(Ultrasound) Imaging

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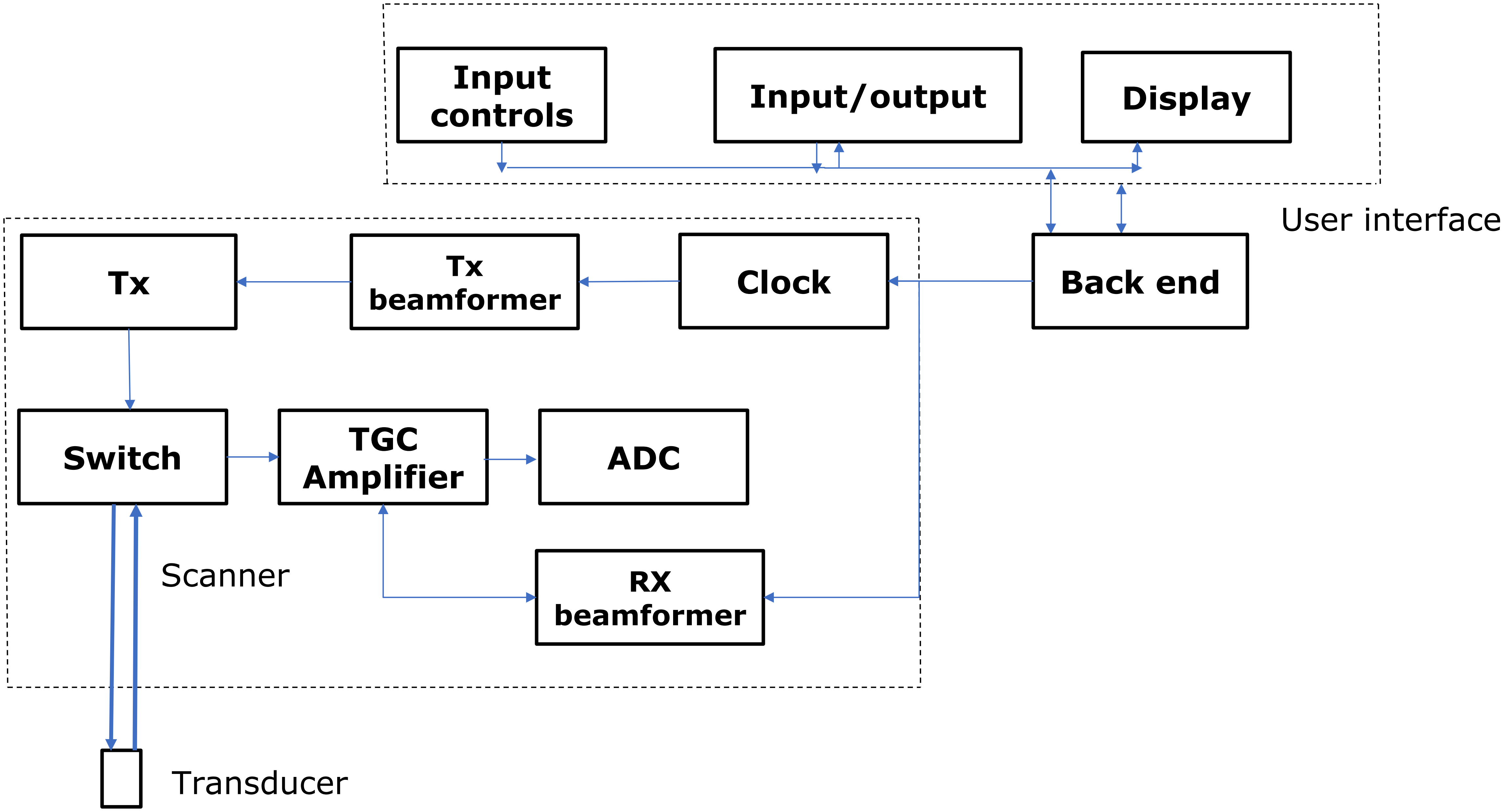
Ultrasonography

- Visualize internal body structures by different modes

❑ **Imaging modes with ultrasound:**

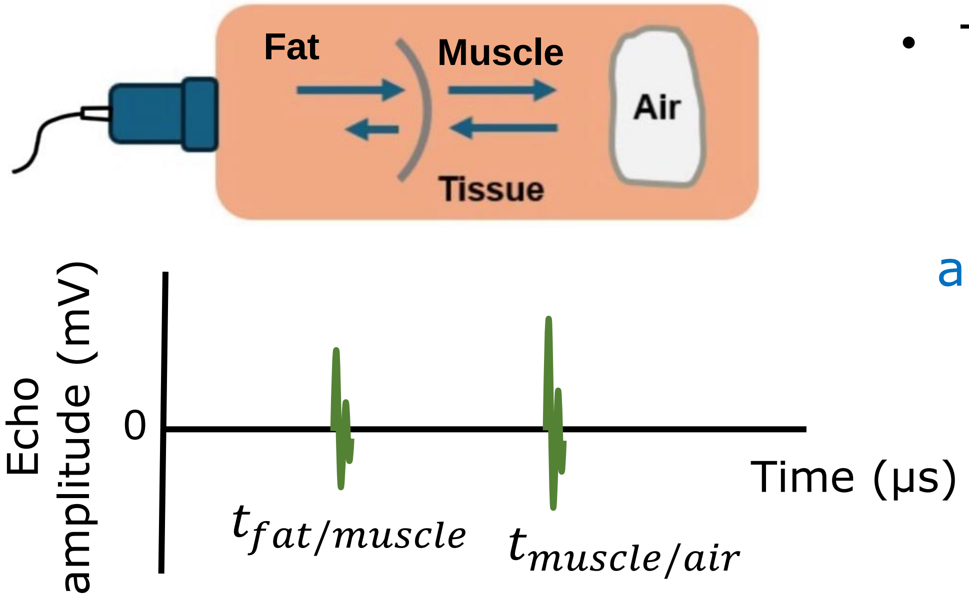
- A-mode (Amplitude mode)
- B-mode (Brightness mode)
- M-mode (Motion mode)
- Doppler mode
  i. Continuous wave
  ii. Pulsed wave
  iii. Color
  iv. Power

Ultrasound imaging system schematic



A-mode (Amplitude mode)

- Based on pulse-echo principle
- Shows instantaneous echo signal amplitude vs. time after transmission of ultrasound pulse



- The range equation:

