ULTRASOUND IMAGING

EE 472 – F2018

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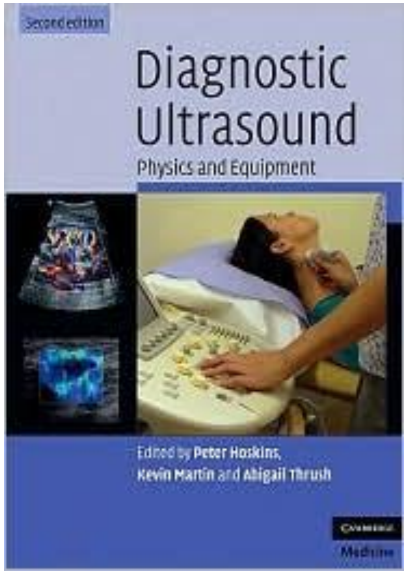
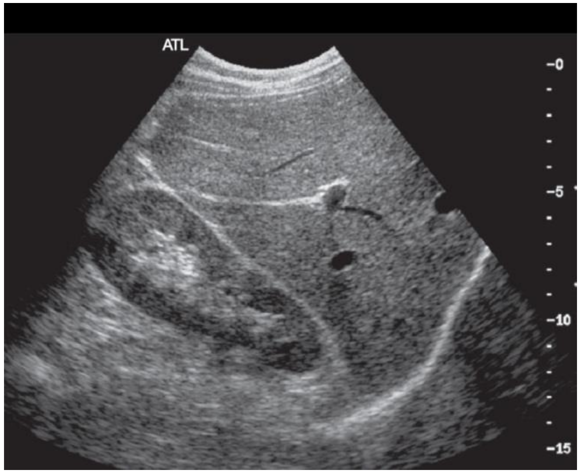
Recommended Textbook

- *Diagnostic Ultrasound: Physics and Equipment*, 2nd ed., by Peter R. Hoskins (Editor), Kevin Martin (Editor), Abigail Thrush (Editor) Cambridge University Press, 2010.



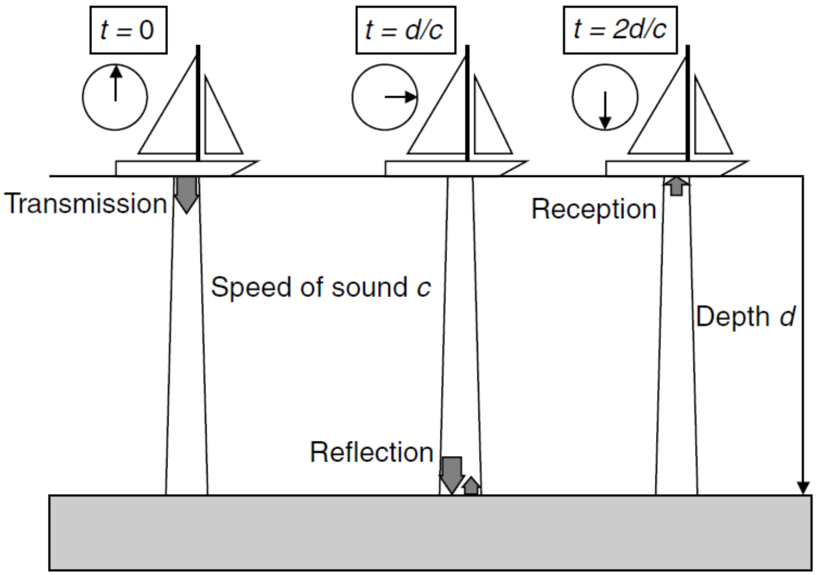
Introduction to B-mode imaging

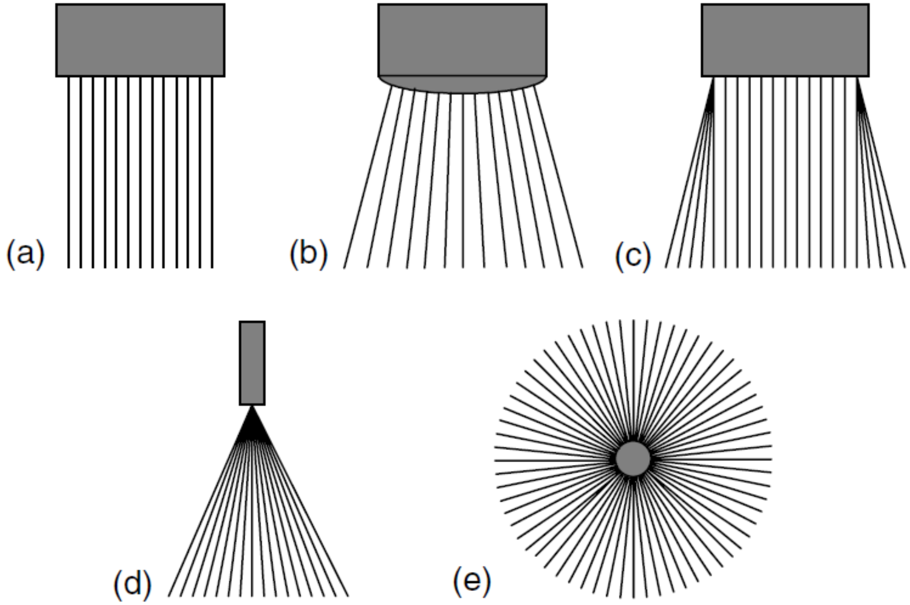
- B-mode image is an anatomic cross-sectional image
- Constructed from echoes (reflection and scattering) of waves
- Echo is displayed at a point in image, which corresponds to relative position of its origin within the body cross section
- Brightness of image at each point is related to strength of echo
  - Term B-mode stands for Brightness-mode



Echo Ranging

- To display each echo in a position corresponding to that of the interface or feature (known as a target) that caused it, the B-mode system needs two pieces of information:
  - (1) Range (distance) of the target from the transducer
  - (2) Position and orientation of the ultrasound beam



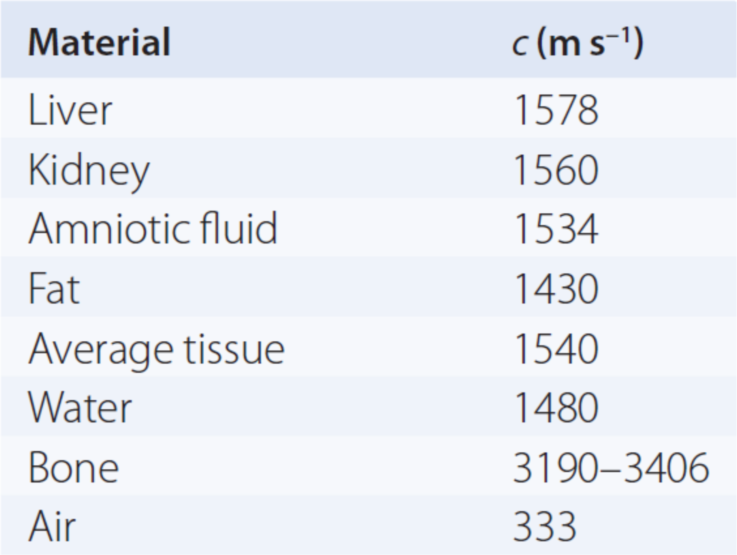


Ultrasound Physics

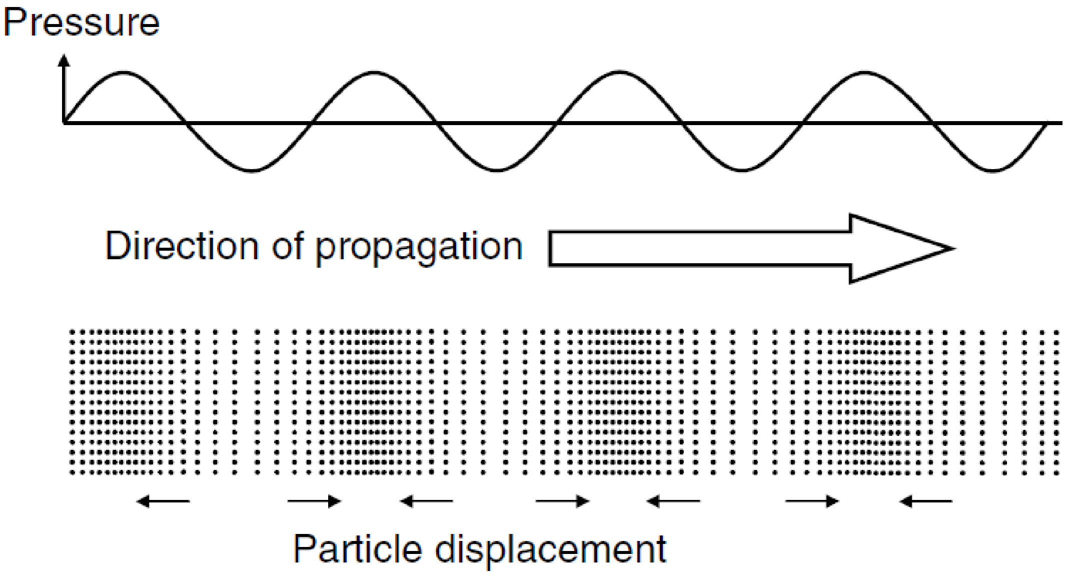
- Sound waves used to form medical images are longitudinal waves, which propagate (travel) only through a physical medium (usually tissue or liquid)
  - Characterized by frequency, wavelength, speed and phase

$$\boxed{c = f\lambda}$$

$$\boxed{\text{Speed of sound } c = \sqrt{k/\rho}}$$

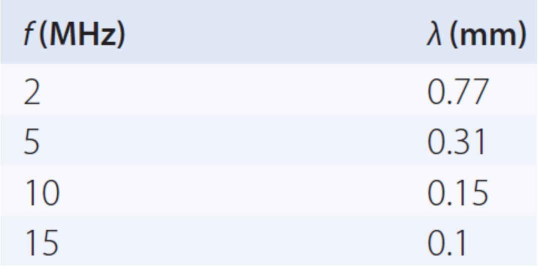


Material	c (m s^{-1})
Liver	1578
Kidney	1560
Amniotic fluid	1534
Fat	1430
Average tissue	1540
Water	1480
Bone	3190–3406
Air	333



Ultrasound Physics

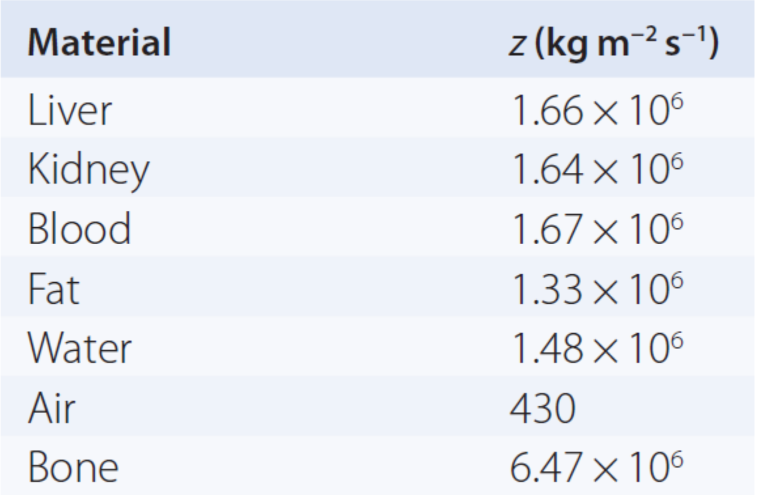
- Medical ultrasound frequencies used in the range 2–15 MHz
  - Higher frequencies are now utilized for special applications
  - Resolution proportional to wavelegth



f (MHz)	λ (mm)
2	0.77
5	0.31
10	0.15
15	0.1

- Acoustic impedance $\boxed{z = p/v}$
  - *p* is the local pressure and *v* is the local particle velocity.
  - Analogous to electrical impedance (or resistance R)

$$\boxed{z = \sqrt{\rho k} \quad = \rho c}$$



Material	z (kg m^{-2} s^{-1})
Liver	1.66×10^6
Kidney	1.64×10^6
Blood	1.67×10^6
Fat	1.33×10^6
Water	1.48×10^6
Air	430
Bone	6.47×10^6

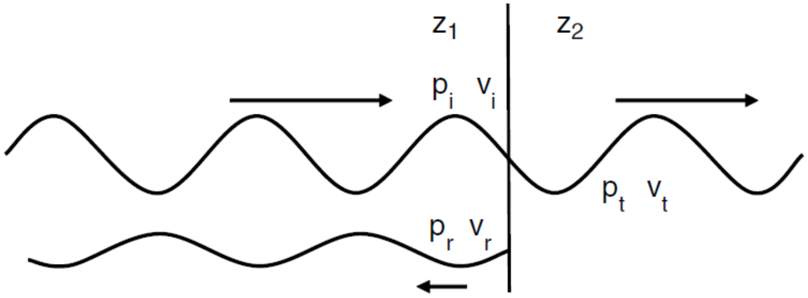
Ultrasound Physics

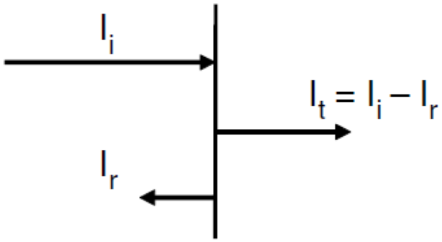
- Reflection: Large Interfaces

$$\boxed{R_A = \frac{p_r}{p_i} = \frac{z_2 - z_1}{z_2 + z_1}}$$

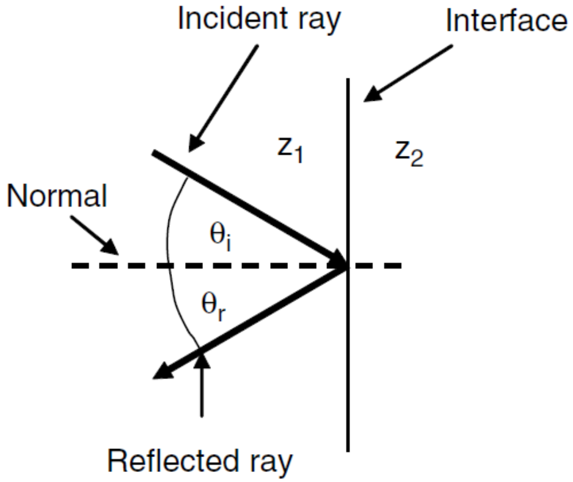
$$\boxed{\frac{I_r}{I_i} = R_i = R_A^2}$$

Interface	R_A
Liver–kidney	0.006
Kidney–spleen	0.003
Blood–kidney	0.009
Liver–fat	0.11
Liver–bone	0.59
Liver–air	0.9995





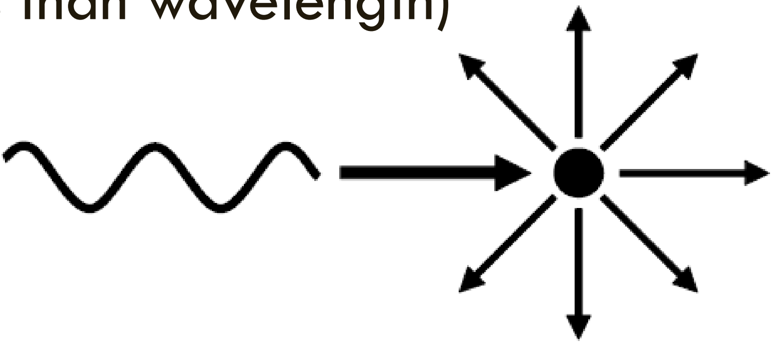
$$\boxed{\theta_r = \theta_i}$$



Ultrasound Physics

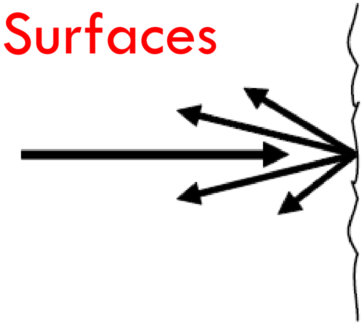
- Scattering: Small Interfaces (size less than wavelength)

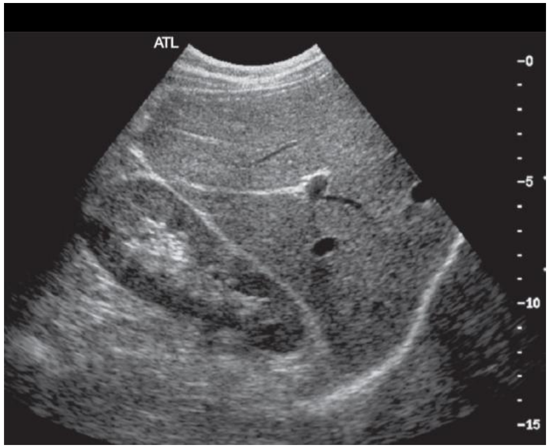
$$\boxed{W_s \propto \frac{d^6}{\lambda^4} \propto d^6 f^4}$$



- Two important aspects of scattering:
  - Ultrasonic power scattered back is small compared to reflections
  - Beam angle-independent appearance in the image unlike reflections

