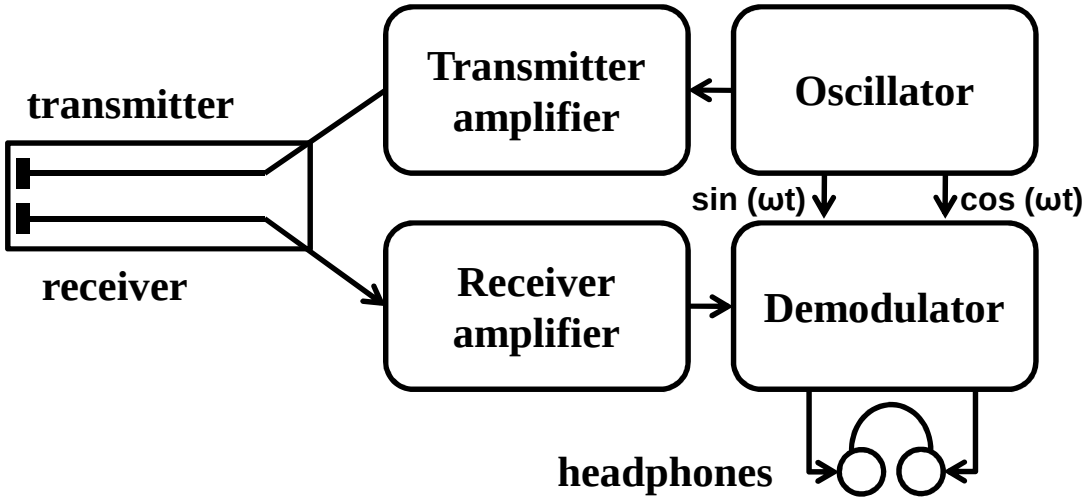
adapted from [Szabo 2004, p. 349]

Continuous Wave (CW) Doppler

- Frequency shift observed clinically (e.g. v_s=0.1 m/s; f_0 = 1 MHz; θ,φ=45º,5º)

$$f_D = -2\times0.1/1540\times\cos45^\circ\times\cos(5^\circ/2) = \mathbf{-92\ Hz}$$

- Demodulated Doppler signal in audio domain!
- Thus, in addition to observing frequency spectrum of return signal, the Doppler shift may be connected to a headphone and a trained doctor can diagnose based on the Doppler shift signal (*cf.* stethoscope)

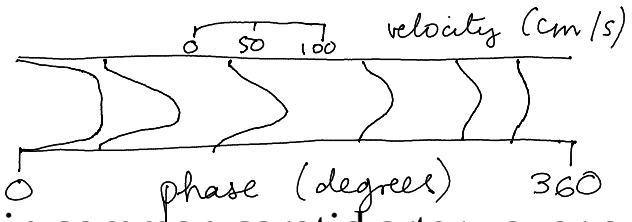


adapted from [Burns 2005]

Continuous Wave (CW) Doppler

What does the doctor hear?

- Mixture of velocities along cross-section of vessel at any one time: distribution of freqeuencies in Doppler shift signal
- Velocity distribution changes over heartbeat cycle: ditto Doppler shift signal
- Backflow causes negative frequency: process demodulated signal so that backflow signal (often a sign of disease, e.g. vessel narrowing [Cobbold 2007, p. 634]) directed to on one ear while forward flow signal directed to other ear
- How to process? Think of Fourier transforms of sine, cosine...



Blood velocity profile in common carotid artery over one heartbeat cycle. Adapted from [Cobbold 2007, p. 629]

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Beyond CW Doppler

- CW Doppler offers high sensitivity
- CW Doppler provides *detailed information*:
  - velocity distribution across vessel (e.g. vessel narrowing will cause combination of forward and backward flow [Cobbold 2007, p. 634])
  - evolution of velocity distribution with time (e.g. heartbeat regularity)
- As a consequence, CW still widely used
- However, in some situations, high spatial resolution is crucial
- One possible solution [Burns 2005, p. 18]: use high transmit frequency.
  - High attenuation → only first vessel is traversed
  - High frequency → higher backscatter from RBC
- Another solution: pulsed transmission
- But how can frequency shift be detected for a pulse (*cf* time-frequency uncertainty)???