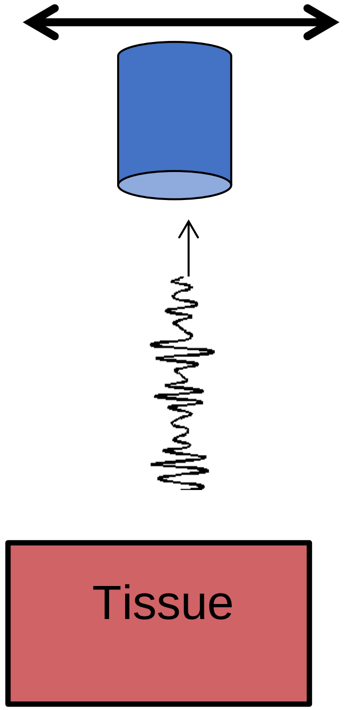
$$t = \frac{2 \times d}{c}$$

arrival time (t); distance from transducer to interface (d); speed of sound (c)

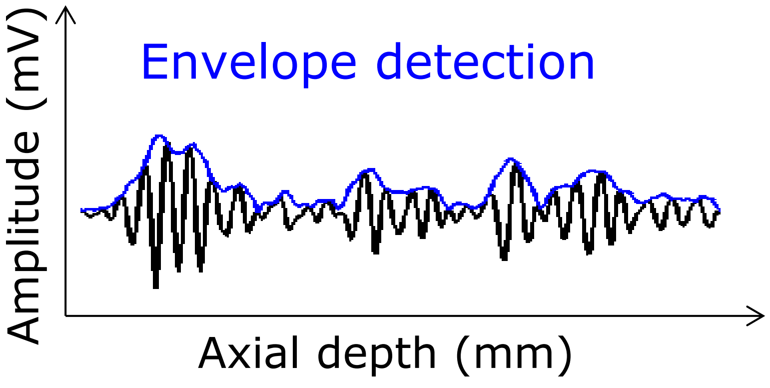
- Only displays echo data from a single beam line
- Used in ophthalmic ultrasound – to get dimensions of eye

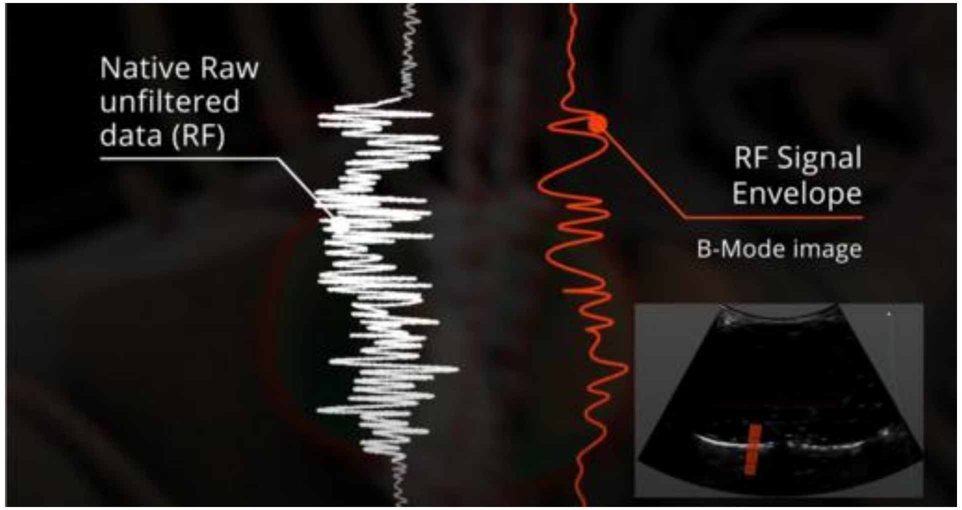
B-mode (Brightness mode)

Transducer
(Single-element or array of elements)



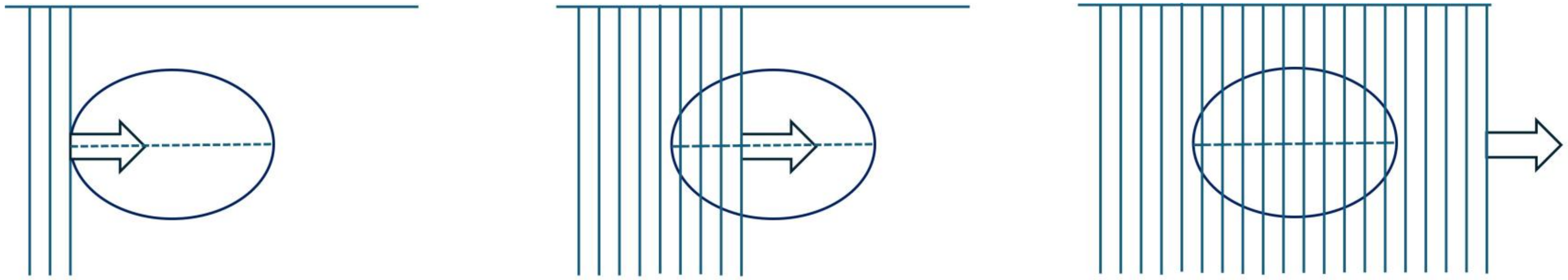
Backscattered A-mode signal



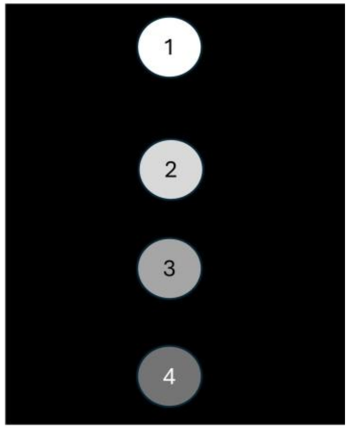


B-mode ultrasound

- Gives two-dimensional information about tissue cross section



An 2D B-mode image is formed line-by-line as the beam moves along the transducer array.