- Diffuse Reflection: Rough Surfaces

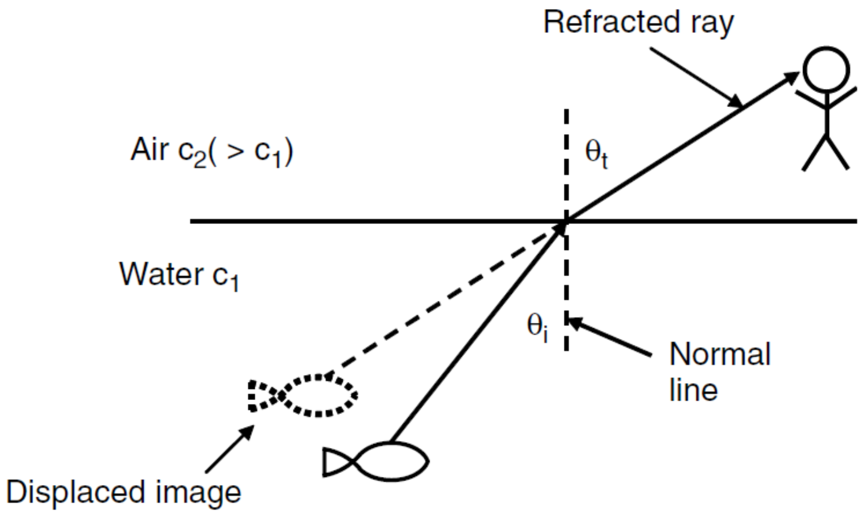




Ultrasound Physics

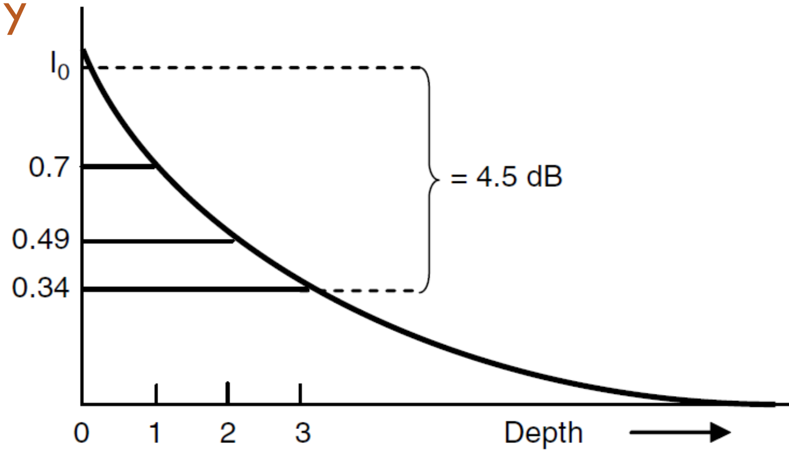
- Refraction: Snell's law

$$\boxed{\frac{\sin\theta_i}{\sin\theta_t} = \frac{c_1}{c_2}}$$



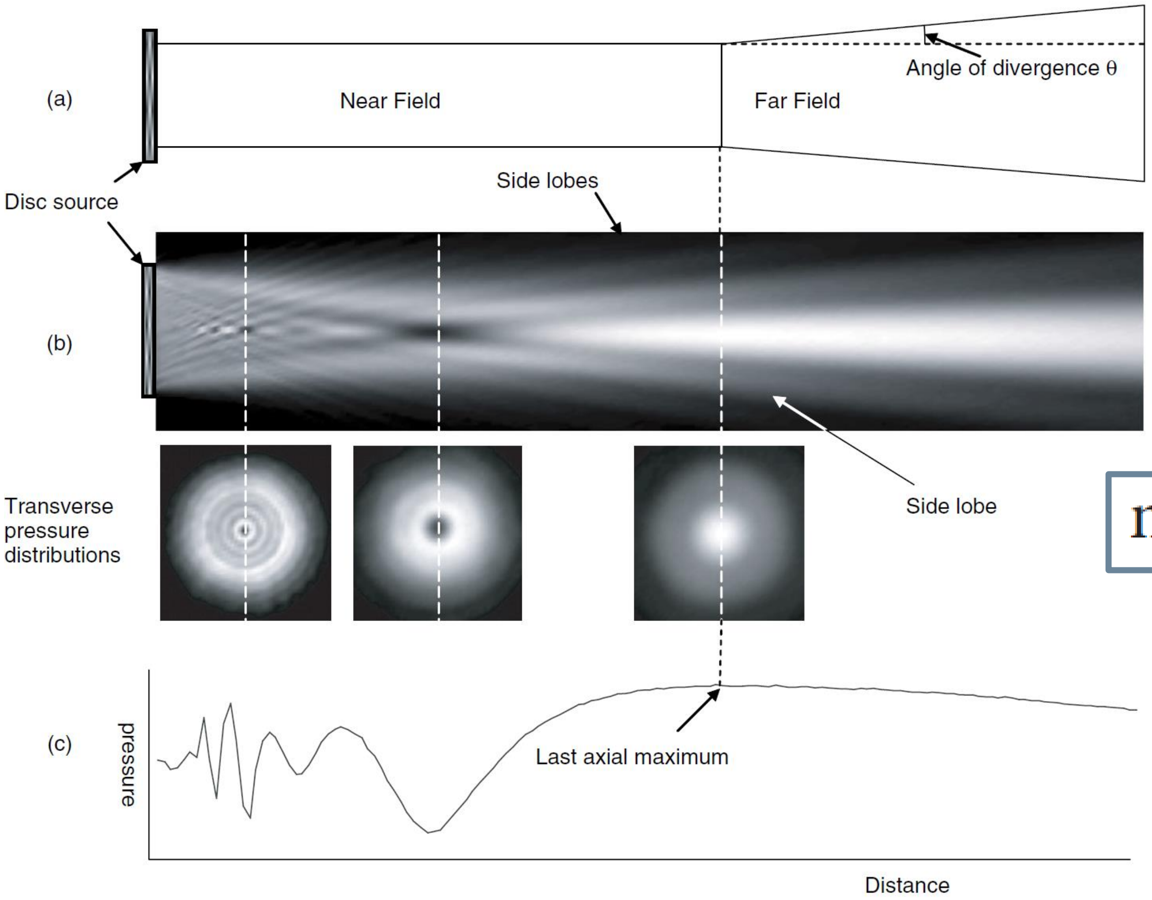
- Attenuation: gradual loss of beam energy
  - Depends on both distance and frequency

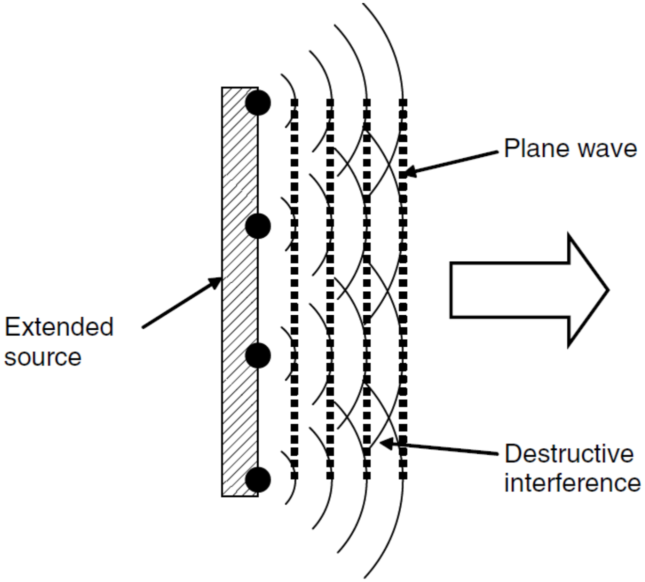
Tissue	Attenuation (dB cm^{-1} MHz^{-1})
Liver	0.399
Brain	0.435
Muscle	0.57
Blood	0.15
Water	0.02
Bone	22



Ultrasound Physics

- Interference and diffraction
  - Constructive/Destructive interference



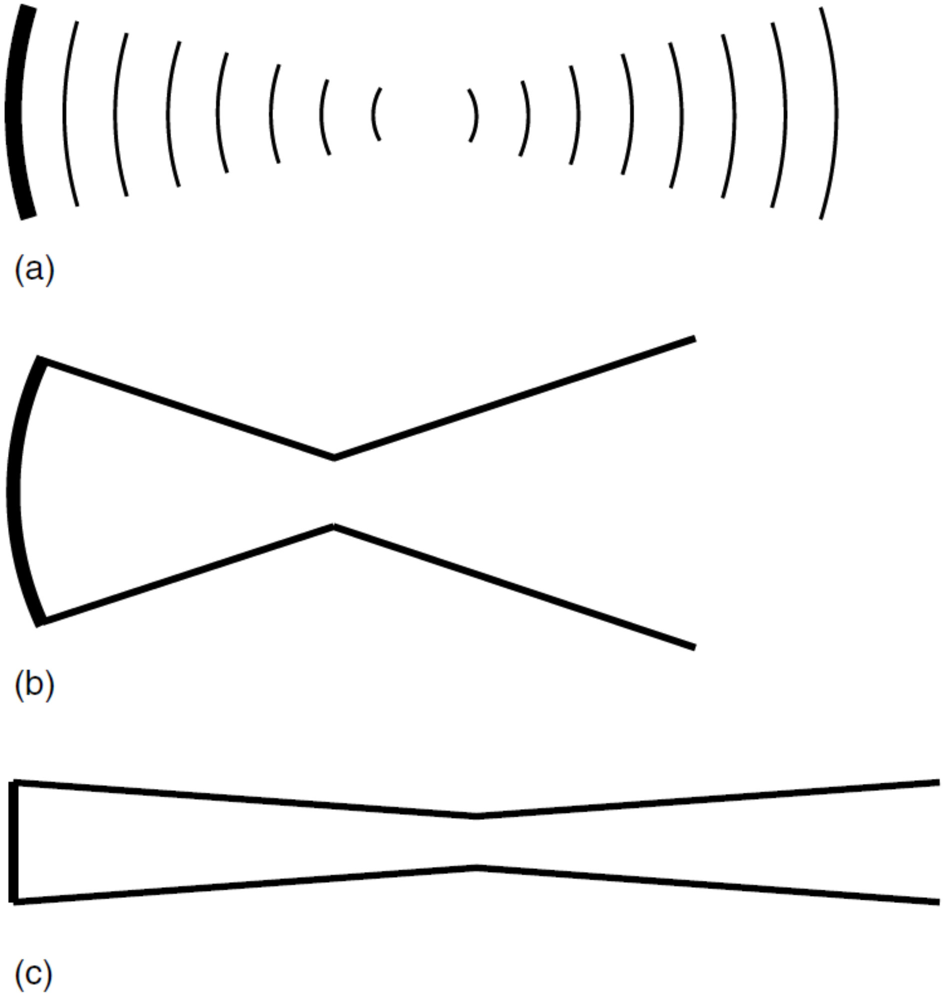


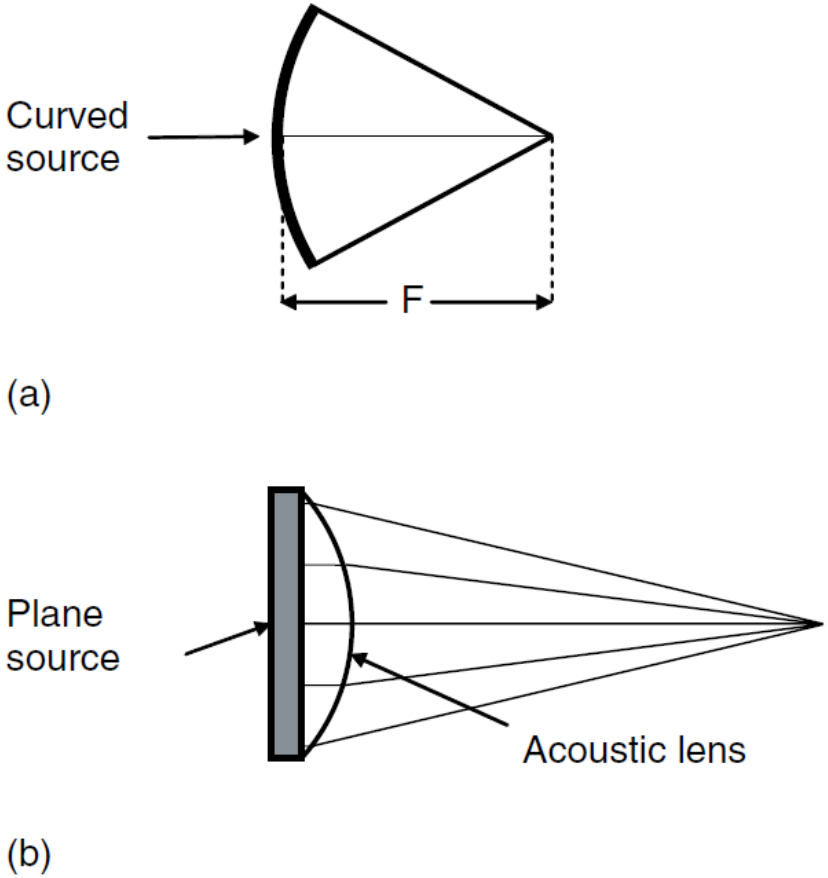
$$\text{near field length} = a^2/\lambda$$