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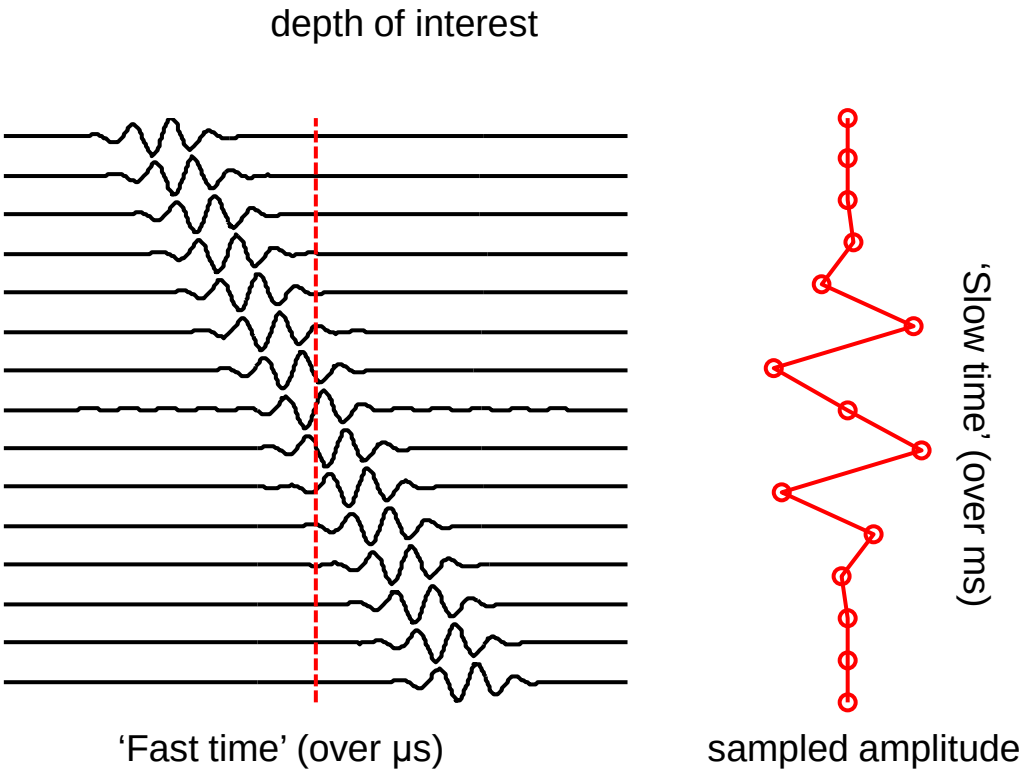
Pulsed Wave (PW) "Doppler"

- Transmit pulses so as to have axial (range) resolution
- Reconstruct Doppler signal from succession of pulses sent at high pulse repetition frequency (PRF) (e.g. 5 kHz)
- Sample A-lines at depth of interest to recover pulse in 'slow-time'
- Central frequency of 'slow-time' pulse returns scatterer speed



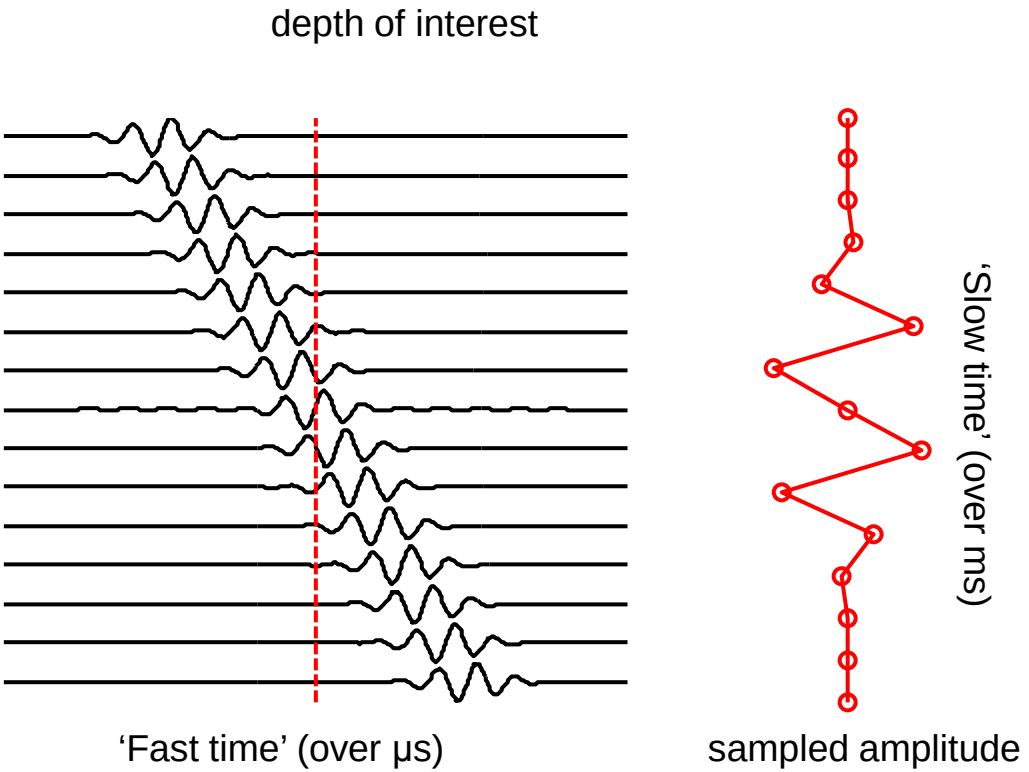
single scatterer moving away from transducer causes increasing delay of echo for each successive A-line
Adapted from [Cobbold 2007, p. 659]