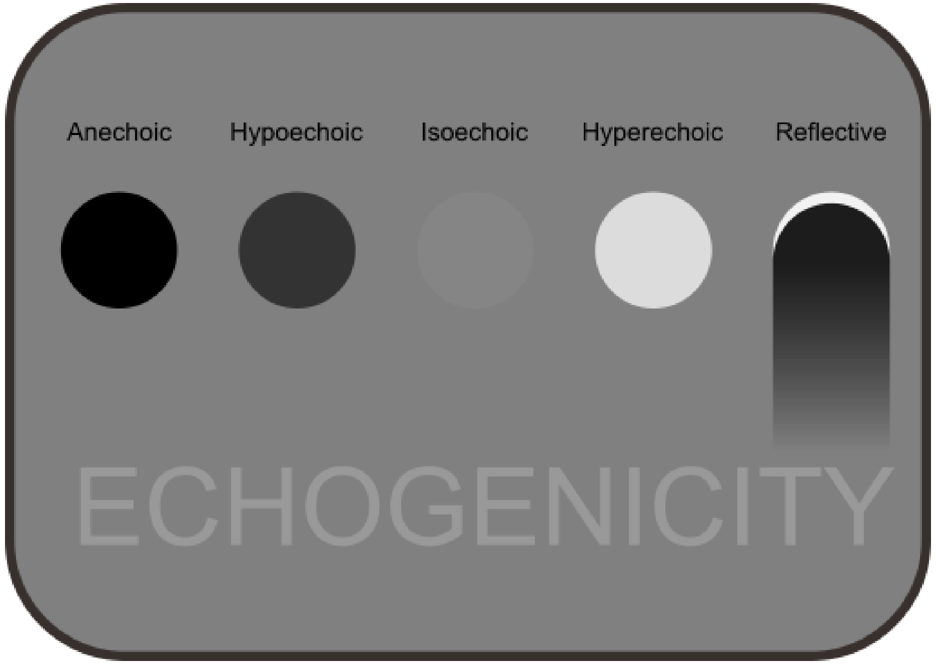
B-mode

Display

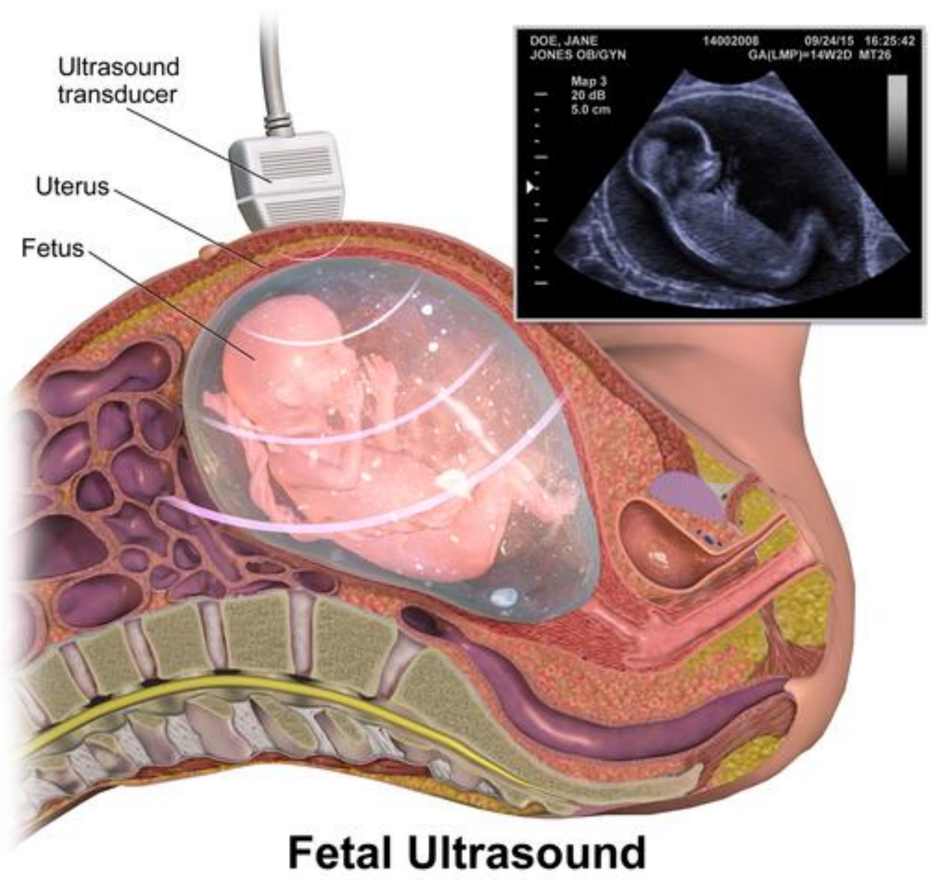
- Brightening of spot represents received amplitude
- Vertical deflection represents reflector distance

B-mode echogenicity

- **Anechoic** structures appear black, meaning no internal echoes
- **Hypoechoic** structures appear darker than the structures around them
- **Isoechoic** structures exhibit the same brightness (echogenicity) as the surrounding structures
- **Hyperechoic** structures are more echogenic (brighter) than surrounding structures



B-mode ultrasound examples

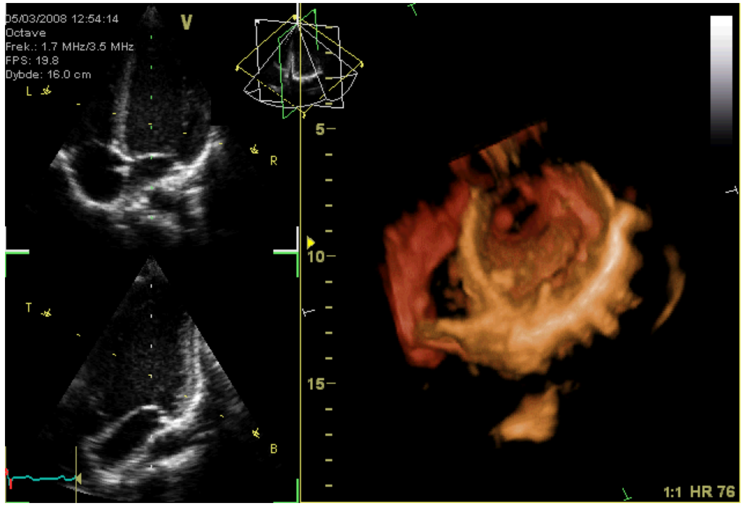


Echocardiography (Ultrasound of the heart)

Renal cyst

1D, 2D, 3D and 4D ultrasound

- A-Mode- 1D
- B-Mode – 2D
- B-mode with matrix array transducer or mechanically scanned linear/phased array transducer – 3D
- 3D imaging with real time processing for “Live” imaging – 4D



Doppler effect

- Occurs when relative motion exists between wave source and wave receiver

Lower frequency

Higher frequency

Christian Andreas Doppler
1803-1853

- Doppler ultrasound based on shift of frequency in an ultrasound wave caused by a moving reflector