$$\sin\ \theta = 0.61\ (\lambda/a)$$

Ultrasound Physics

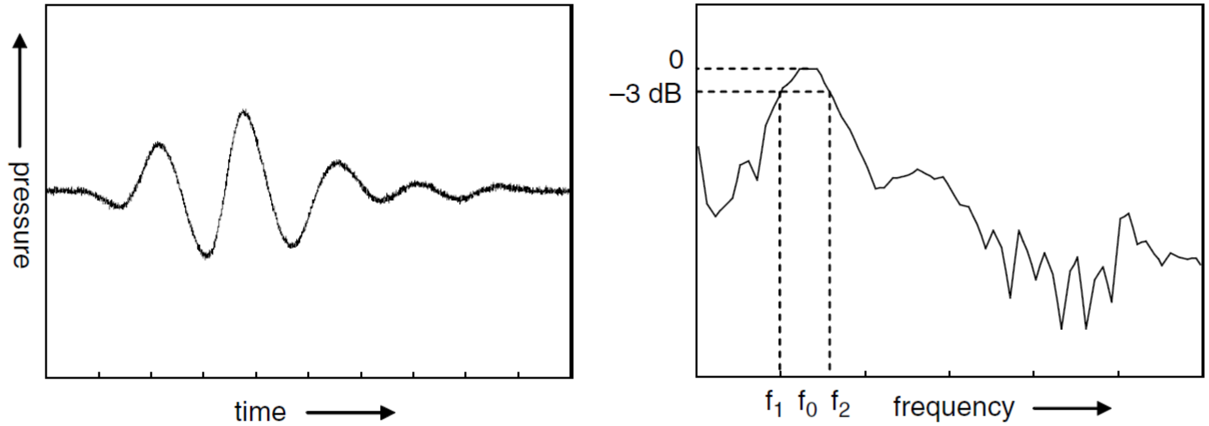
- Focusing: narrower ultrasound beam



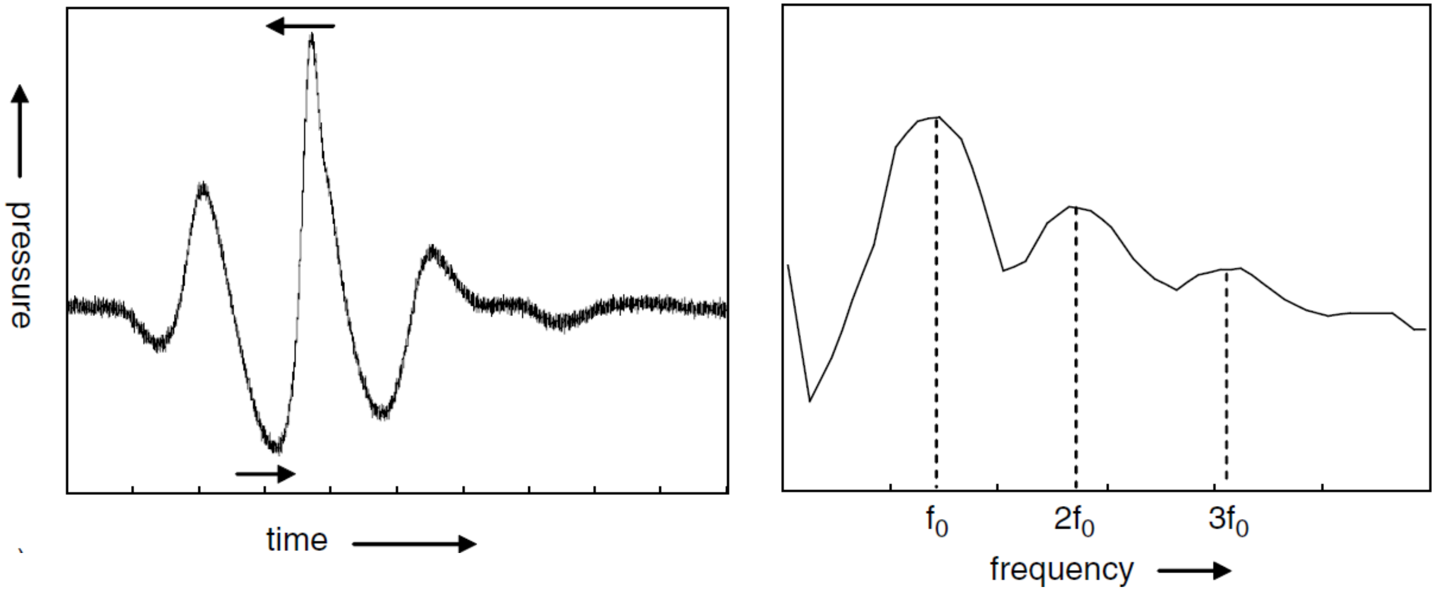


Ultrasound Physics

- Ultrasound pulse

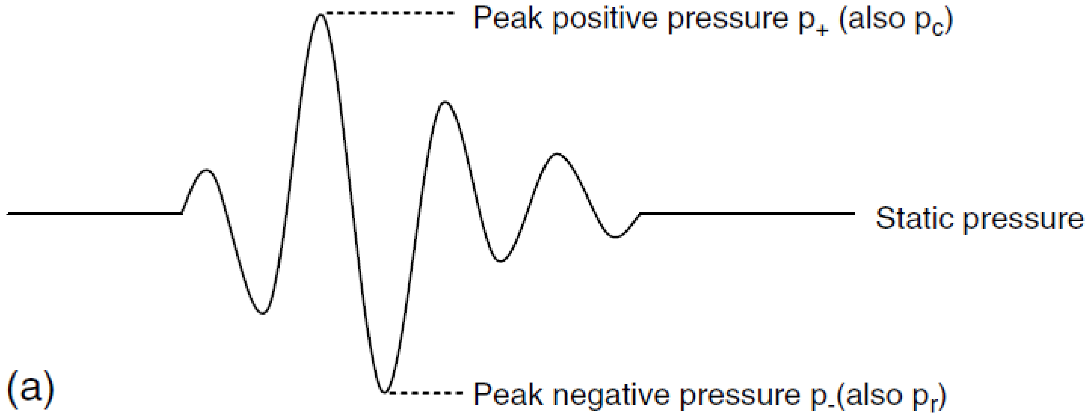


- Harmonic Imaging

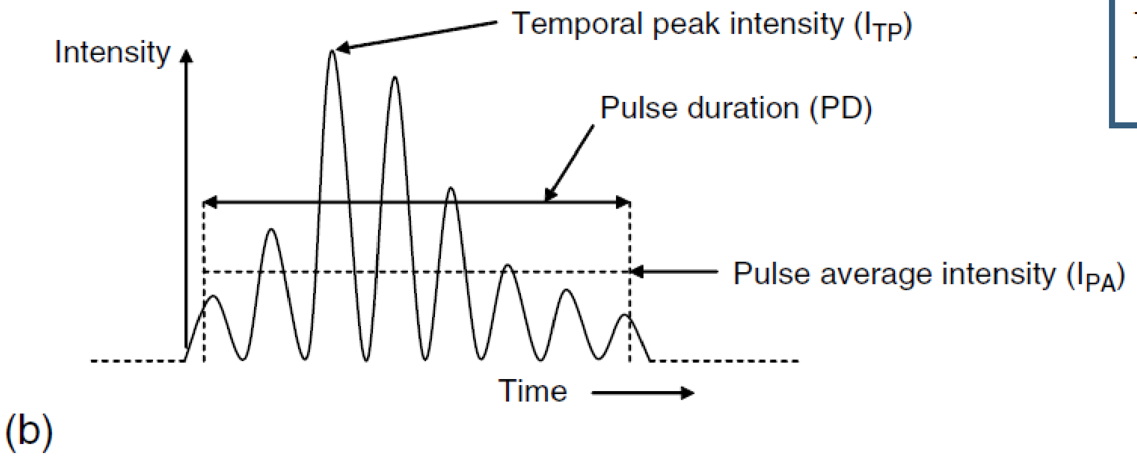


Ultrasound Physics

- Acoustic pressure and intensities within ultrasound beam



$$\boxed{I = \frac{p^2}{z}}$$

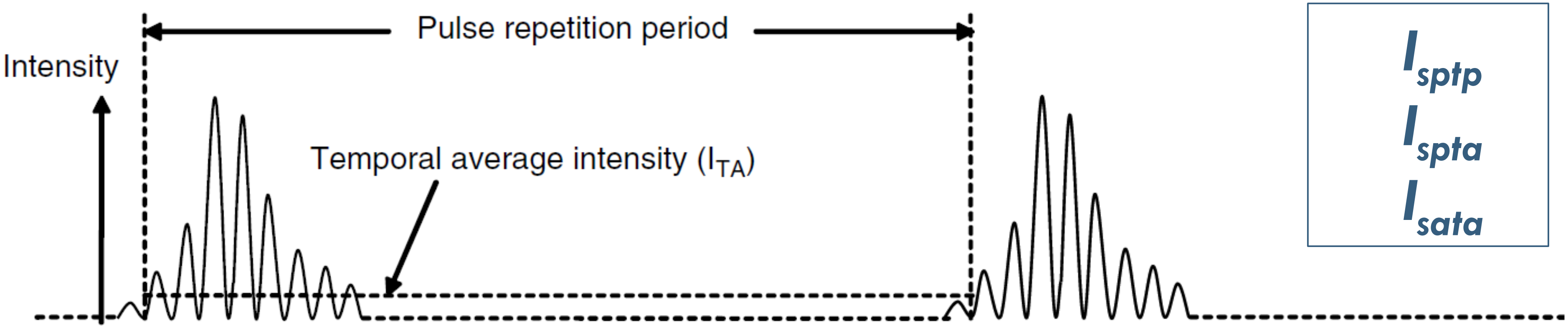


$$\boxed{\mathrm{PD} = 1.25 \times \left(T_{90} - T_{10}\right)}$$

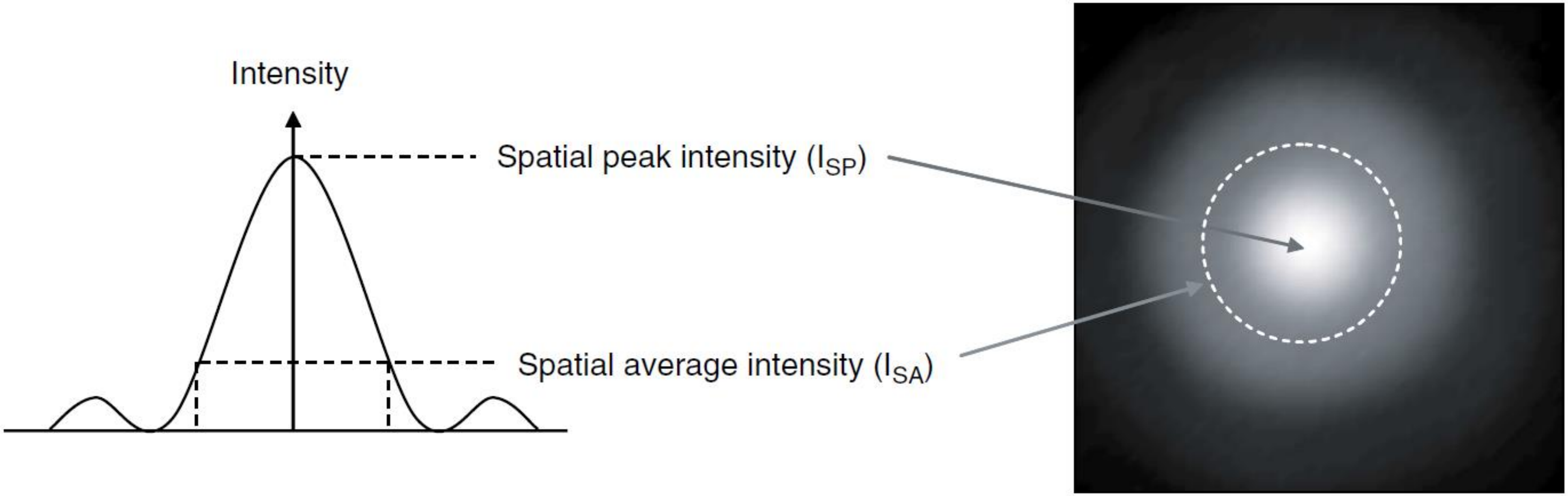
$$\boxed{I_{PA} = \mathrm{PII} / \mathrm{PD}}$$

Ultrasound Physics

- Acoustic pressure and intensities within ultrasound beam

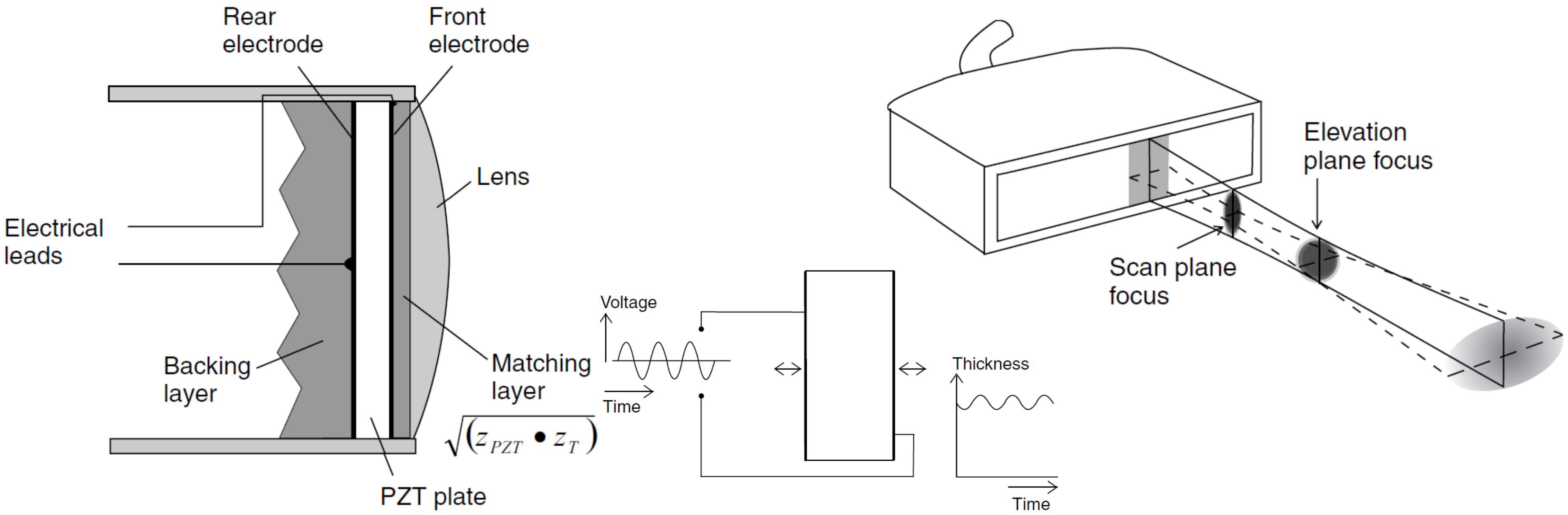


I_{sptp}
I_{spta}
I_{sata}



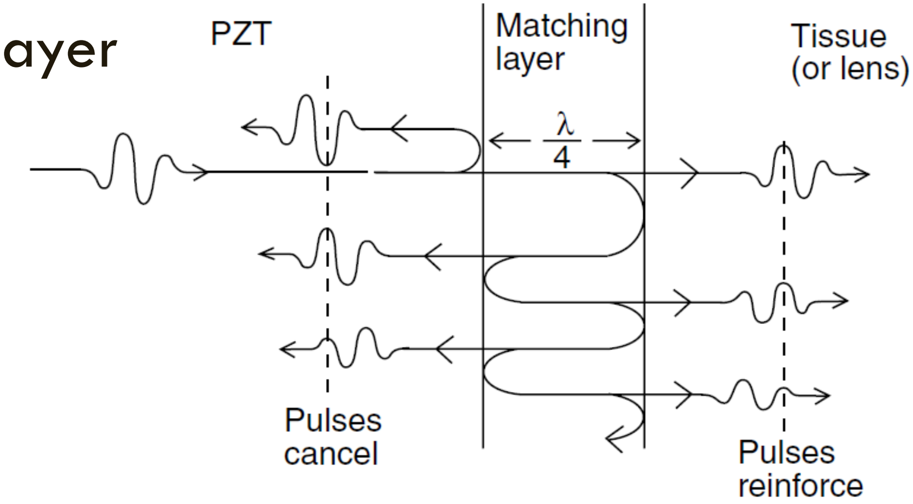
Transducers and Beamforming

- Transducer: device that actually converts electrical transmission pulses into ultrasonic pulses and, conversely, ultrasonic echo pulses into electrical echo signals
- Beamformer: part of scanner that determines the shape, size and position of the interrogating beams by controlling electrical signals to and from the transducer array elements