Pulsed Wave (PW) "Doppler"

- PRF determines maximum velocity that can be detected without aliasing (Nyquist sampling) (*exercise*)
- Note similarity of expressions for conventional Doppler shift and PW Doppler shift (*exercise*):

$$f_D \approx \left(-2\frac{v_s}{c}\cos\theta\right) f_0$$

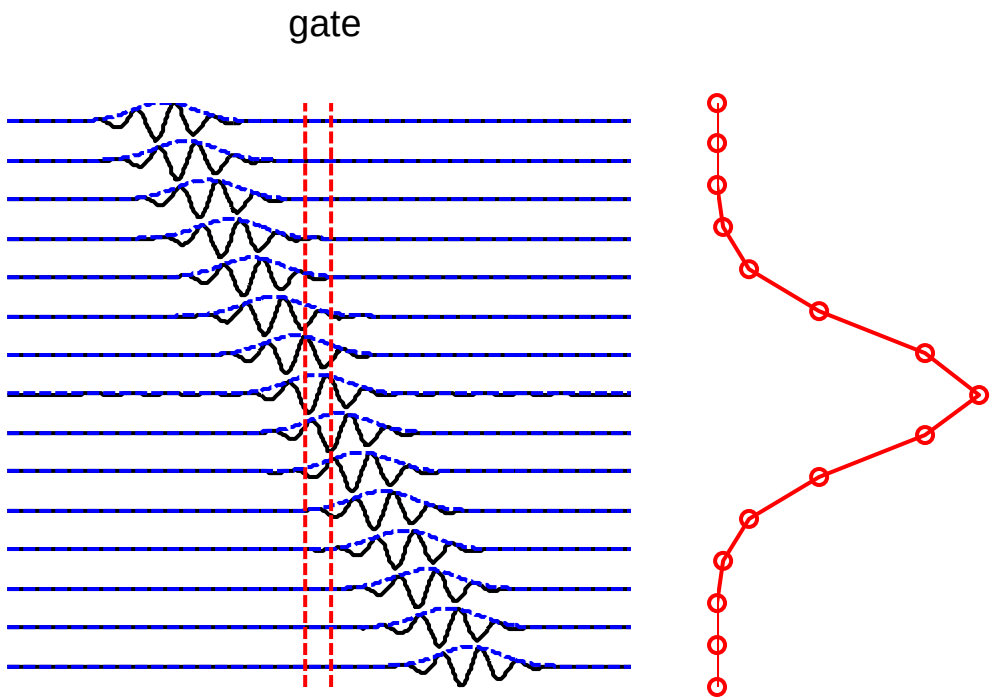
$$f_{PW} \approx \left(-2\frac{v_s}{c}\cos\theta\right) f_c$$



single scatterer moving away from transducer causes increasing delay of echo for each successive A-line
Adapted from [Cobbold 2007, p. 659]