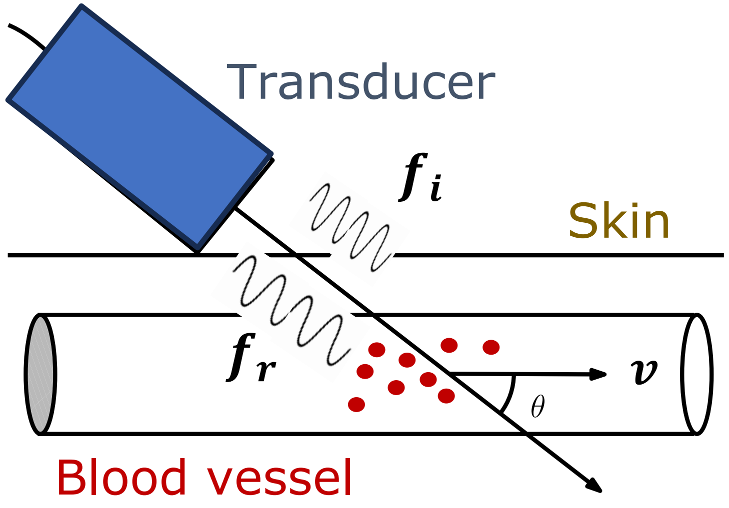
- Used to measure velocities of moving tissues
  - Blood flow

Doppler shift

- Doppler frequency shift, $\boldsymbol{f_D}$

$$\boldsymbol{f_D} = \frac{2 \times \boldsymbol{v} \times \boldsymbol{cos(\theta)}}{\boldsymbol{c}} \times \boldsymbol{f_i}$$

$\boldsymbol{v}$: blood flow velocity
$\boldsymbol{c}$: speed of sound
$\boldsymbol{\theta}$: angle between direction of blood flow and ultrasound beam (Doppler angle)
$\boldsymbol{f_i}$: frequency of sound incident on reflector

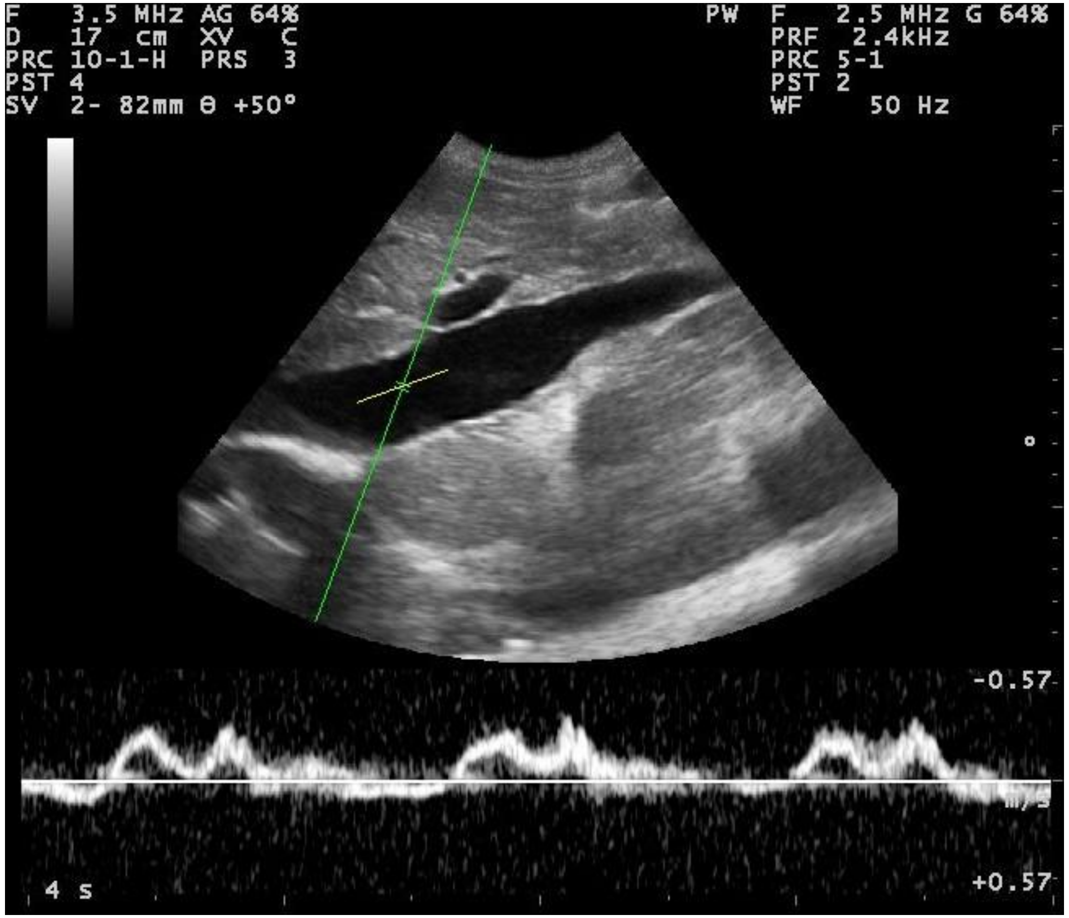


- Blood velocity can be calculated by rearranging equation:

$$\boldsymbol{v} = \frac{\boldsymbol{f_D} \times \boldsymbol{c}}{2 \times \boldsymbol{f_i} \times \boldsymbol{cos(\theta)}}$$