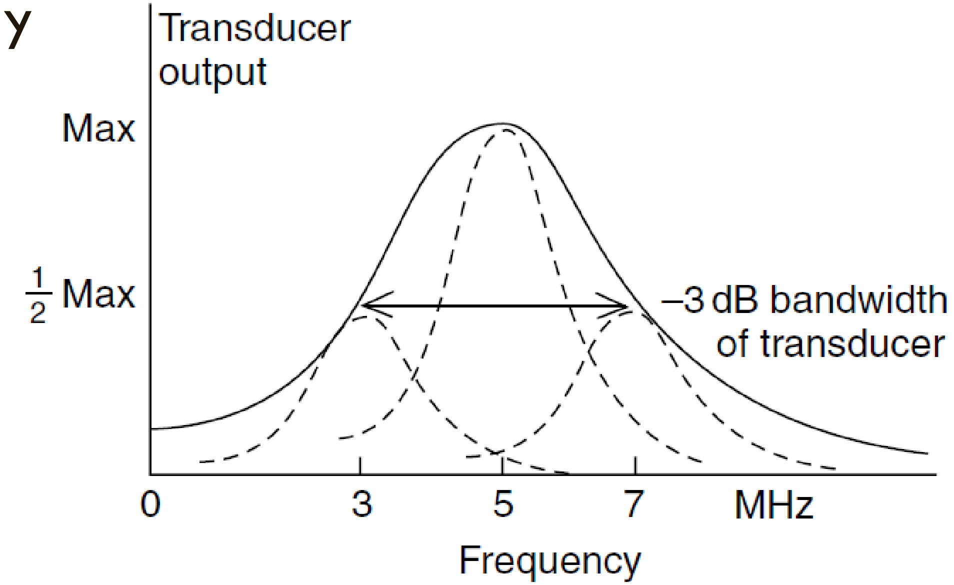


Transducers and Beamforming

- Quarter-wavelength matching layer

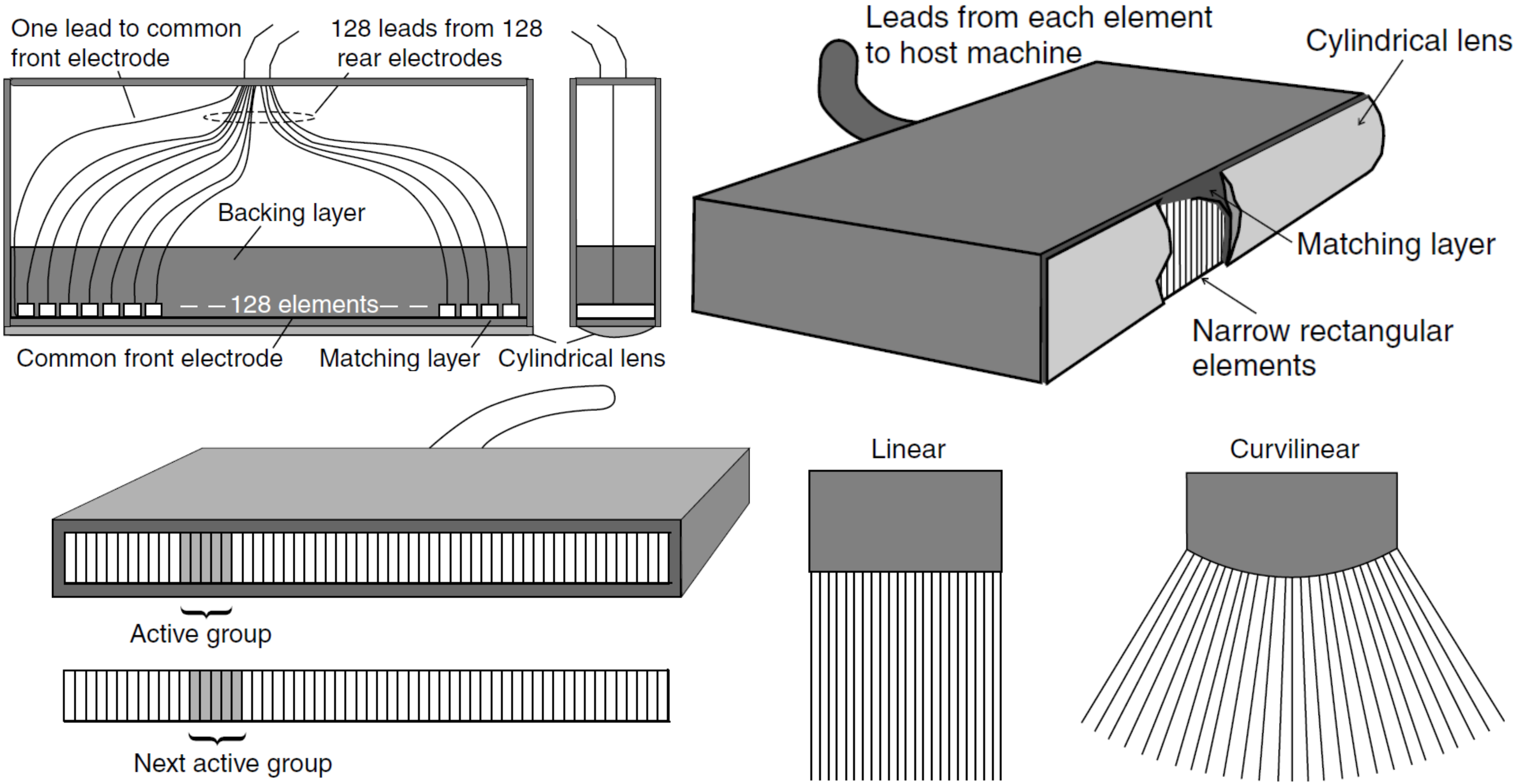


- Bandwidth for multi-frequency transducers



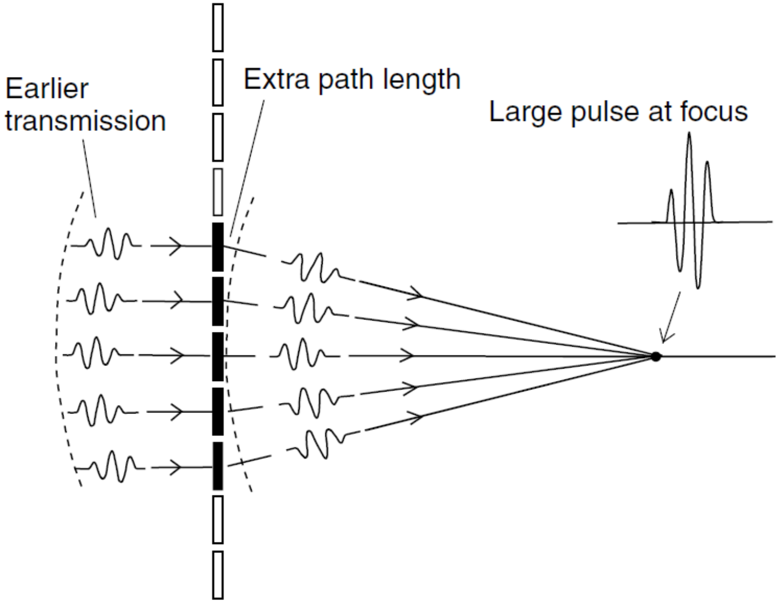
Transducers and Beamforming

- Linear- and curvilinear-array transducers

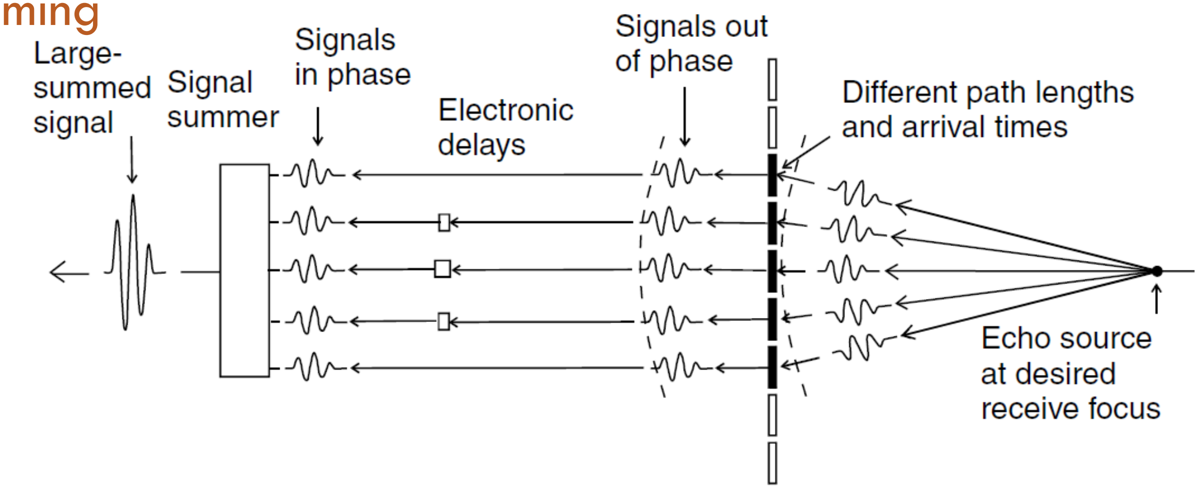


Transducers and Beamforming

- Transmission Focusing

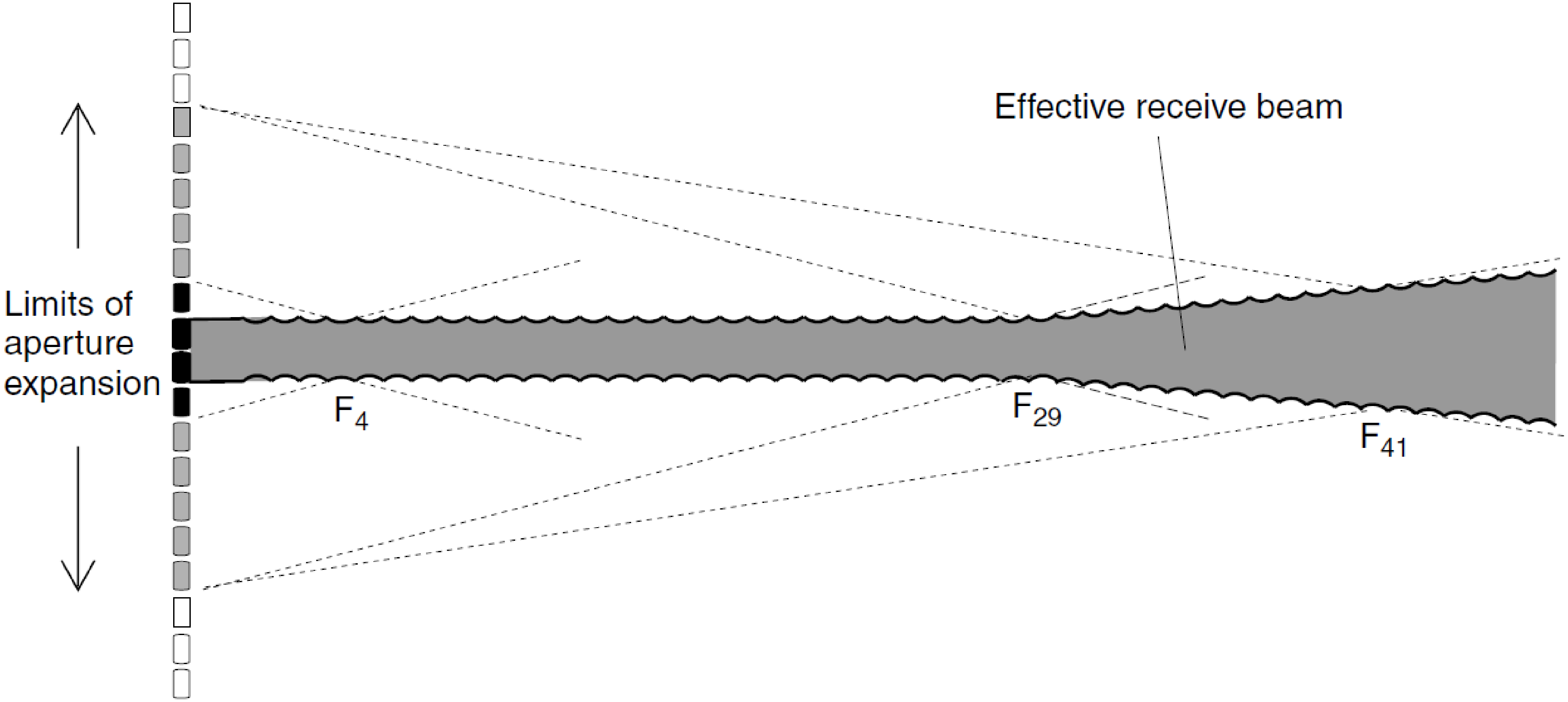


- Reception focusing
  - Delay-Sum beamforming



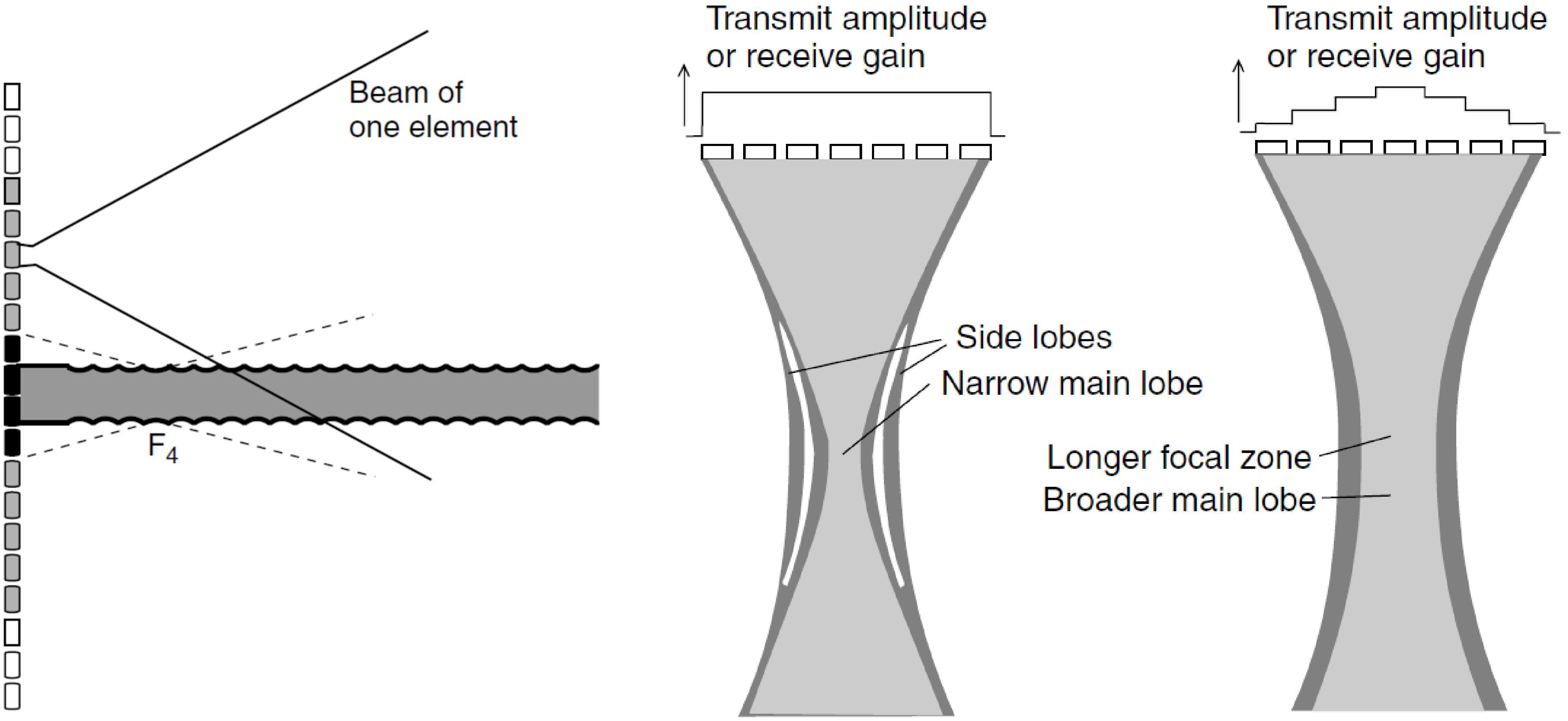
Transducers and Beamforming

- Dynamic reception focusing



Transducers and Beamforming

- Beamforming: selecting active elements and apodization

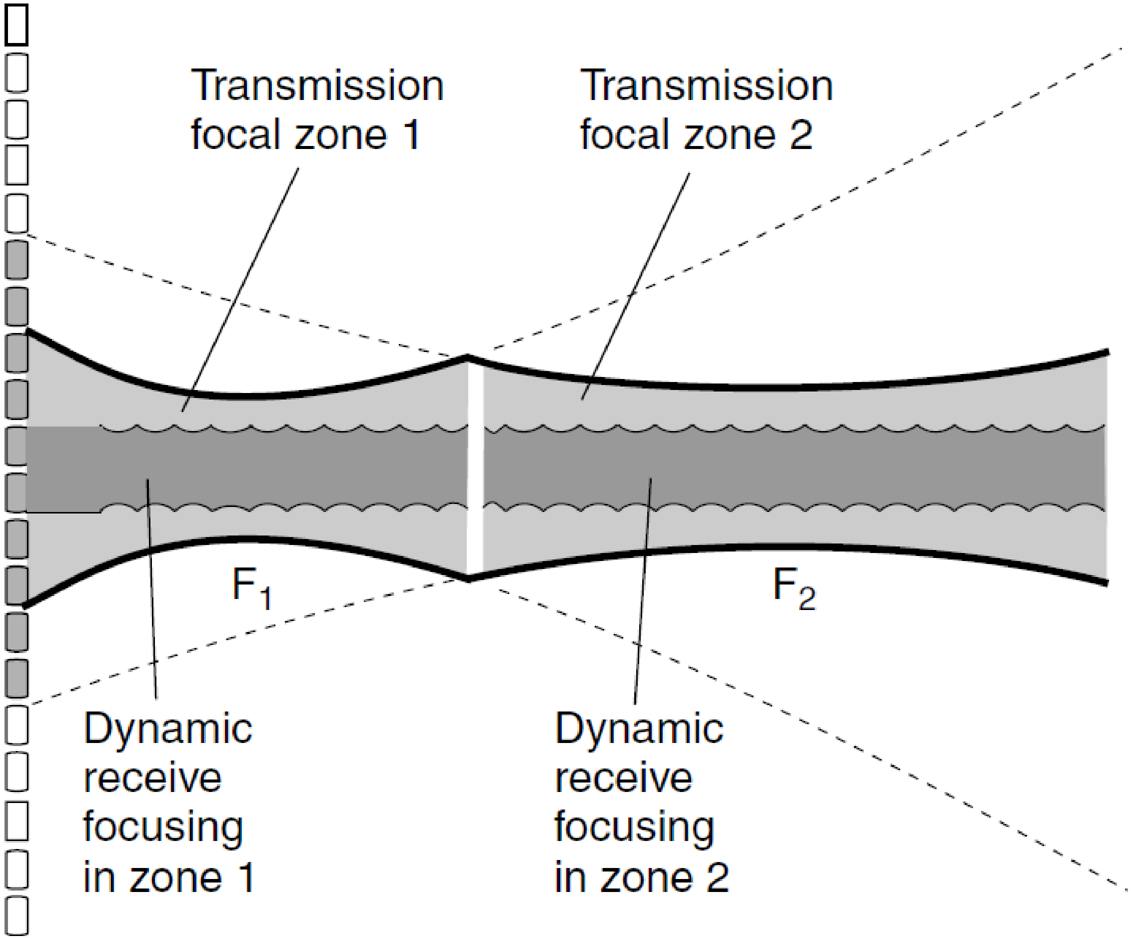


Uniform excitation

Non-uniform excitation
(apodization)