Gated PW

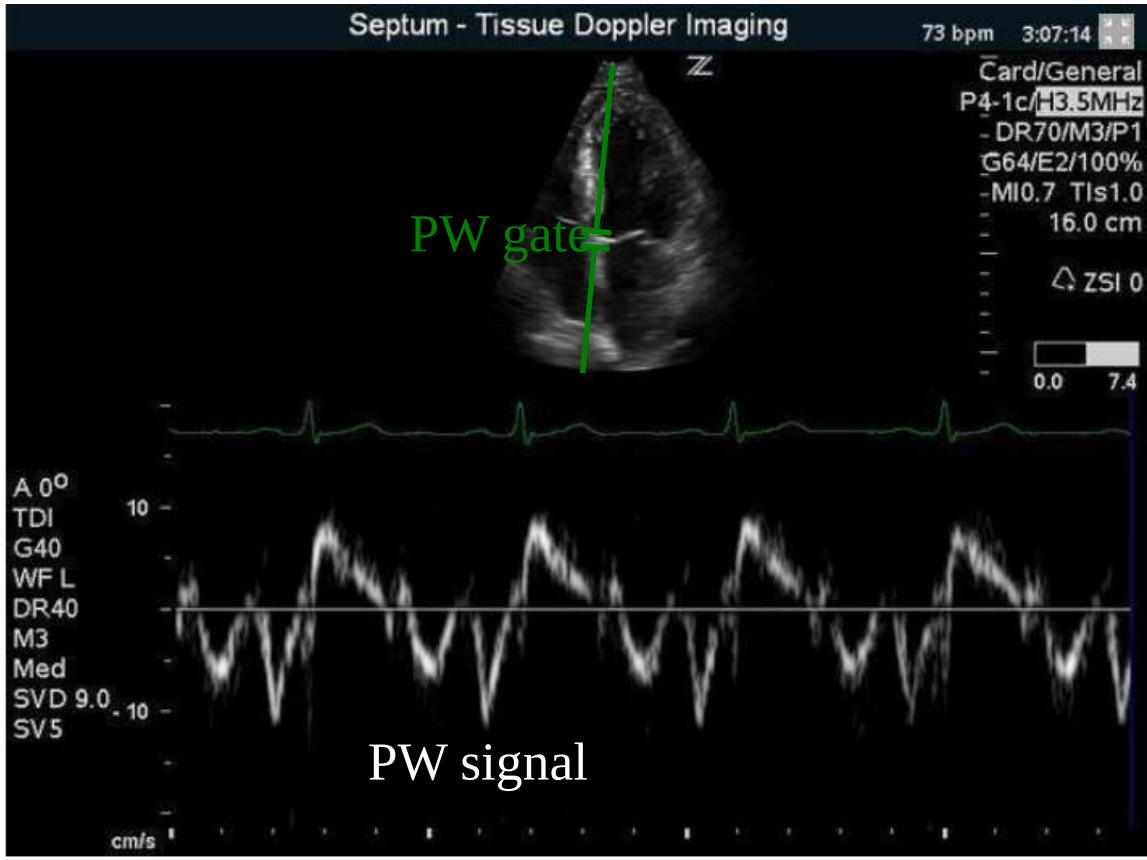
- take envelope of echoes
- integrate over **gated** time corresponding to some range of depths
- multiply by slow-time cosine wave
- resulting reconstructed „Doppler signal” waveform has
  - improved SNR
  - decreased axial resolution



modification of single-location PW in order to increase SNR
the envelope of A-line echoes are summed over a gate around the location of interest
Adapted from [Cobbold 2007, pp. 659,673]

Duplex scanning

- B-mode/single-gated PW
- Use B-mode to find location of interest
- Place PW gate at that location
- Various methods to estimate frequency spectrum
- User can often specify angle of flow to compensate for angular term in Doppler equation



Duplex imaging (B-mode, single-gated PW) with sync. ECG
(N.B.: this is tissue Doppler! See later slide)
Courtesy of Zonare Medical Systems
http://www.zonare.com/products/clinical-images/id_11/