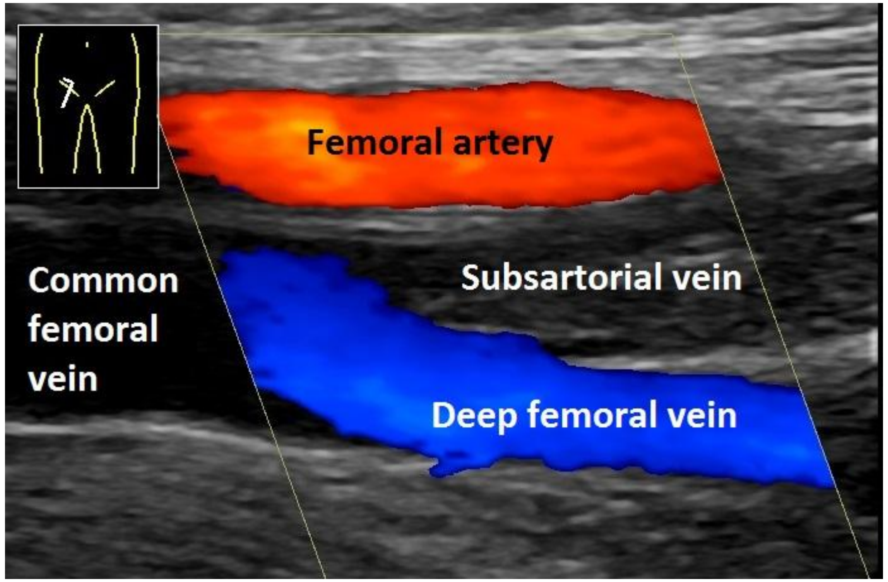
Doppler ultrasound example

Doppler ultrasound image of inferior vena cava

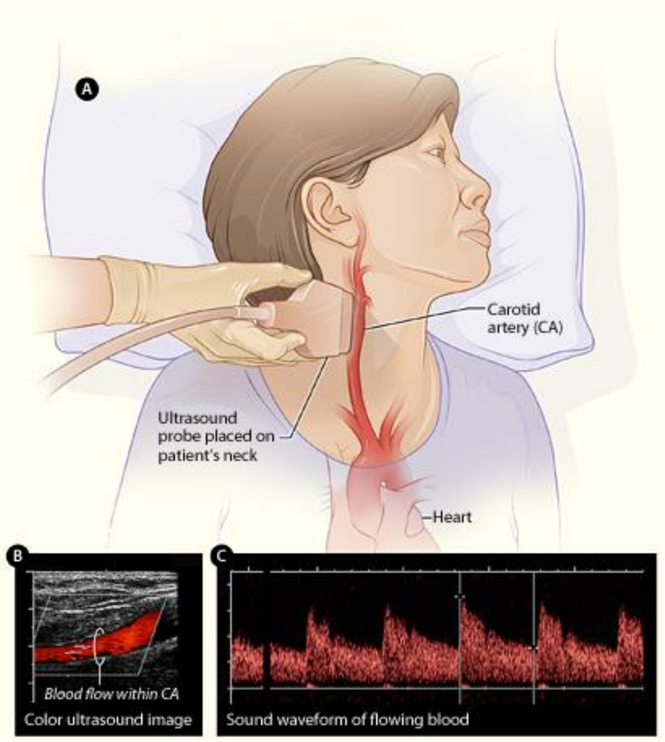


Color Doppler

- 2D Doppler image of blood flow
- Towards the transducer → RED
- Away from the transducer → BLUE
- Red and blue display provides → direction and velocity of flow



Mikael Häggström, M.D. Author info - Reusing images- Conflicts of interest: NoneMikael Häggström, M.D.Consent note: Written informed consent was obtained from the individual, including online publication., CC0, via Wikimedia Commons



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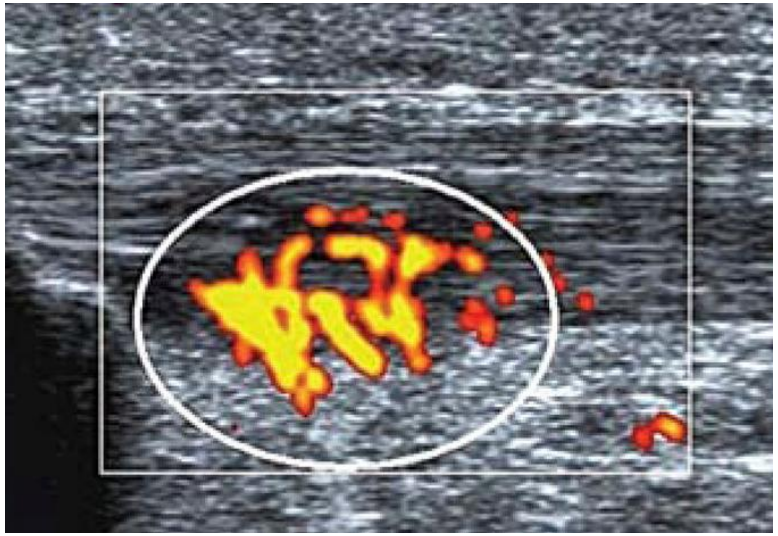
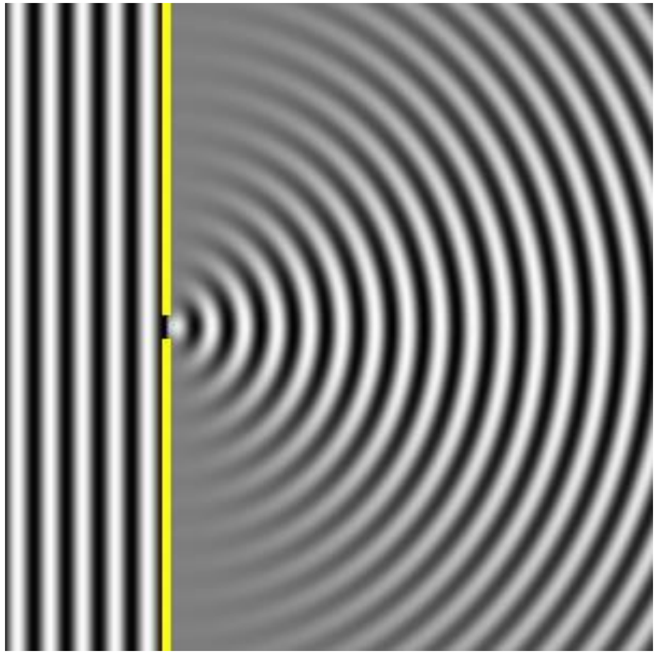
Power Doppler

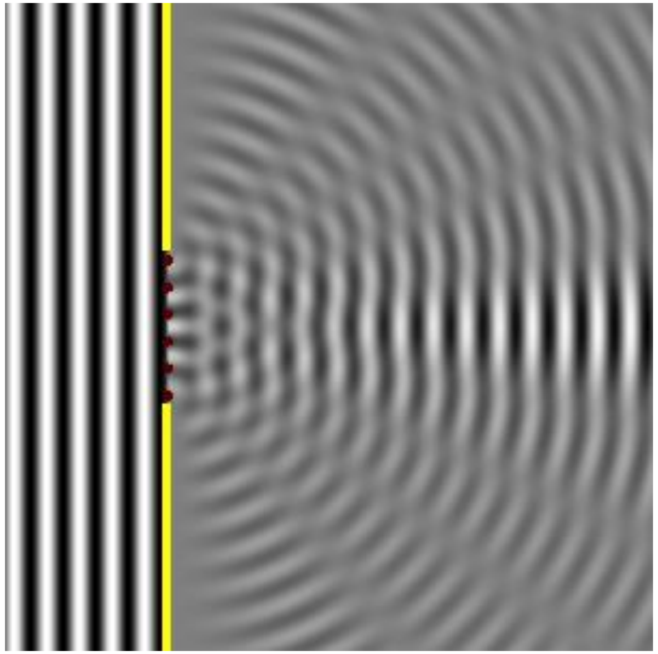
- More sensitive to flow than color Doppler
- Color-coded image of blood flow based on intensity rather than direction
- Useful tool for examining low velocity blood flow



Ultrasound image of vascular flow showing marked neovascularity within the abnormal tendon