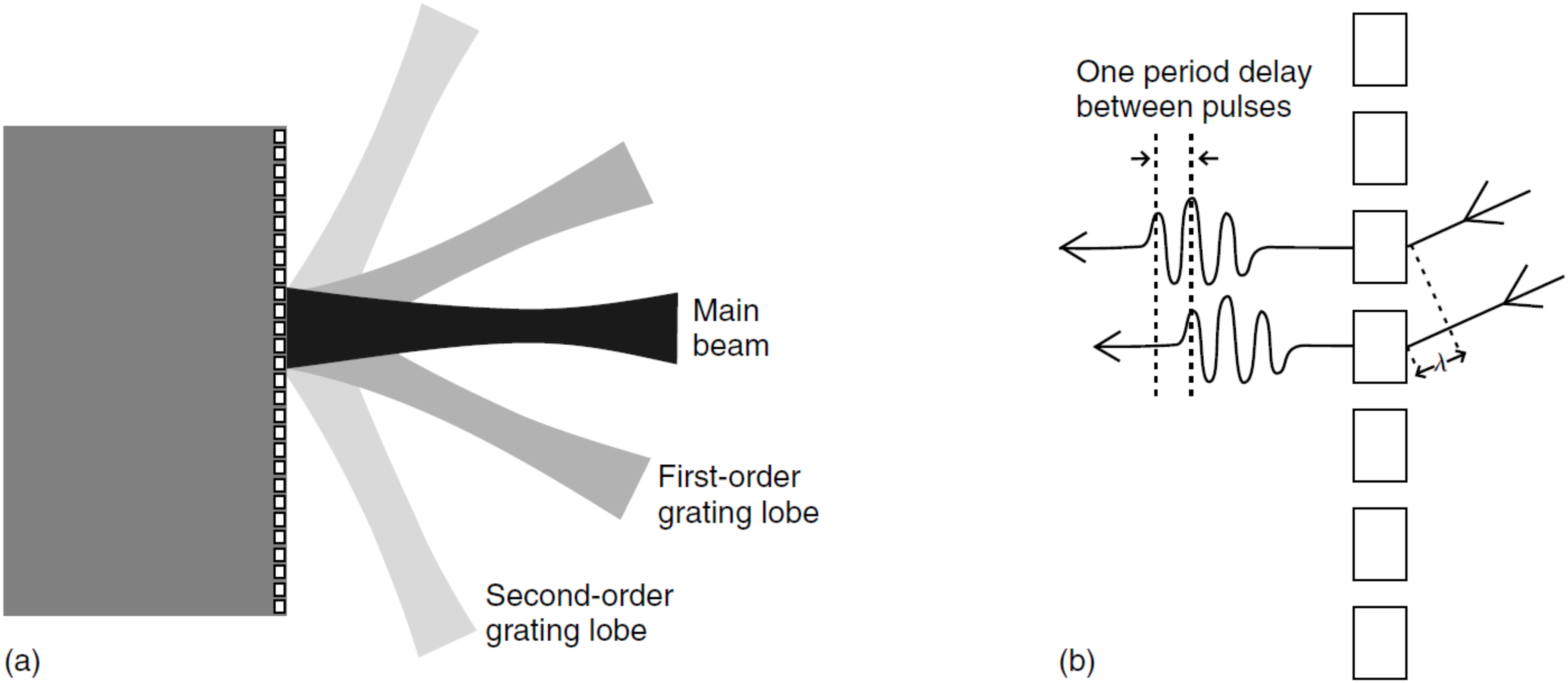
Transducers and Beamforming

- Beamforming: Multiple Transmission zones



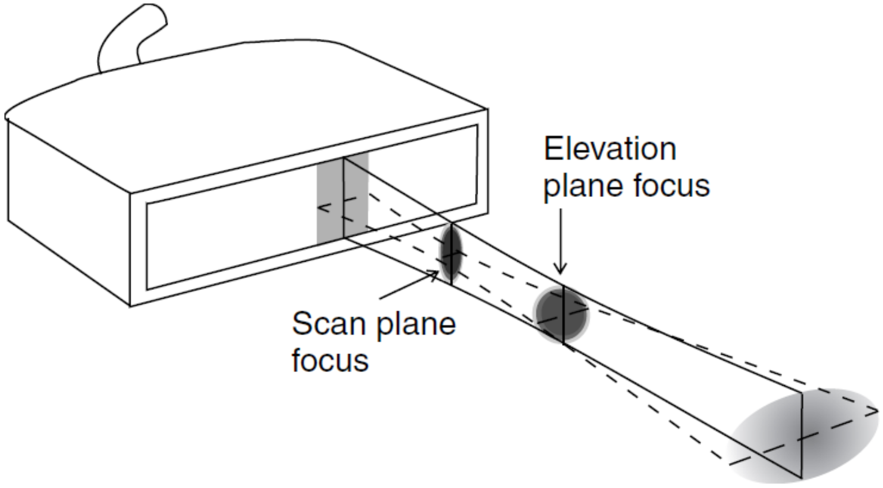
Transducers and Beamforming

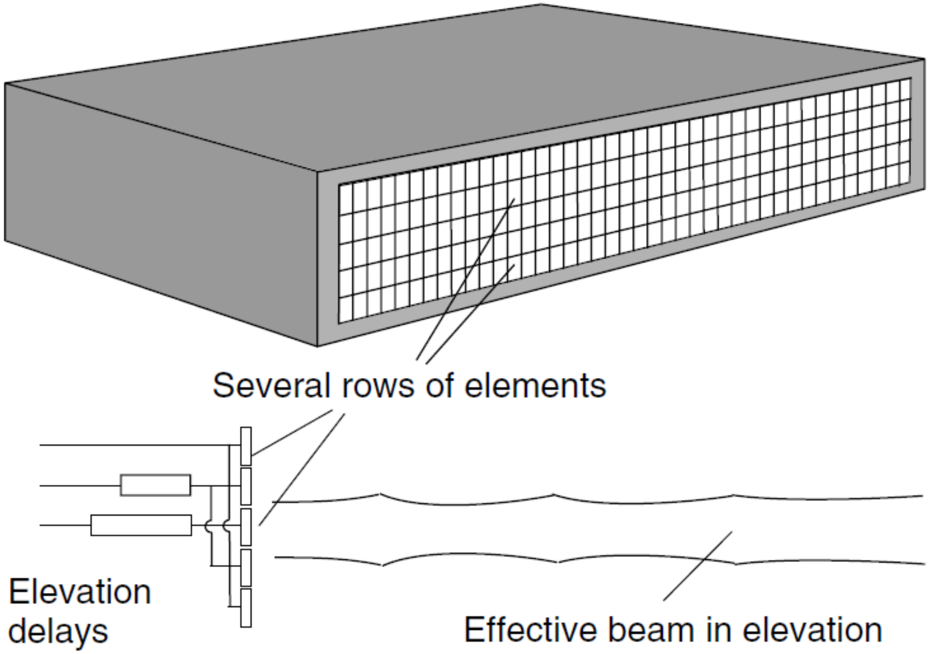
- Beamforming: Grating lobes
  - No grating lobes, if the center-to-center distance between elements is half a wavelength or less



Transducers and Beamforming

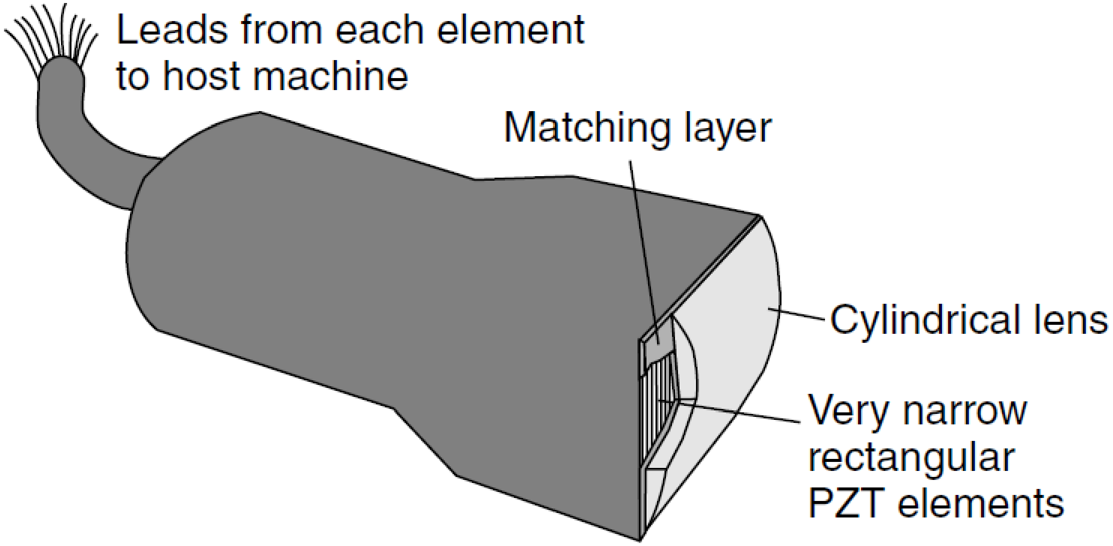
- Slice thickness: elevation direction
  - 1.5D or 2D arrays

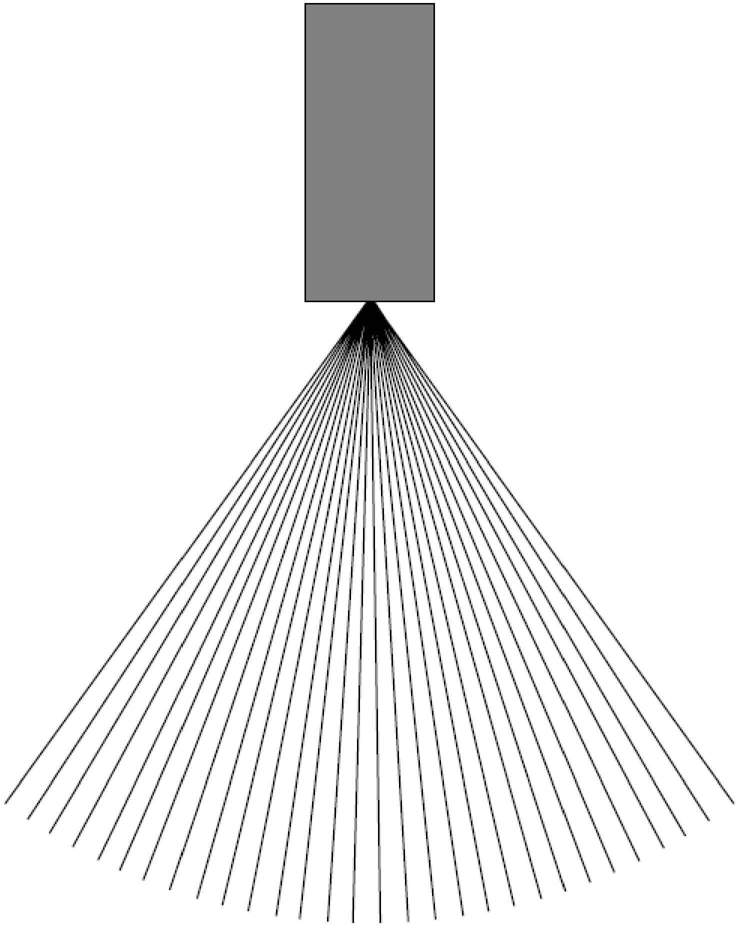




Transducers and Beamforming

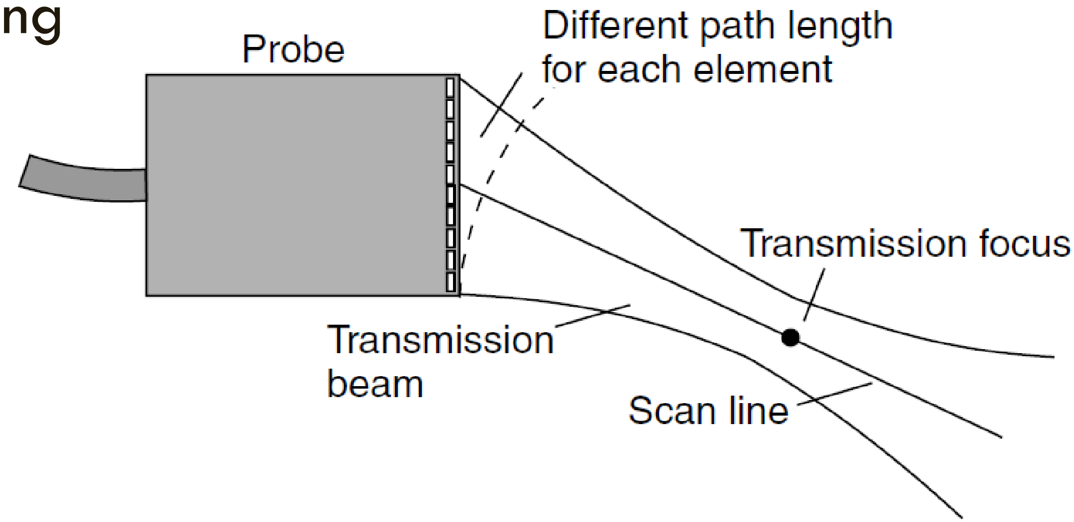
- Phased Array transducers

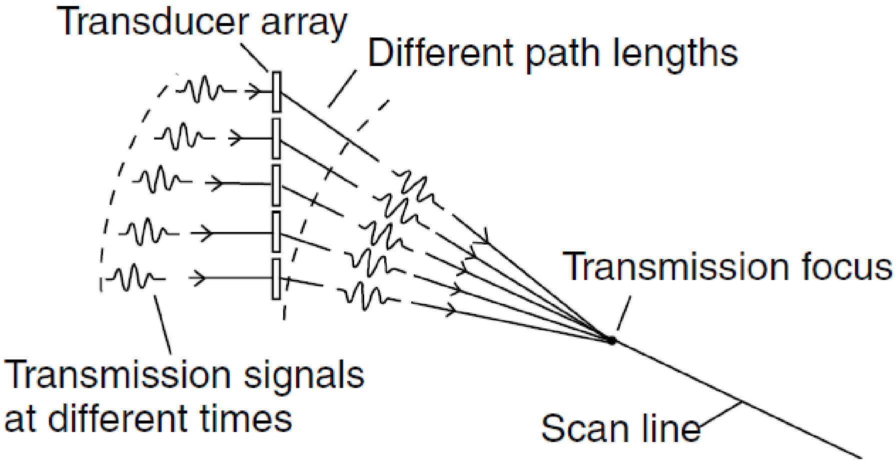




Transducers and Beamforming

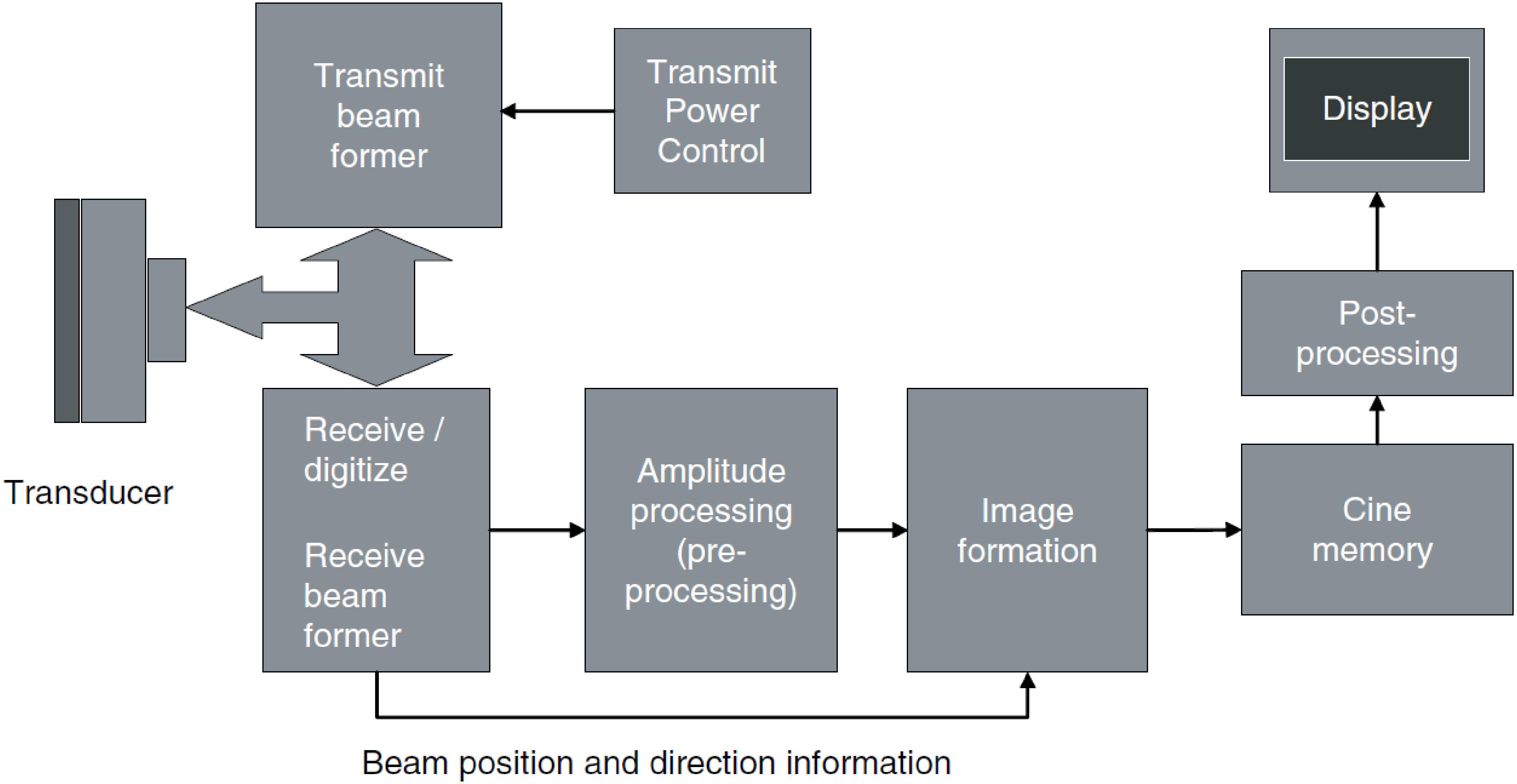
- Electronic steering/focusing





B-Mode Instrumentation

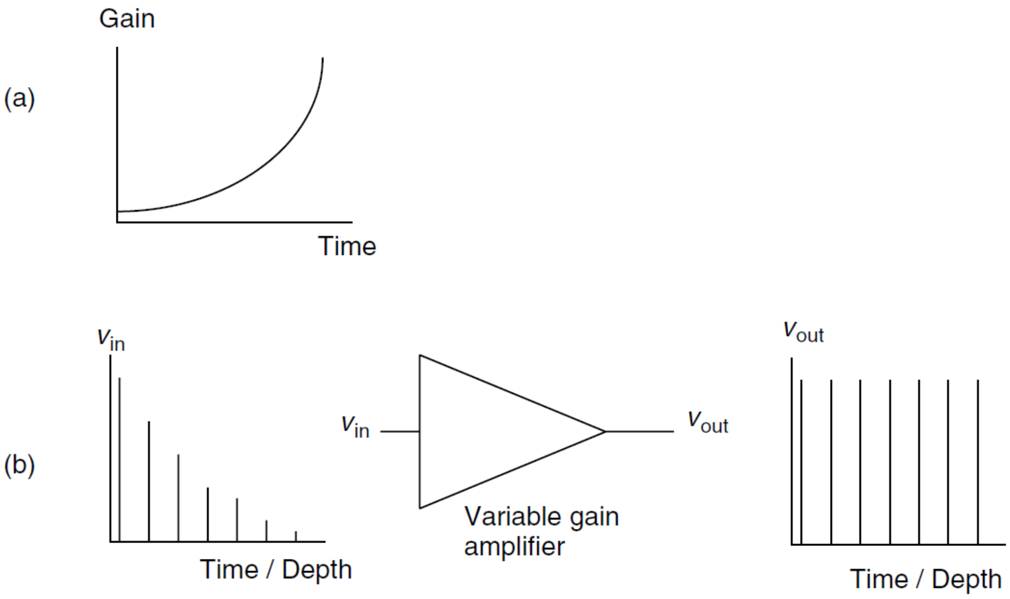
- Processing block diagram



B-Mode Instrumentation

- Time-Gain Compensation

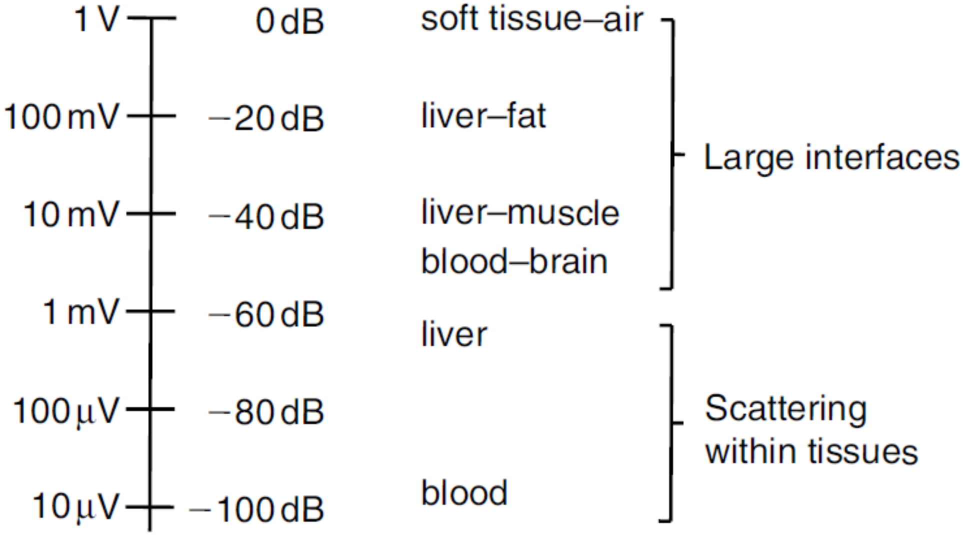
TGC slide controls



B-Mode Instrumentation

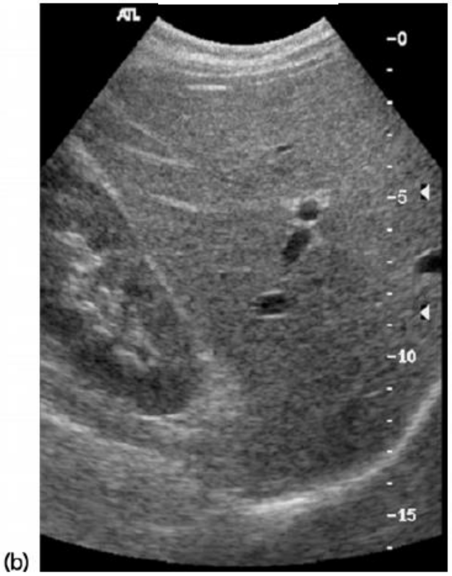
- Dynamic range of echoes

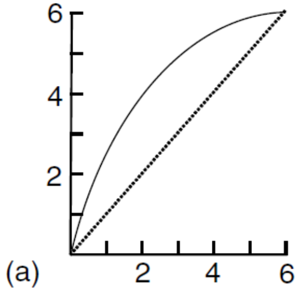
Bits	Max count	DR (dB)
4	15	24
8	255	48
10	1023	60
12	4095	72