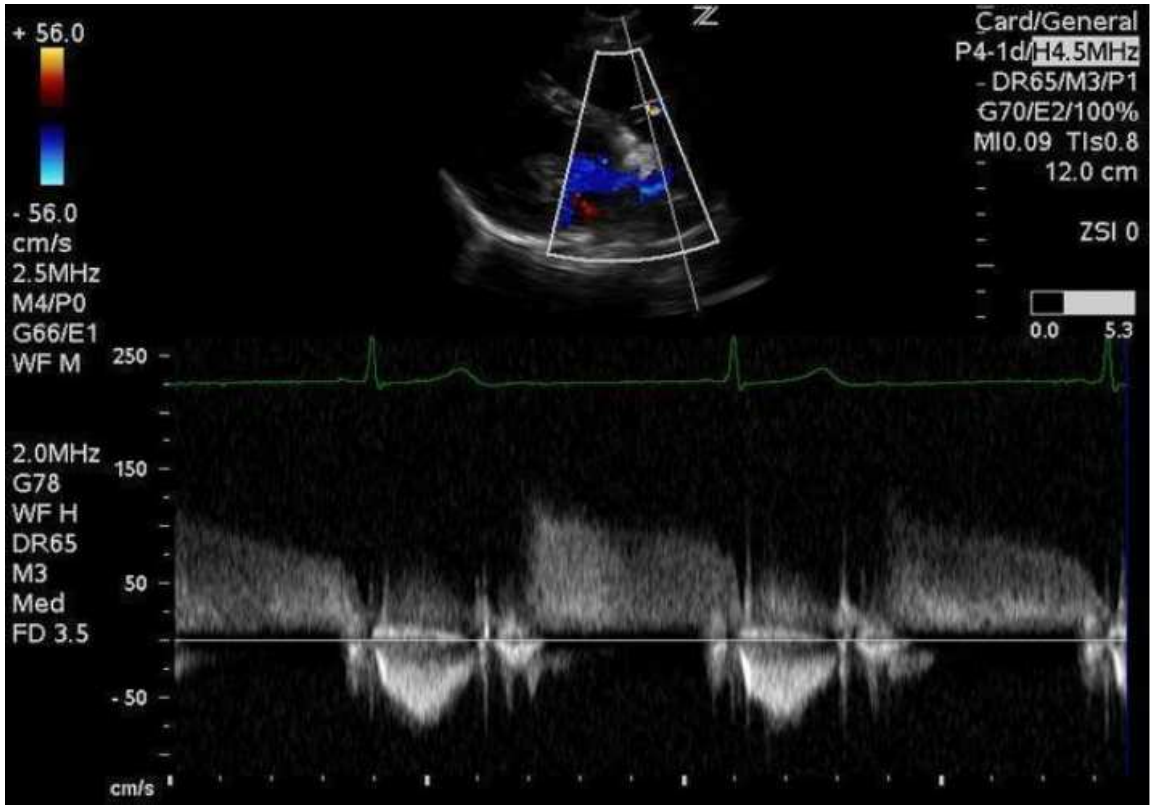
Color flow imaging

Aim: display mean velocity as 2-D map

Mean Doppler shift→mean *v*

Solutions

- generate Doppler signal for many gates, calculate mean *f* shift for each (obsolete)
- generate continuous estimate of mean *f* shift (preferred)



Pulmonic regurgitation
Courtesy of Zonare Medical Systems
http://www.zonare.com/products/clinical-images/id_15/

Color flow imaging – autocorrelation processor

[Burns 2005, p. 23; *Cobbold 2007, pp. 701–706; Wells 1999, p. 29]

Instantaneous frequency given by the derivative of instantaneous phase

Compute changes in phase from one A-line to the next *for each location* to estimate local frequency shift

Example of phase estimation*:

$$\tan^{-1}\left(\frac{Q}{I}\right)$$

quadrature signal

in-phase signal

Vector flow:

Combine color flow images from several angles to yield vector flow of blood

See [Maniatis 1994] for illustration

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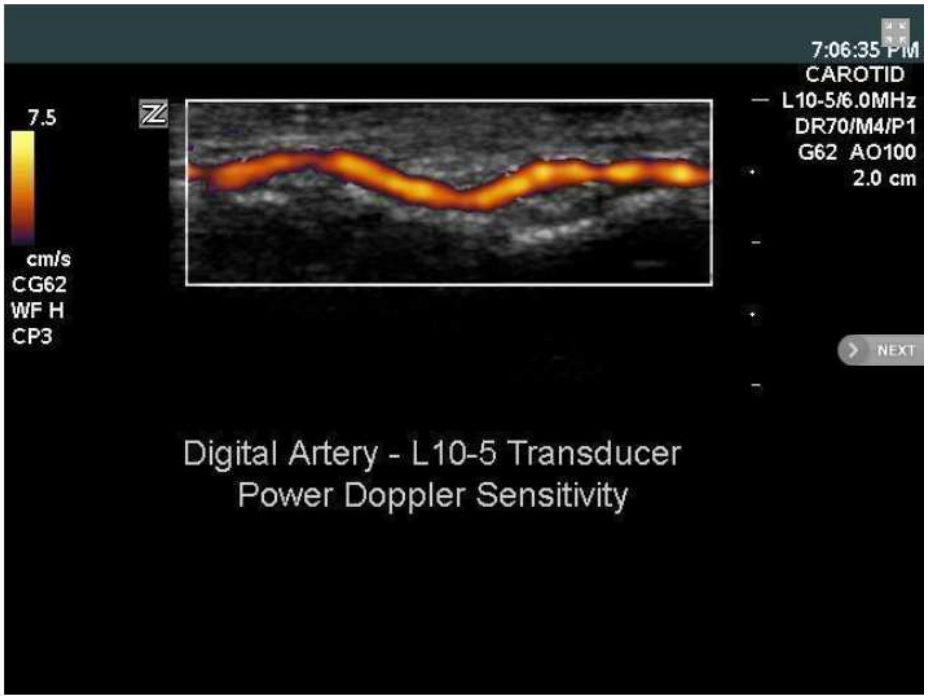
Color flow imaging –