Fields from array transducers: Huygen’s principle





Planar scalar wave diffraction – single and extended slit

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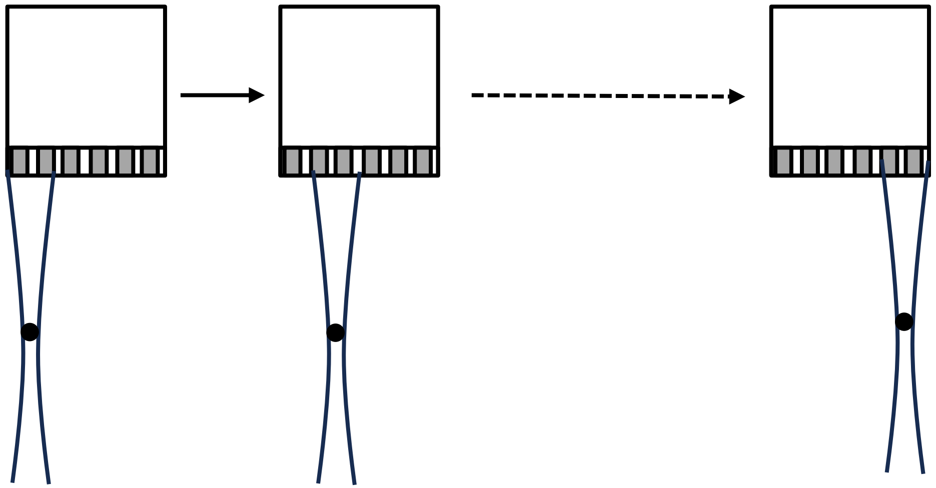
Linear array imaging

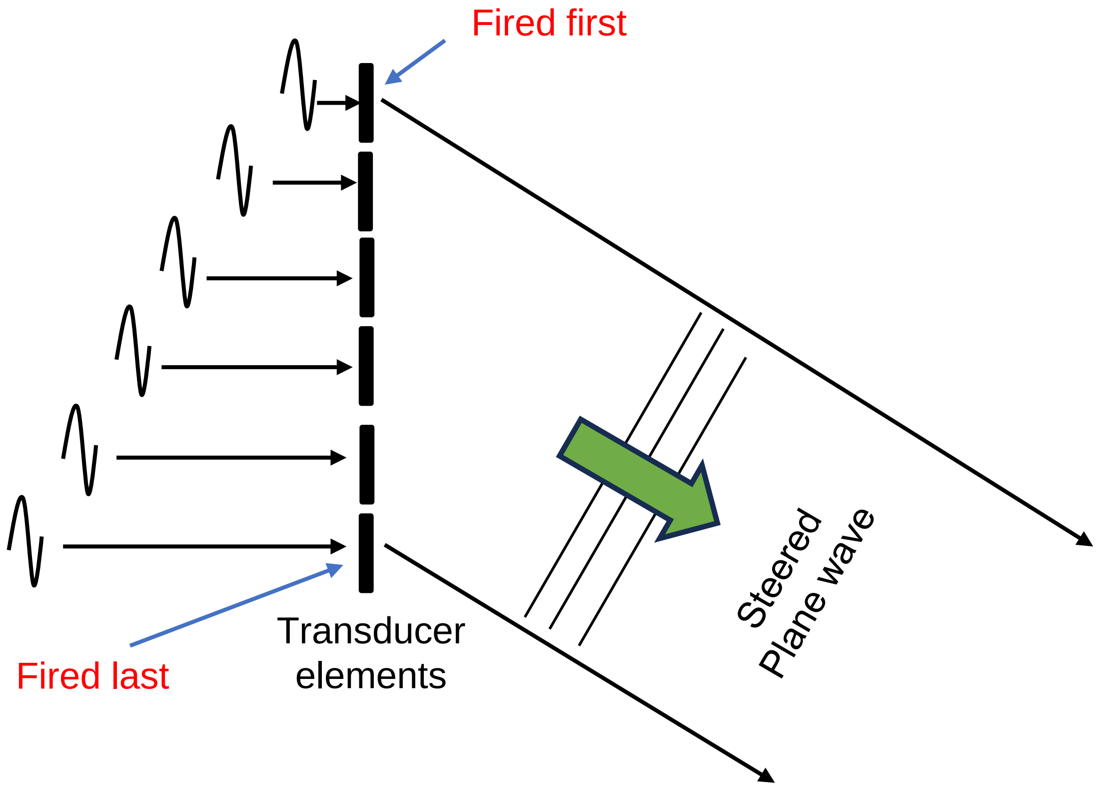
- In linear array imaging, a few elements are grouped and fired to get an A-line
- Delays can be used to create a focused beam and, therefore, improve lateral resolution
- A 128-element linear array transducer can be fired by grouping 32 elements (1st element to 32nd element, 2nd element to 33rd element, 3rd element to 34th element, and so on).



Number of A lines to make an image=number of elements-number of grouped elements+1

Phased arrays

- In phased array transducers, the phase of individual elements can be electronically controlled to get desired directionality to the ultrasound beam
- Beam steering can be used to get a larger beam area compared to linear arrays

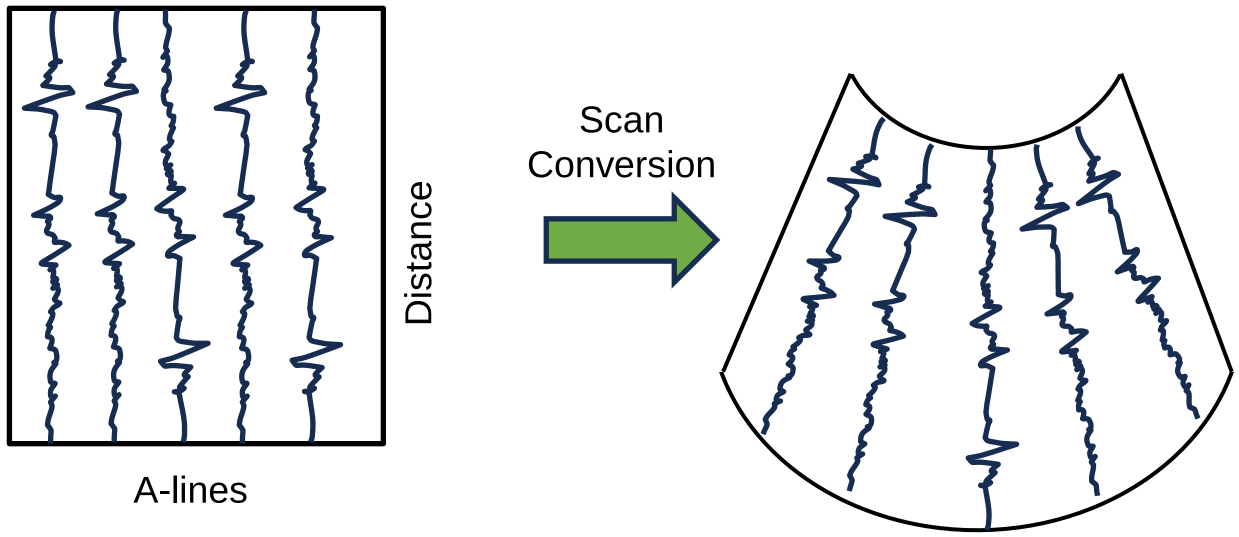


Sector (curvilinear) arrays

- In sector arrays, the elements are arranged on a curve, enabling a wider area of imaging
- The beam pattern is in the shape of a sector, and not rectangular