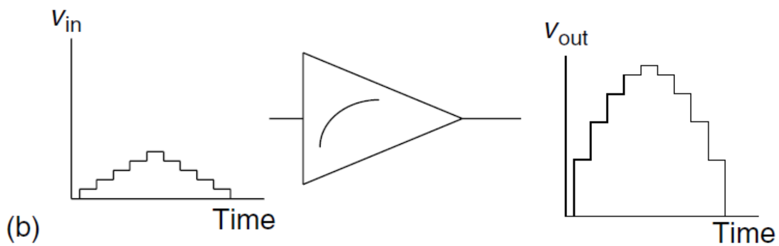


40 dB

80 dB

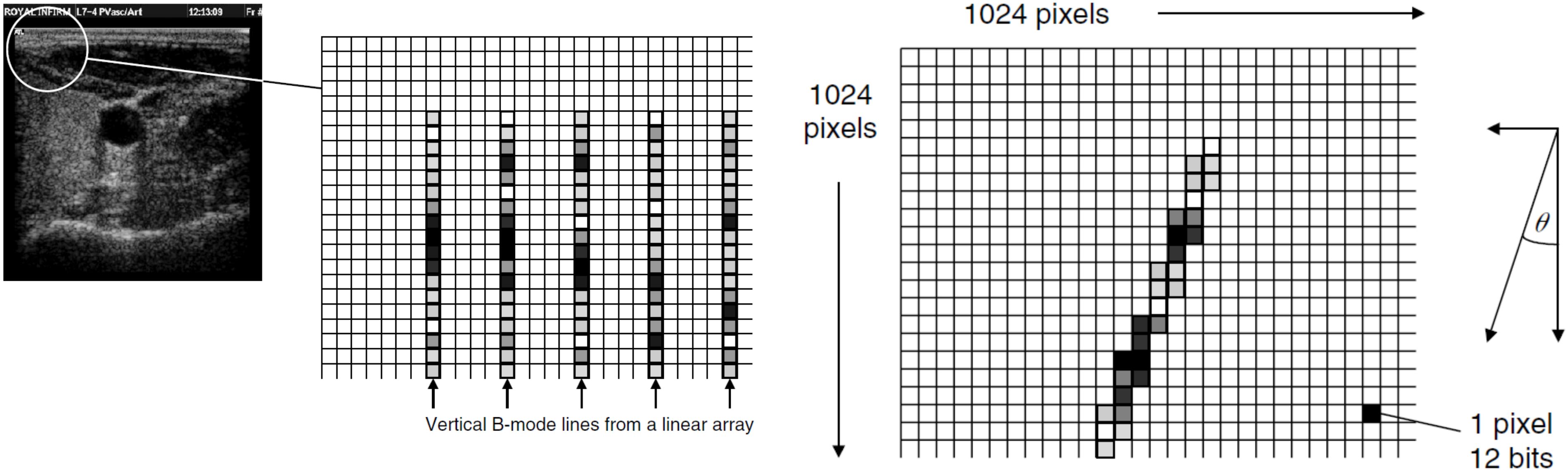






B-Mode Instrumentation

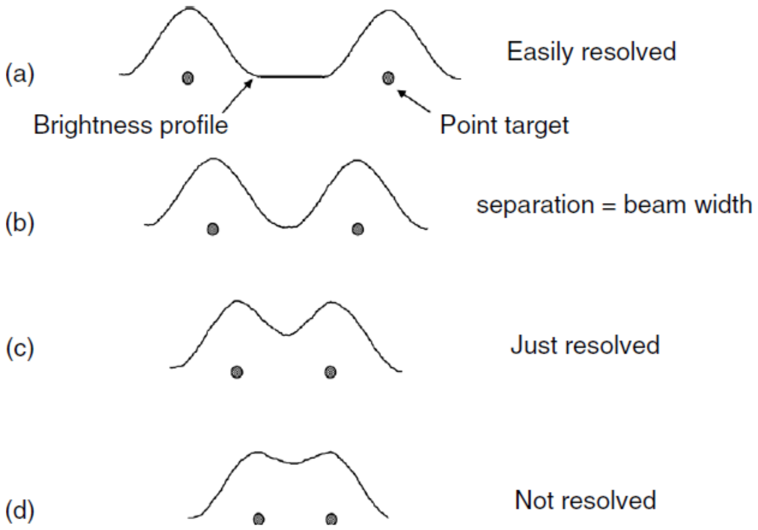
- Image reconstruction: scan conversion and interpolation

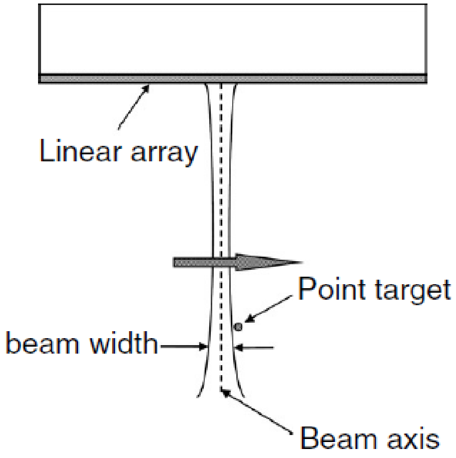


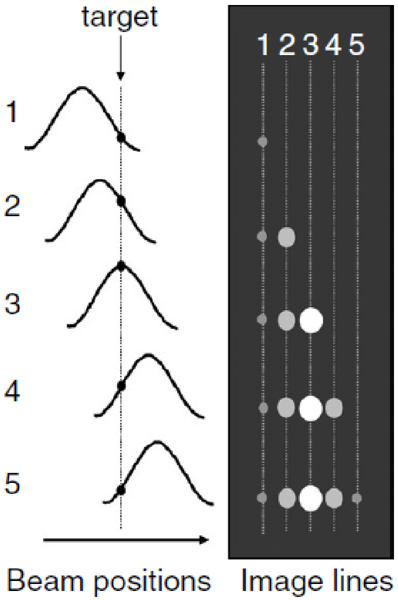
- Real-time display: frame every 1/25 s
- Freeze: updating frame stops
- Cine Loop: recording of real-time scan as a movie
- Frame Averaging: moving average filter to improve SNR

B-Mode Image Properties

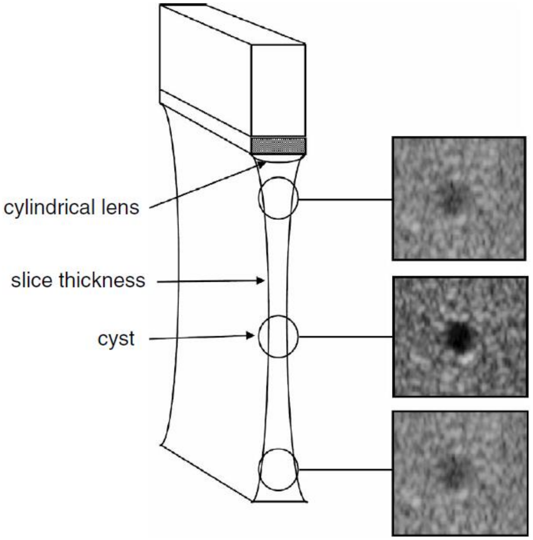
- Lateral Resolution





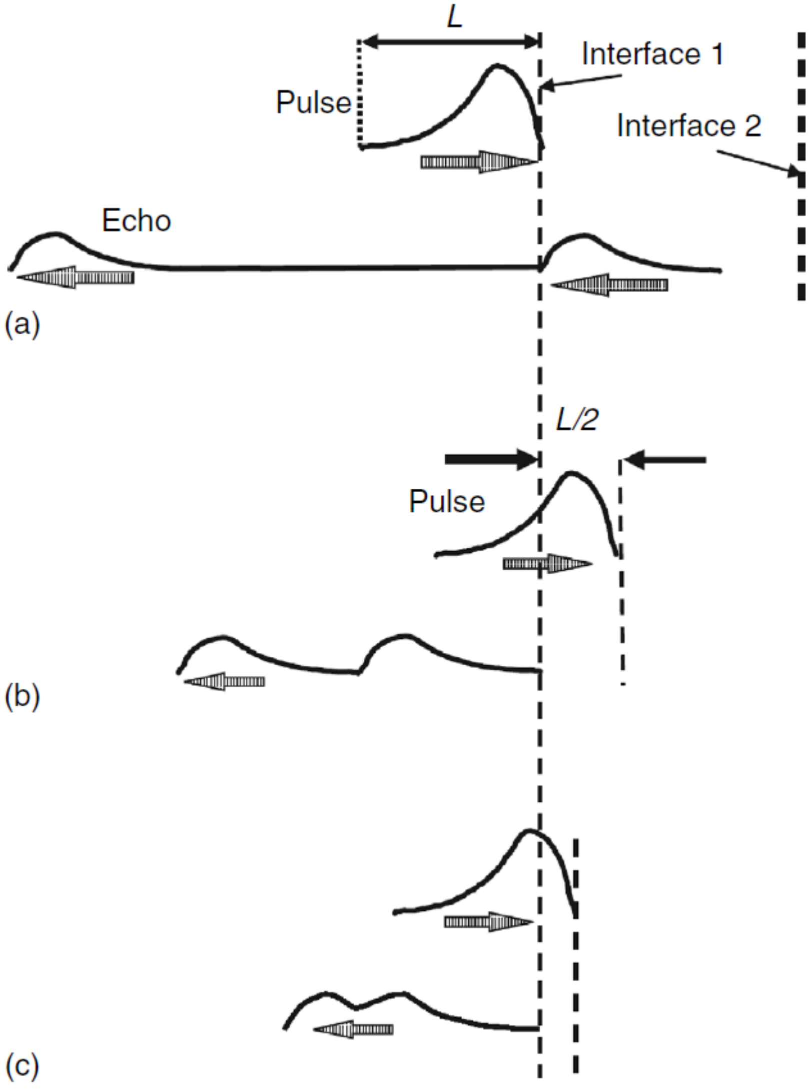


- Thickness resolution
  - Elevation

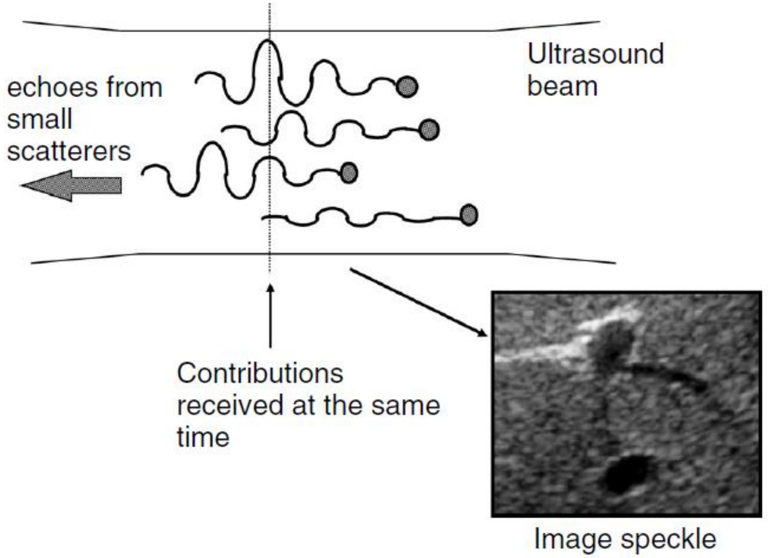


B-Mode Image Properties

- Axial resolution
  - Half pulse length



- Speckle
  - Random yet stationary pattern

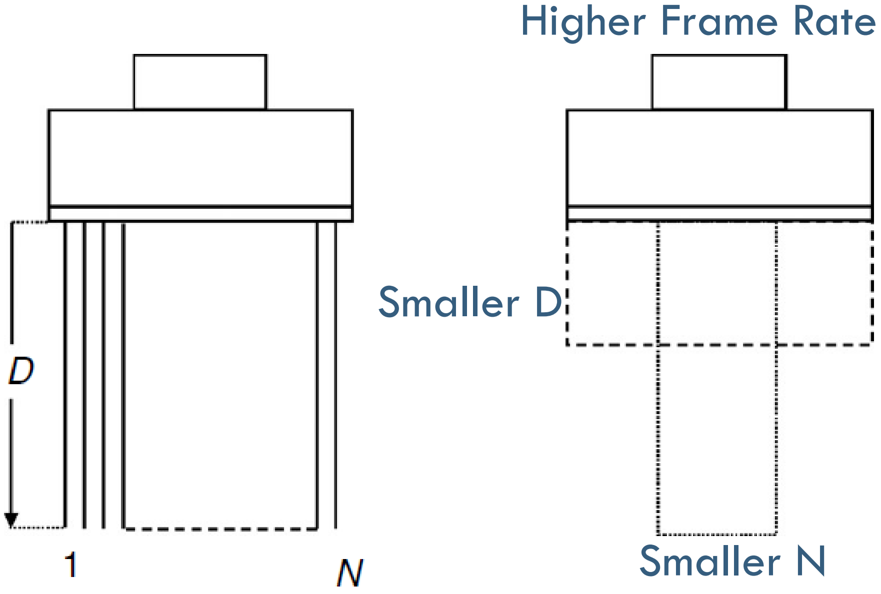


B-Mode Image Properties

- Frame time / Frame rate
  - Time to scan a complete image

$$\text{frame time} = 2DN/c$$

$$\text{frame rate} = (c/2DN)$$



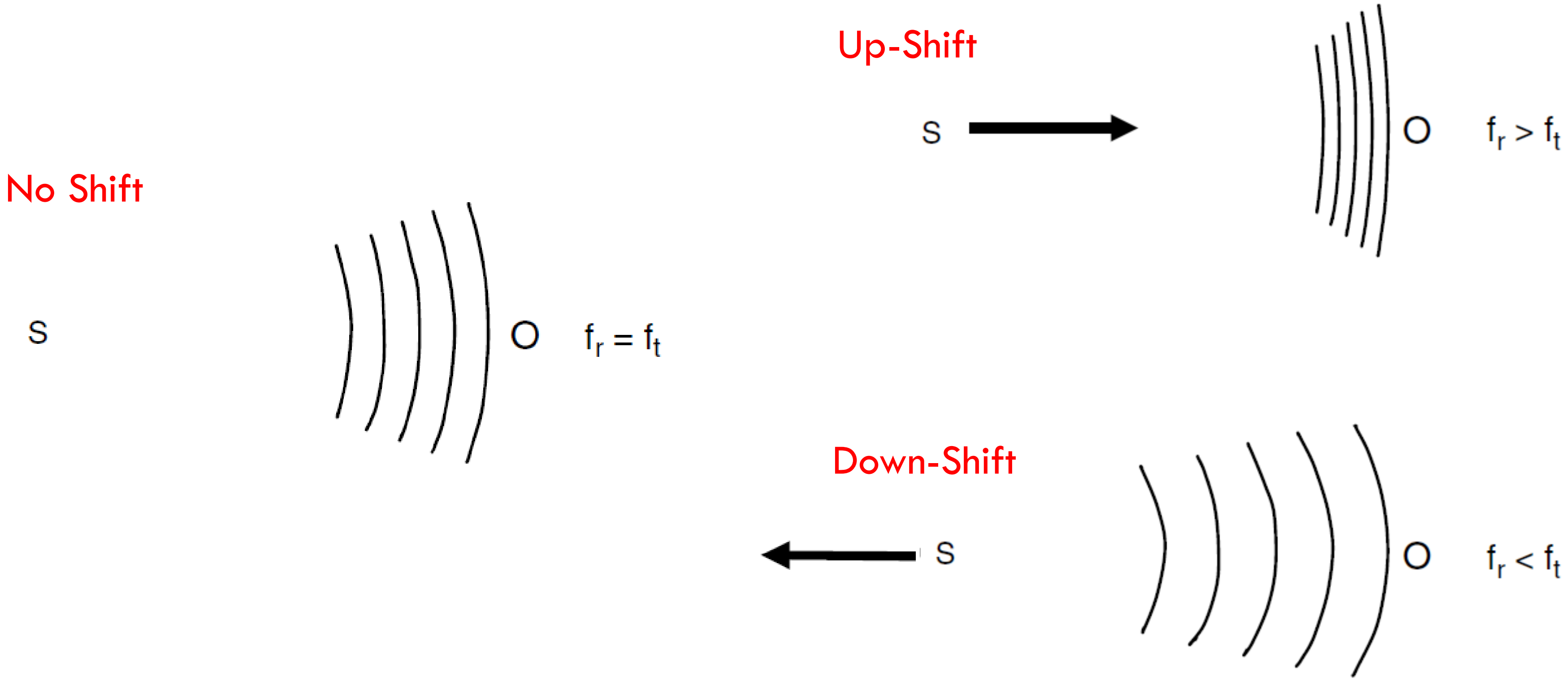
- Example: time to scan 1 cm= 2x1cm/c= 2 cm/(1540 m/s) = 13 µs