Power Doppler [Rubin 1994]

- Display integrated power of Doppler signal rather than mean frequency shift (i.e. variance of image pixel across subsequent transmissions)
- Not really based on Doppler effect!
- Much greater sensitivity
- Can be used normal to direction of blood flow
- No directional information (or dependence)
- Difficult to obtain quantitative information about velocity



Courtesy of Zonare Medical Systems
http://www.zonare.com/products/clinical-images/id_10/

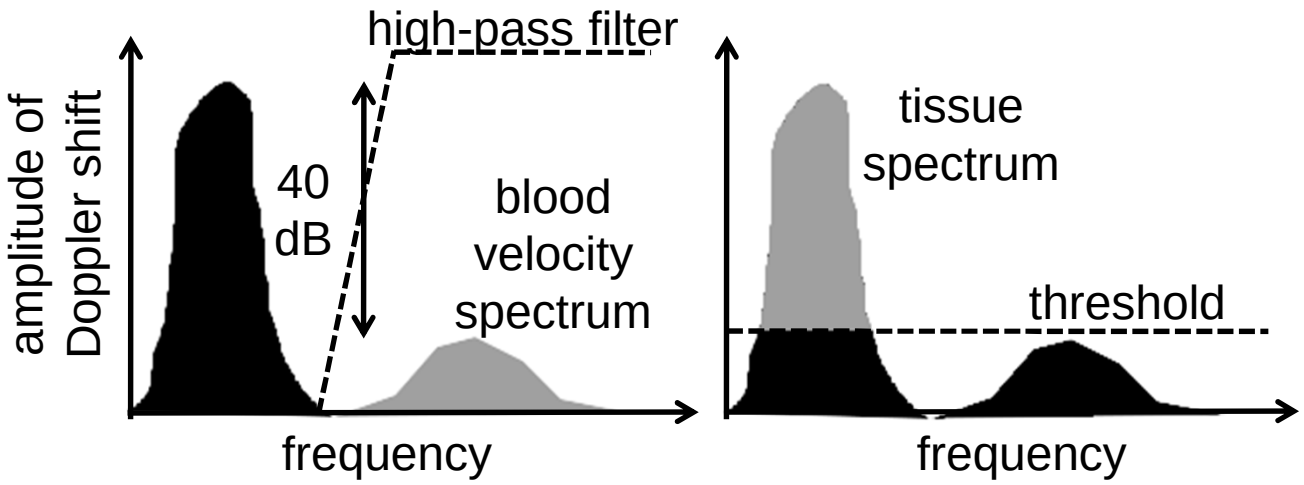
Tissue Doppler [Cobbold 2007, pp. 722-723]

Blood is also tissue! It is a special form of connective tissue.

Solid tissue moves slower (<10 cm/s) than blood

Solid tissue creates stronger echoes

Appropriate filtering can filter out Doppler signal from solid structures



Adapted from [Cobbold 2007, p. 723]