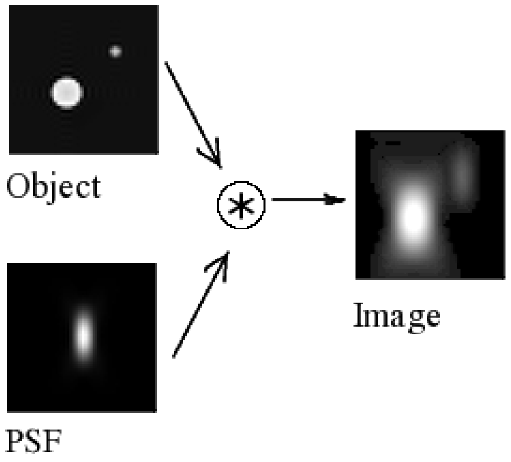
Scan Conversion

- The data acquired is stored as a 2D matrix, which is converted to polar coordinates during reconstruction



Spatial resolution

- Ability to differentiate structures located close by in space
- Point spread function is analyzed to determine the image quality of an imaging system
- Anisotropic for ultrasound, determined by transducer aperture, element directivity, apodization, pitch, imaging position, steering angle



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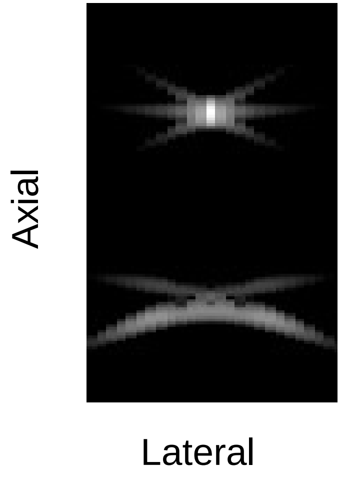
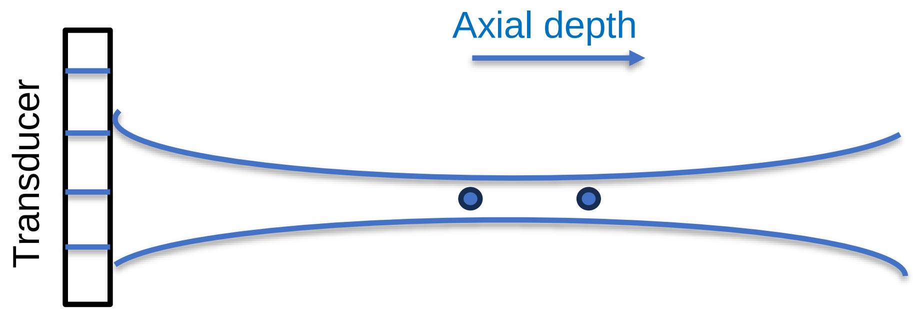
Ultrasound image of a phantom with wire targets



Spatial resolution – Axial

- A measure of how close two reflectors can be to one another along the axis of an ultrasound beam and still be resolved as separate reflectors
- Depends on pulse length
- Short pulse excitation
- Impulse excitation
- Transducer should be adequately damped
- Modulated sine burst generated because of transducer



Number of cycles in pulse

Pulse length

$$r_A = \frac{\lambda N}{2} = \frac{c \times \Delta T}{2}$$

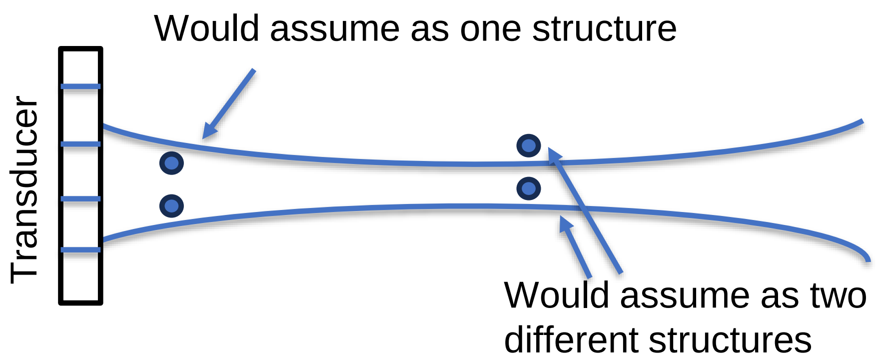
Lateral resolution

- Ability to differentiate two structures located apart laterally
- Lateral resolution:

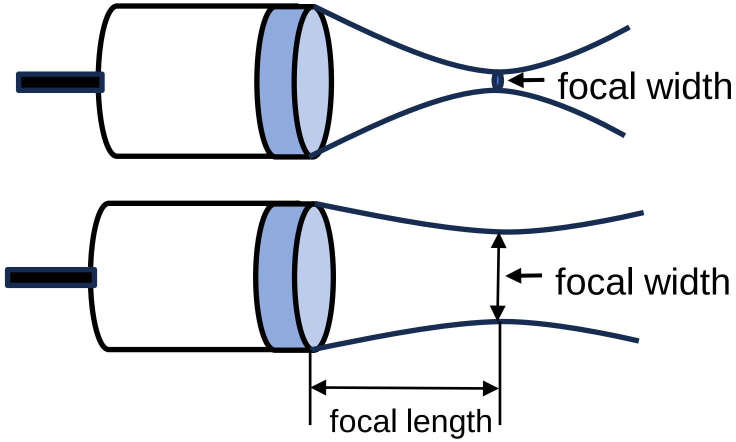
$$r_L = \frac{\lambda z}{D}$$

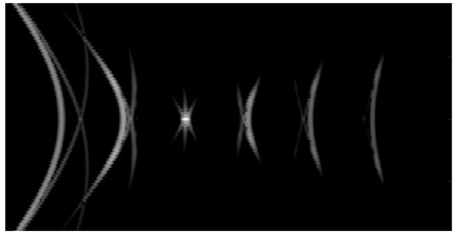
Axial distance (z)

Transducer diameter (D)