Then, frame time to scan a 20 cm depth with 128 lines=13 µs x20 x128

Frame rate = 1/ frame time = 30 frames/s

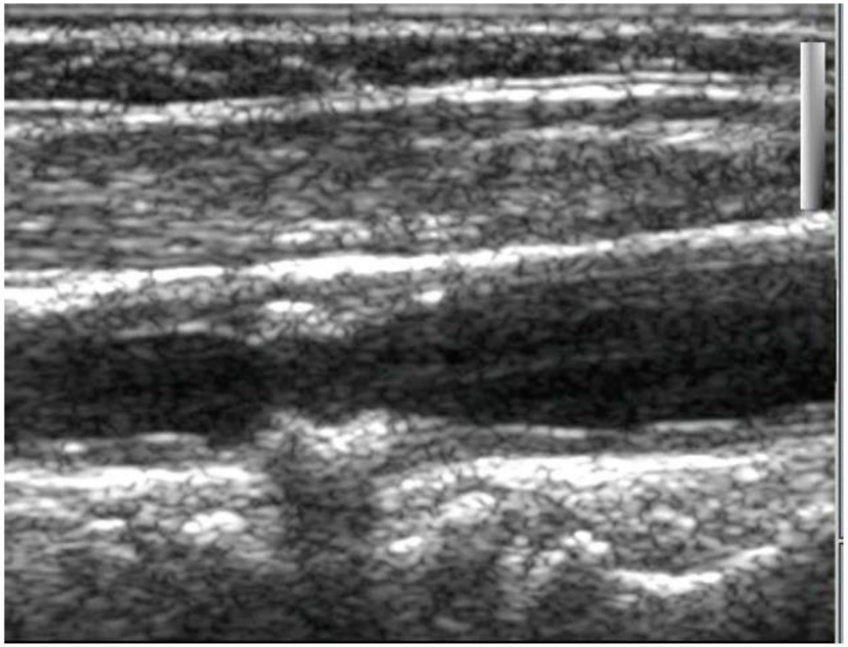
Doppler Ultrasound

- **Doppler effect**: Change in the observed frequency of the sound wave compared to the emitted frequency which occurs due to relative motion between observer and source

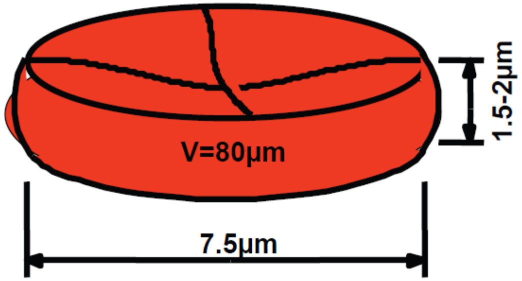


Doppler Ultrasound

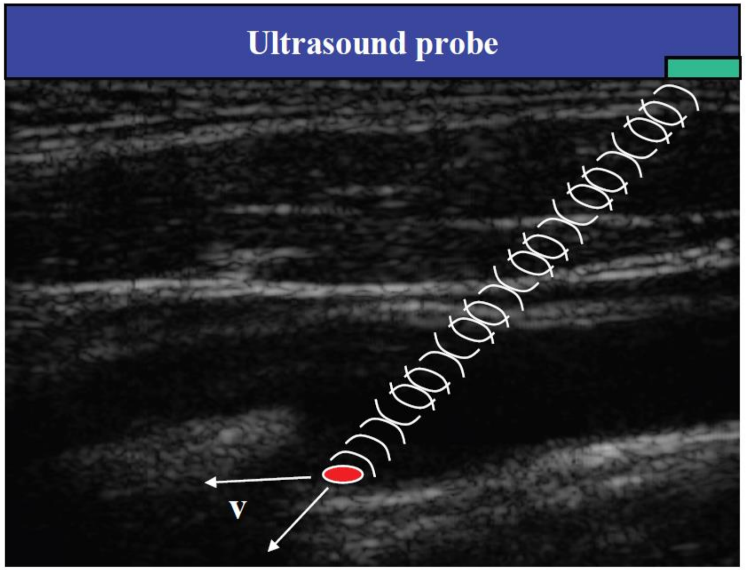
- RBCS in blood are hardly visible in ultrasound images
  - Scattering because of its very small size



Carotid artery with calcified plaque



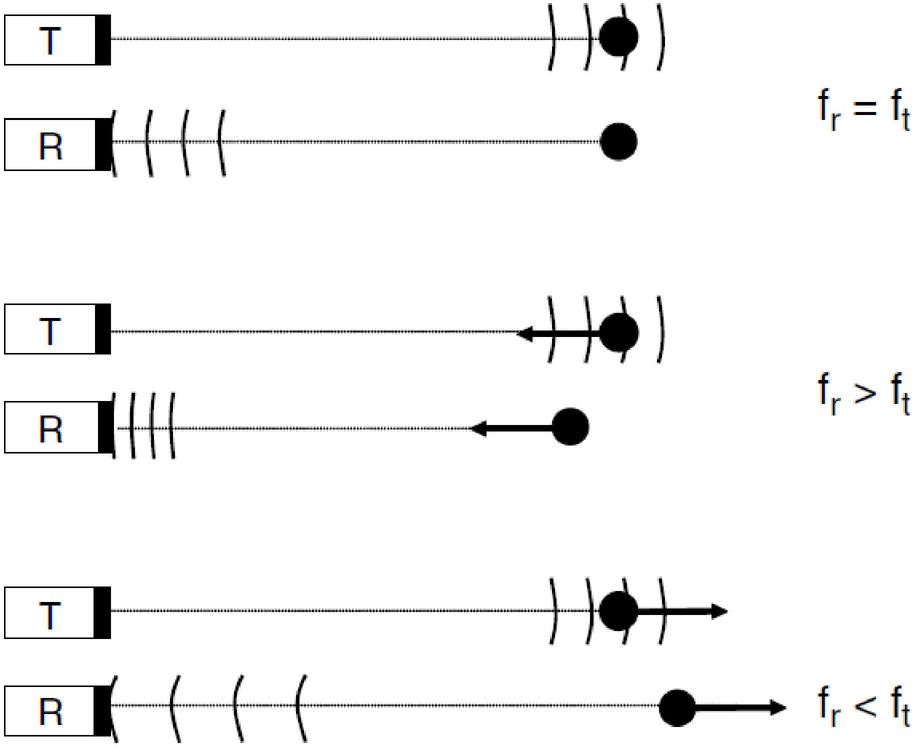
Red blood cell

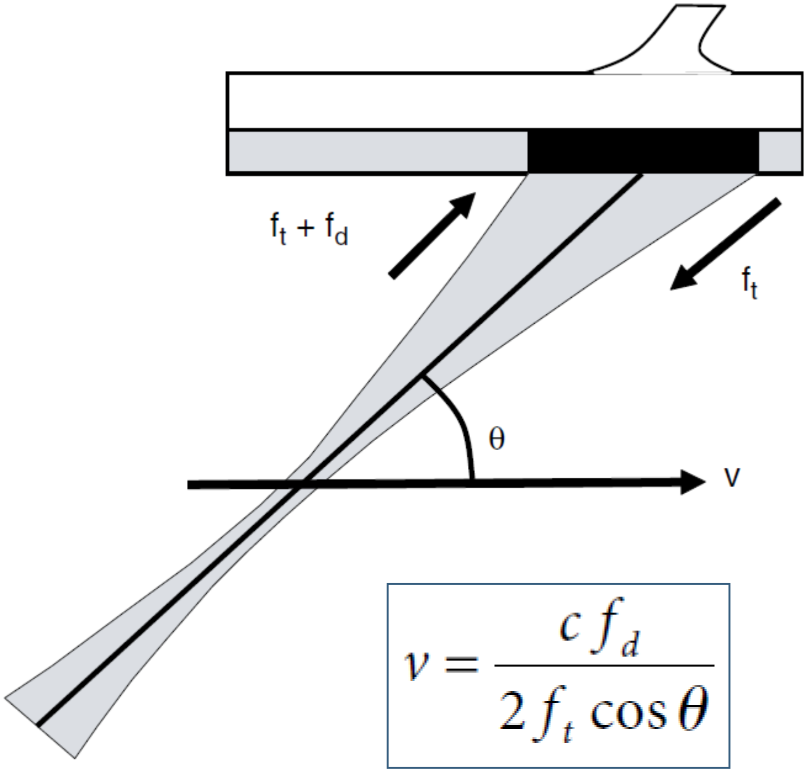


Doppler Ultrasound

- Doppler Shift Equation

$$f_d = f_r - f_t = \frac{2 f_t v \cos\theta}{c}$$



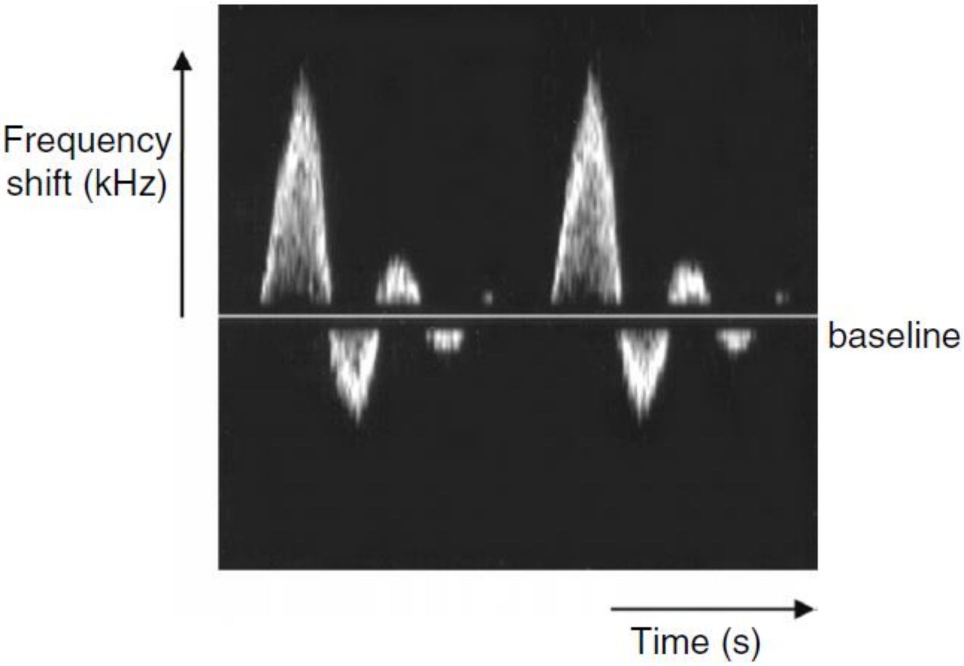


$$v = \frac{c f_d}{2 f_t \cos\theta}$$

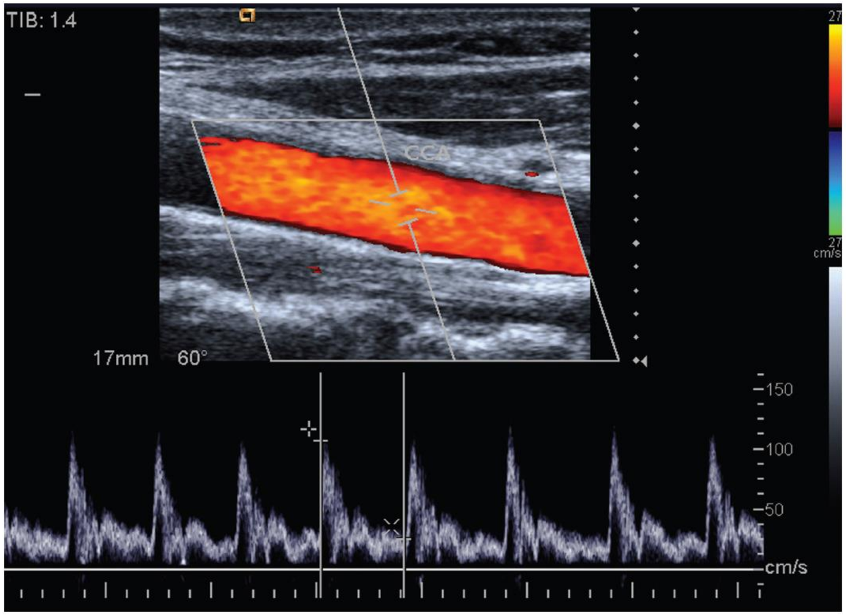
Doppler Ultrasound

- Doppler display modes

Spectral Doppler

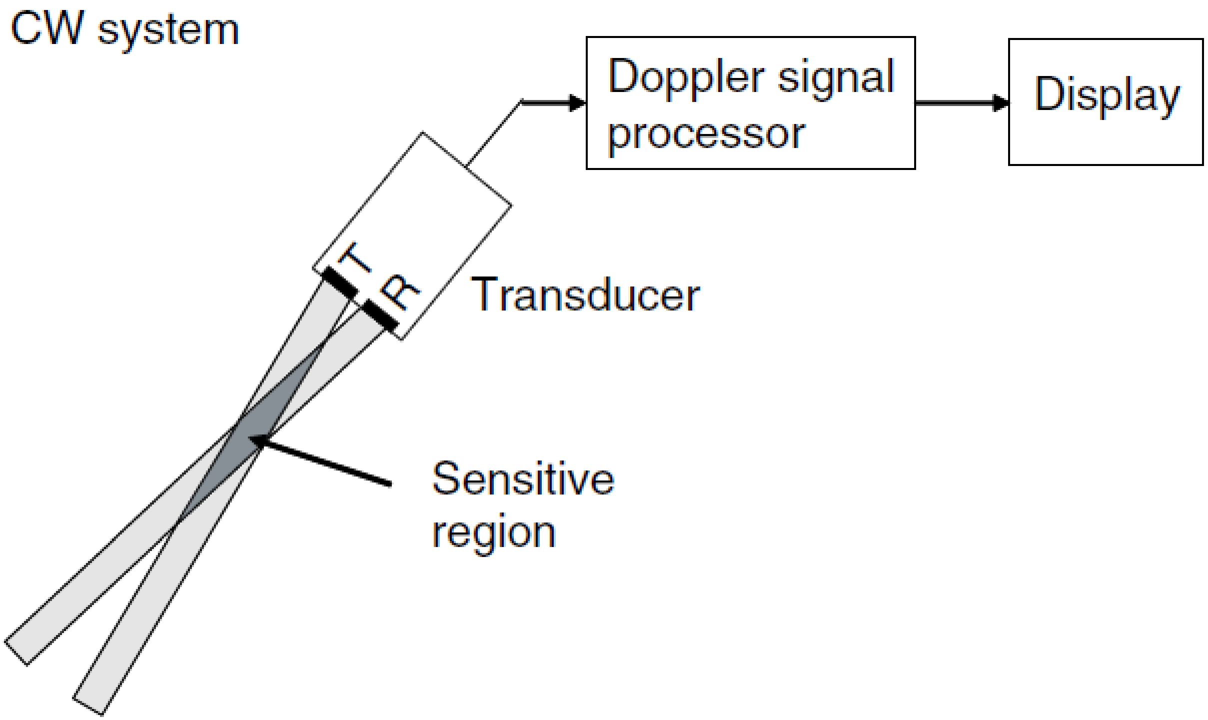


Color Doppler



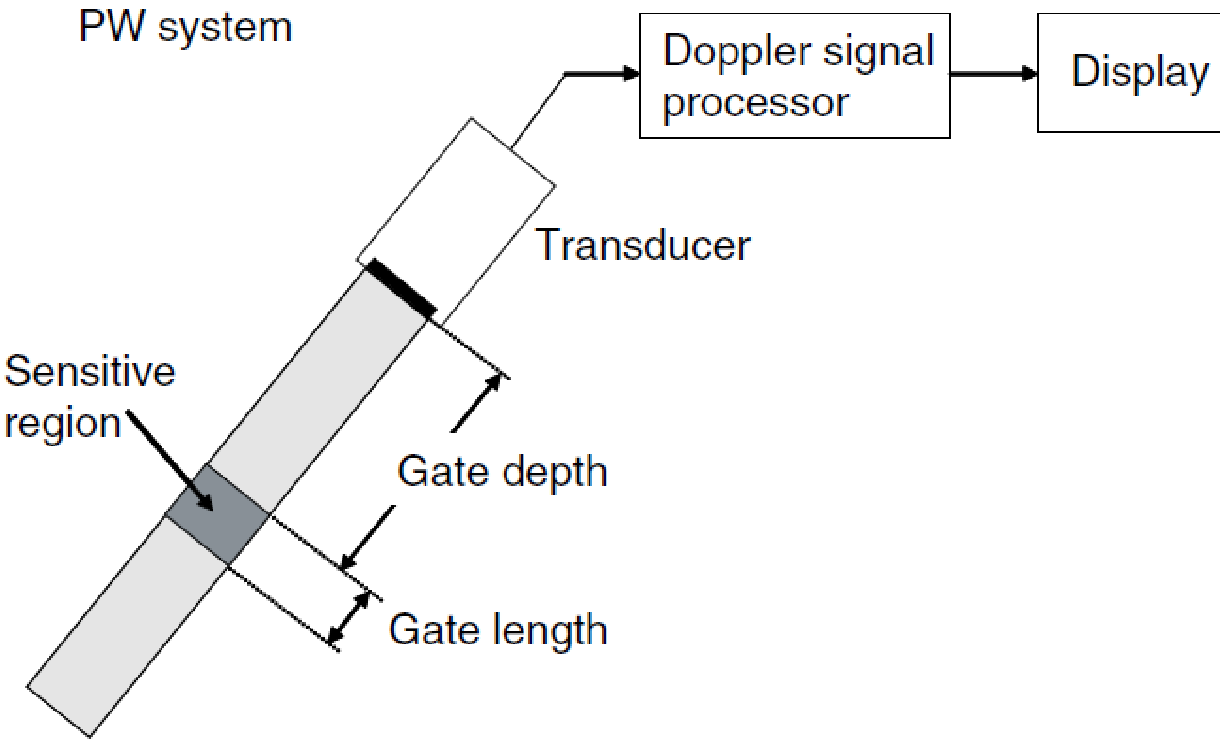
Doppler Ultrasound

- Continuous Wave (CW) Doppler
  - Only a small region for Doppler sensitivity
  - No range information
  - No limitation on maximum velocity and high velocity accuracy