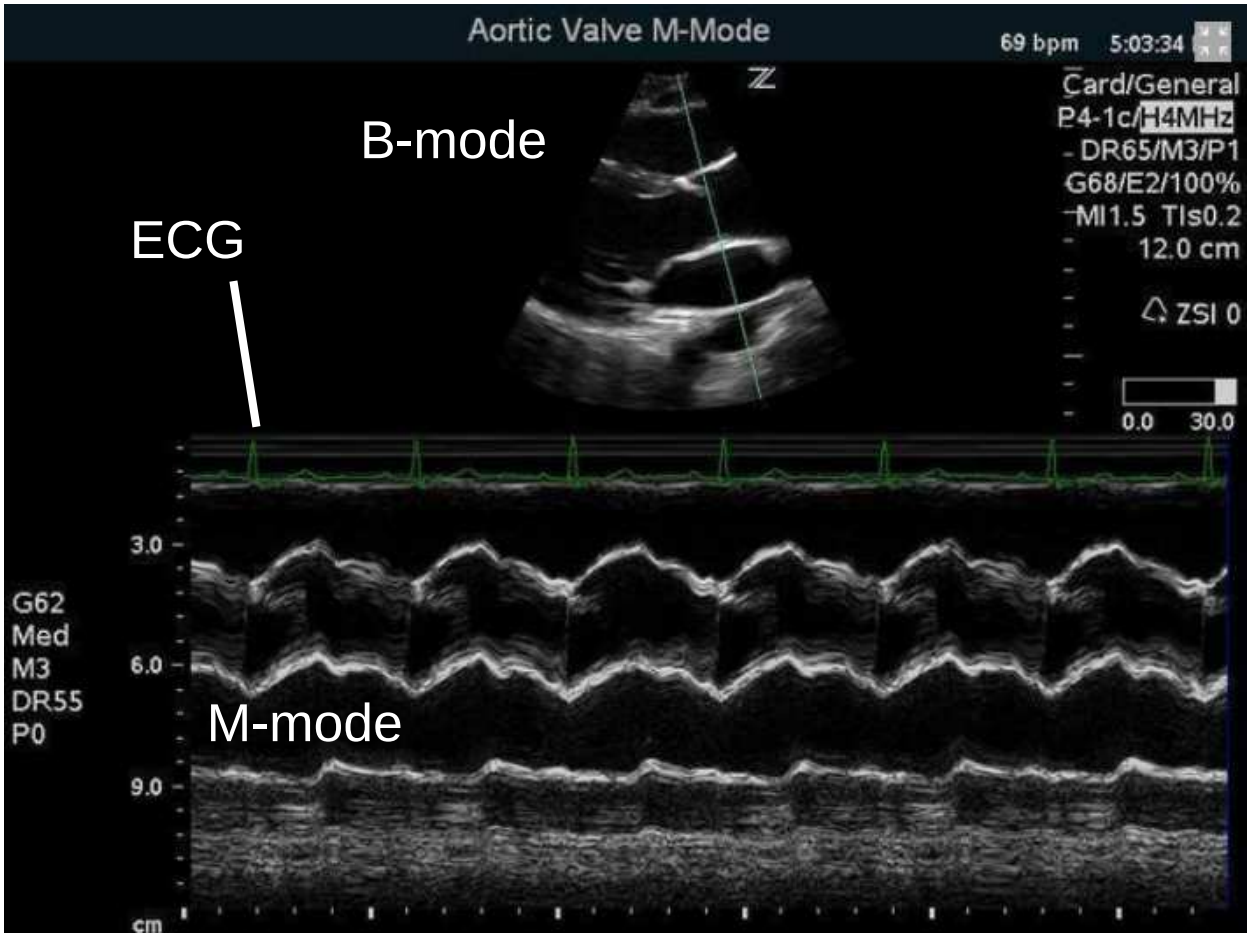
Other ultrasound-based motion analysis methods

- M-mode
- Transit time velocimetry
- B-flow
- Scatterer tracking

M-mode (motion-mode)

[Cobbold 2007, pp. 423–425; Szabo 2004, pp. 303–304]

- Observe single A-line with time
- Motion of organ boundaries clearly visible (e.g. heart wall motion)
- Very simple and effective

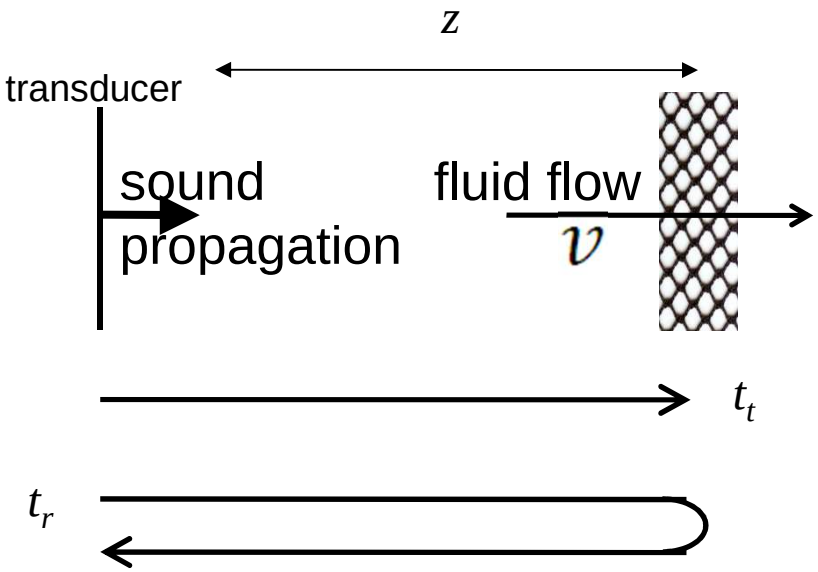


Duplex imaging (B-mode, M-mode) with synchronous ECG
Courtesy of Zonare Medical Systems
http://www.zonare.com/products/clinical-images/id_12/