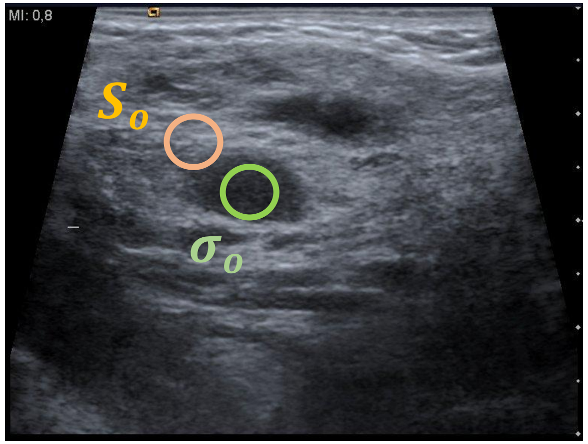
- Depends on beamwidth at imaging location
- Best lateral resolution is obtained at the focus





Signal-to-noise ratio

$$SNR = \frac{S_o}{\sigma_o}$$

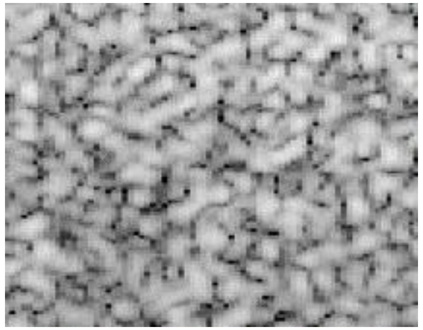


- Noise caused by thermal motion of electrons
- Use of highly sensitive crystals, and proper shielding improves SNR
- Use low noise electronics (preamplifier)
- Higher transmit energy within safety limits

Improving signal-to-noise ratio

- Digitization with high number of bits
- Spatial filtering (beamforming)
- Spatial/temporal averaging (compounding)
- Postprocessing for noise reduction
- Speckle reduction algorithms

Ultrasonic speckle



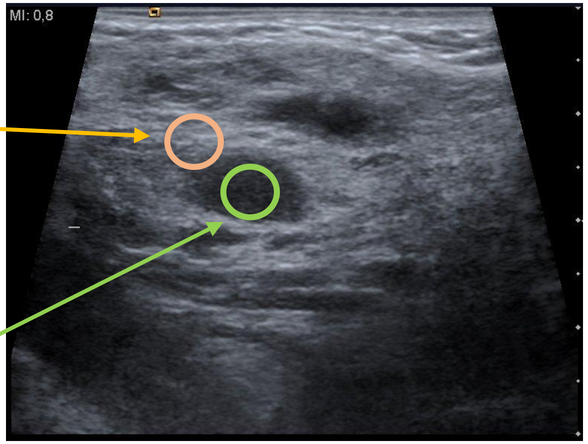
Contrast resolution

- Ability to differentiate two scatterers that differ in intensity

$$Contrast = 20log_{10}\left(\frac{S_r}{S_b}\right)$$

Echo signal amplitude of region of interest

Echo signal amplitude of background



- Contrast-to-noise ratio

$$CNR = \frac{|S_r - S_b|}{\sqrt{\sigma_r^2 + \sigma_b^2}}$$

Standard deviations of signal amplitudes

Contrast resolution

- Spatial (lateral) resolution depends on main lobe width
- Contrast resolution depends on the side lobe level

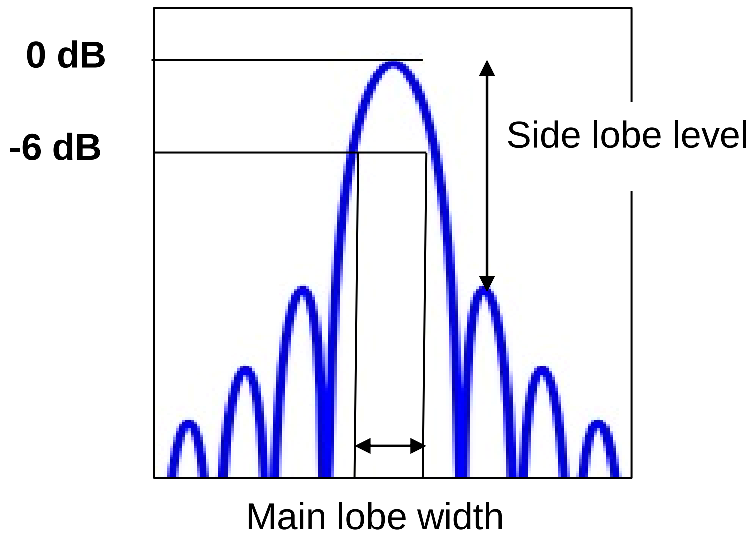
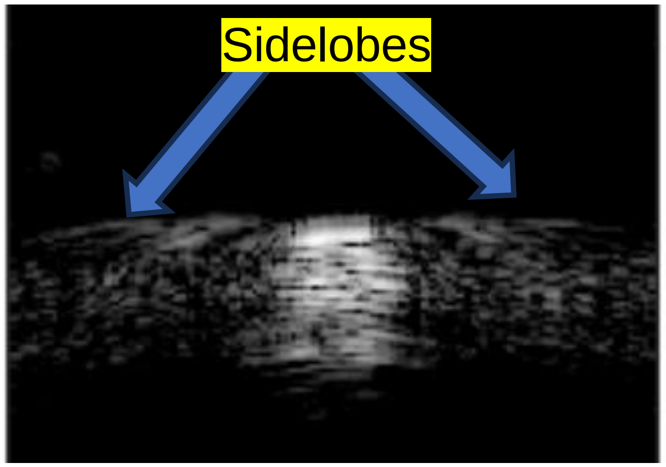


Image of a bubble cloud in a phantom showing side lobes



Contrast resolution

- Compression of dynamic range improves contrast by highlighting weaker scatterers
- Presence of speckle degrades contrast
- Higher dynamic range of systems improves contrast
- Ultrasound contrast agents used to improve contrast from vascular organs

Frame rate

- Pulse Repetition Period (PRP): Time duration between two consecutive pulses applied to the transducer.
- PRP depends on the maximum depth of imaging required.
- Pulse Repetition Frequency (PRF)=1/PRP

$$Time\ to\ obtain\ one\ image = number\ of\ A\ lines * PRP$$

$$Frame\ Rate = \frac{1}{Time\ to\ obtain\ one\ image}$$

- A higher frame rate improves temporal resolution

Summary

- Different modes of ultrasound
- 1D, 2D, 3D, and 4D Ultrasound
- Echogenicity in ultrasound images
- Doppler effect and its modes in ultrasound
- Transducer arrays
- Image quality – resolution – spatial and temporal, signal to noise ratio, contrast
- Thanks for patiently hearing about sound that we cannot hear!