Transit time velocimetry

The concept

- Arises from the propagating medium
- Effective speed of propagation changed material flow
- Spectral characteristics of signal not affected!
- Measure bulk flow
  - wind speed (anemometry)
  - production control



$$t_t = \frac{z}{c+v}$$

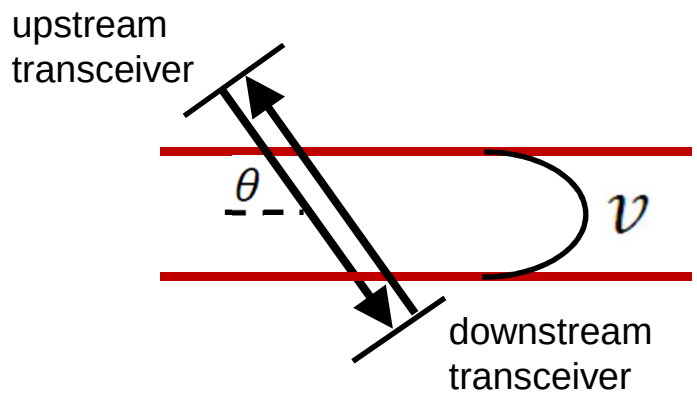
$$\Delta t = \frac{z}{c+v} - \frac{z}{c} = z\left(\frac{c-(c+v)}{(c+v)c}\right) \approx \frac{-zv}{c^2}$$

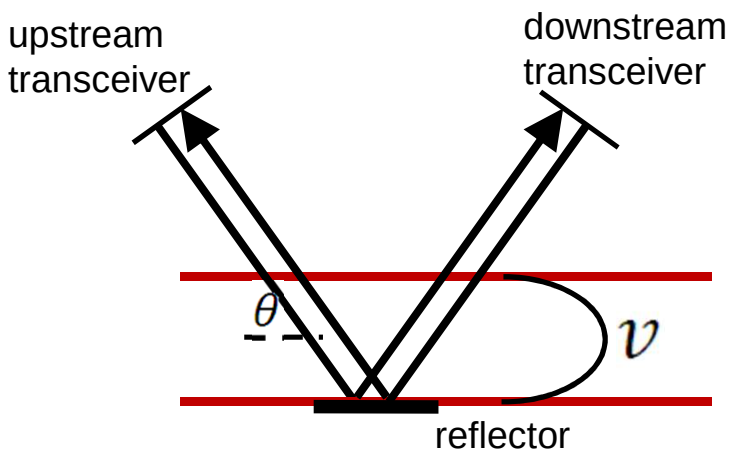
Transit time velocimetry

The application [Cobbold 2007, p. 614]

- Width of vessel not known *a priori*
- Calculate *difference* in arrival times **Δ*t***
- Changing flow profile → *v* needs to be integrated over the propagation path in the vessel

$$\Delta t = \frac{2}{c^2} \int v \cos\theta \, \mathrm{d}l$$





B-flow – motivation

Problem [Cobbold 2007, p. 657]:

- RBC scattering weak
  - 20–60 dB less than surrounding tissue
  - 0–20 dB SNR
- As a consequence, B-mode images do not show RBC well

Aim:

- Modify B-mode to highlight scattering from RBCs
- This would allow visualisation of blood flow

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B-flow – application [Chiao *et al.* 2000]

- Transmit coded pulse sequence
- Compress pulse sequence using matched (cross-correlation) or mismatched filtering (latter suppresses range lobes)
- Range lobes produced by coded excitation (partially) cancelled using two transmissions
- Suppress stationary signals (“tissue equalization”)
- Combination of pulse compression and tissue equalization allows blood to have significant enough signal
- See http://www.gehealthcare.com / usen / ultrasound / genimg / images / bfc_spleen_500.jpg for illustration

Scatterer tracking – 1-D tracking [Hein and O'Brien 1993]

- Comparison of A-lines over several frames
- Pseudo-algorithm:

```
For each segment of each A-line:
    • divide into short (~μs) segments;
    • perform 1-D cross-correlation on corresponding
      segment of previous A-line
    • peak of cross-correlation corresponds to maximum-
      likelihood estimate of scatterer displacement
```

- In practice, source of tracked signal is often speckle
- Although speckle is an interference effect from several scatterers
  - short durations: scatterers move together, speckle unchanged, tracking successful
  - longer durations: speckle decorrelation occurs

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Scatterer tracking – optical flow

- Extend tracking to 2-D cross-correlation to yield maps of optical flow
- Similarly to segmentation-registration of multiple modalities, combination of scatterer tracking and boundary segmentation mutually beneficial for both tasks [Hillier 2010]

Optical flow image of a heart
arrows indicate direction of motion
[Hamou and Sakka 2009]

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