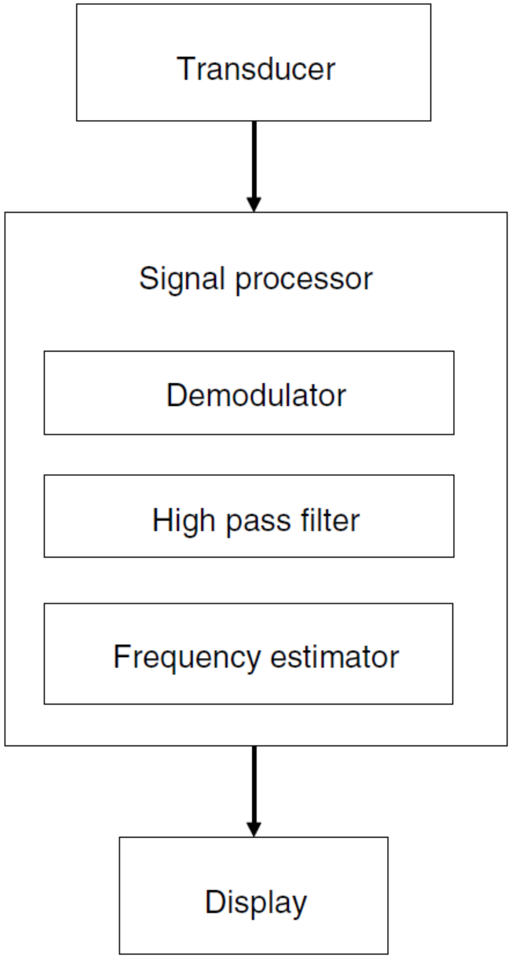
Doppler Ultrasound

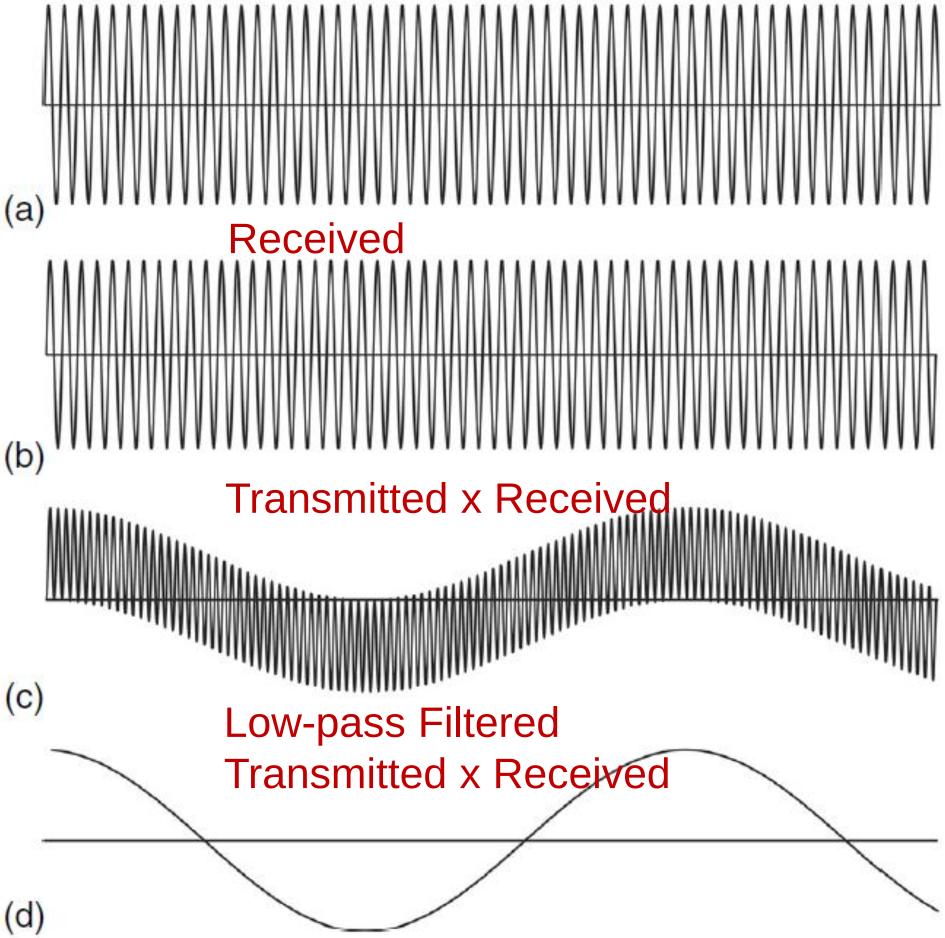
- Pulsed-Wave (PW) Doppler
  - Range information is available and region is selectable by user
  - Limitations on maximum velocity and accuracy



Doppler Ultrasound

- CW Signal Processing





Transmitted

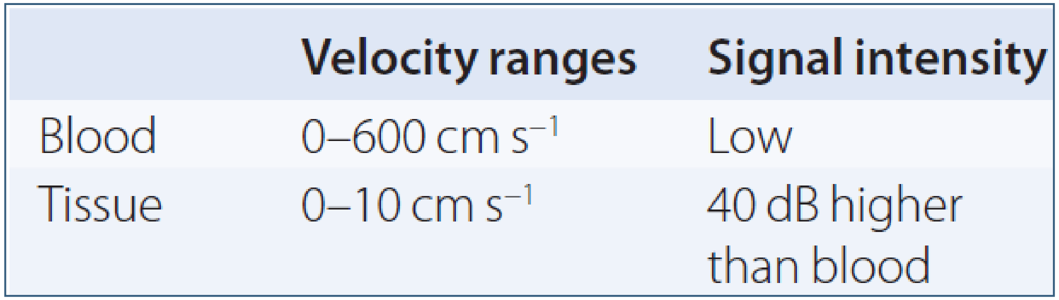
Received

Transmitted x Received

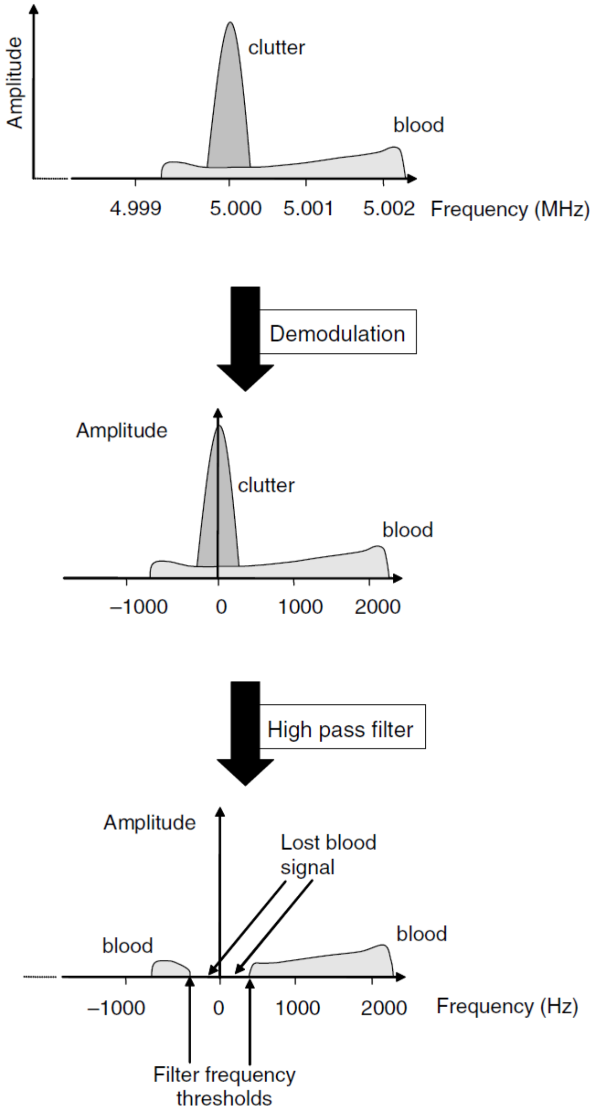
Low-pass Filtered Transmitted x Received

Doppler Ultrasound

- Clutter: signal from stationary tissues
  - Low Doppler shift and much stronger signal
  - Signal from stationary tissue and wall motion
  - Critical step in Doppler processing

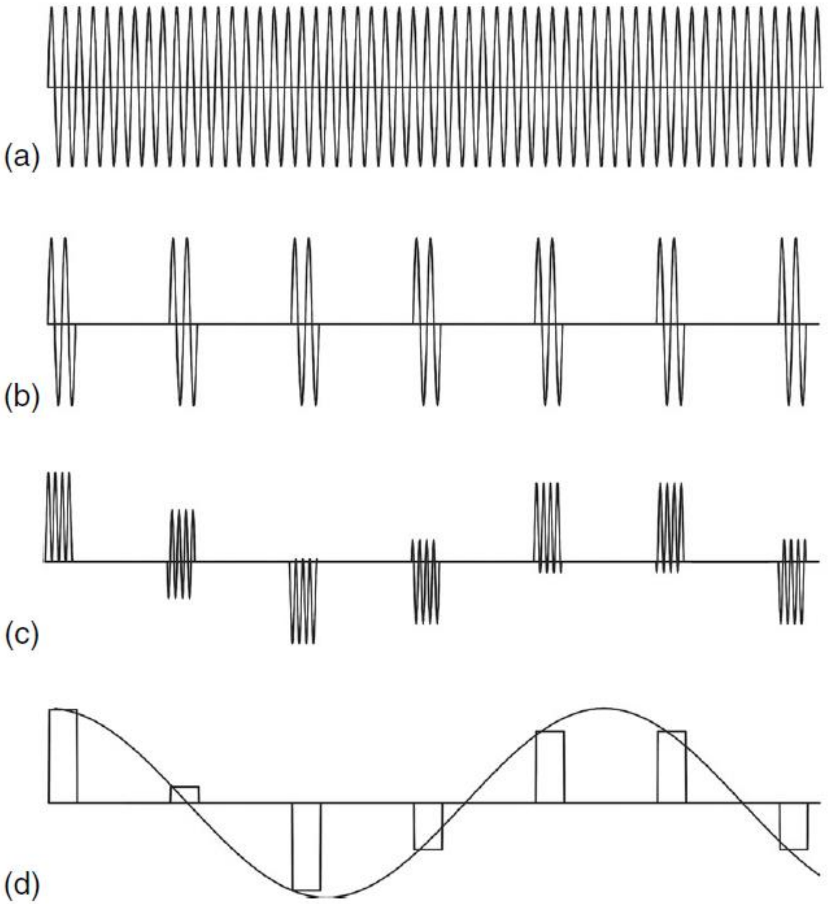


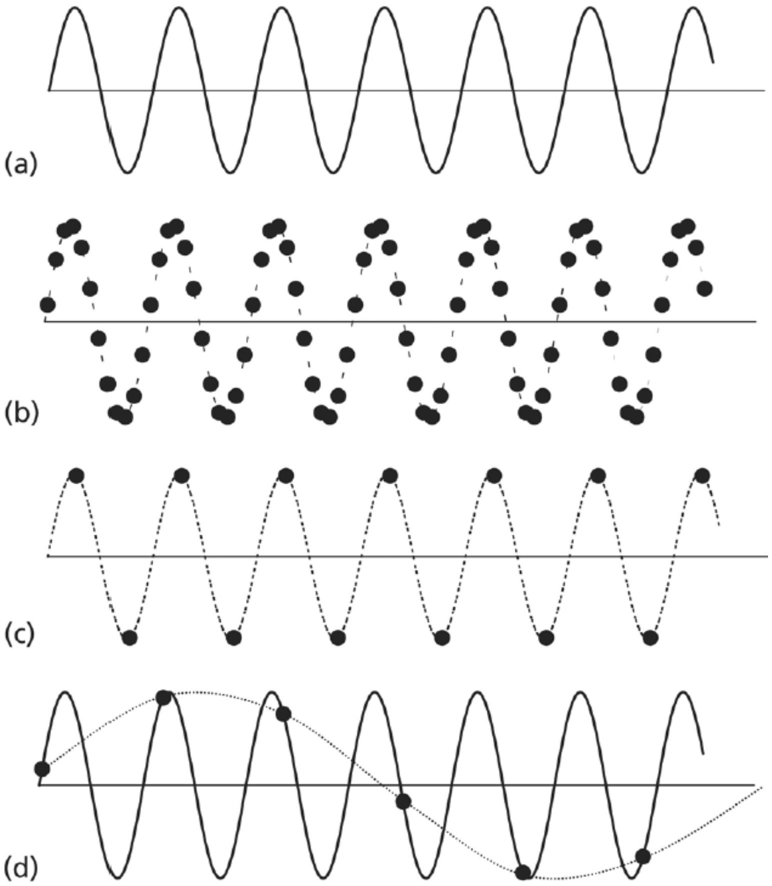
	Velocity ranges	Signal intensity
Blood	0–600 cm s^{-1}	Low
Tissue	0–10 cm s^{-1}	40 dB higher than blood



Doppler Ultrasound

- PW Doppler processing: Sampled version of CW Doppler
  - Aliasing may occur

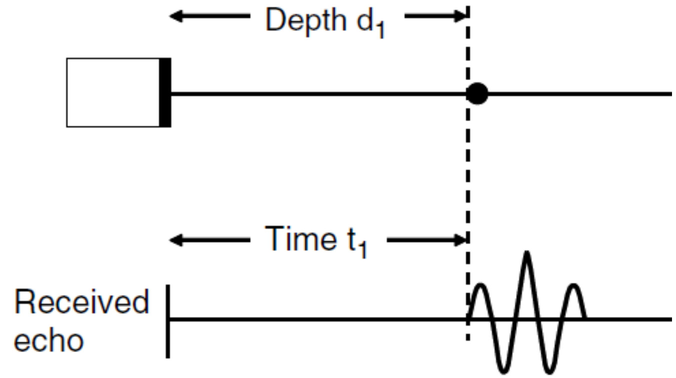




Doppler Ultrasound

- Time-domain PW processing techniques

(a) First pulse, time t_1

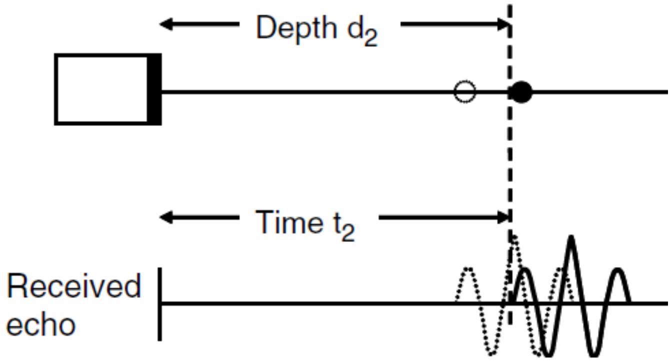


$$d_1 = c\,t_1/2, \qquad d_2 = c\,t_2/2$$

$$d_m = d_2 - d_1$$

$$d_m = c(t_2 - t_1)/2$$

(b) Second pulse, time t_2



$$\mathrm{PRI} = t_2 - t_1 \qquad \mathrm{PRI} = 1/\mathrm{PRF}$$

$$v = d_m / \mathrm{PRI} = (t_2 - t_1)\,c\,\mathrm{PRF}/2$$

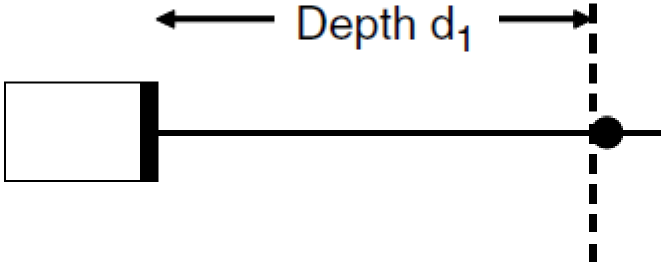
Doppler Ultrasound

- Example: Consider Doppler imaging of a vessel at depth d1= 10 cm. derive the maximum detectible velocity if the transmitted signal frequency was 5 MHz and Doppler angle was 45°.

Time to collect one sample = PRI = 13µs/cm x (10 cm)= 130µs

Sampling frequency = PRF = 1/PRI= 7692 Sa/s = $2\ f_d^{max}$

$$v = \frac{c\, f_d}{2\, f_t \cos\theta} \Rightarrow v_{max}=(1540 \times 7692/2)/(2 \times 5 \times 10^6 \times \cos(45°))$$

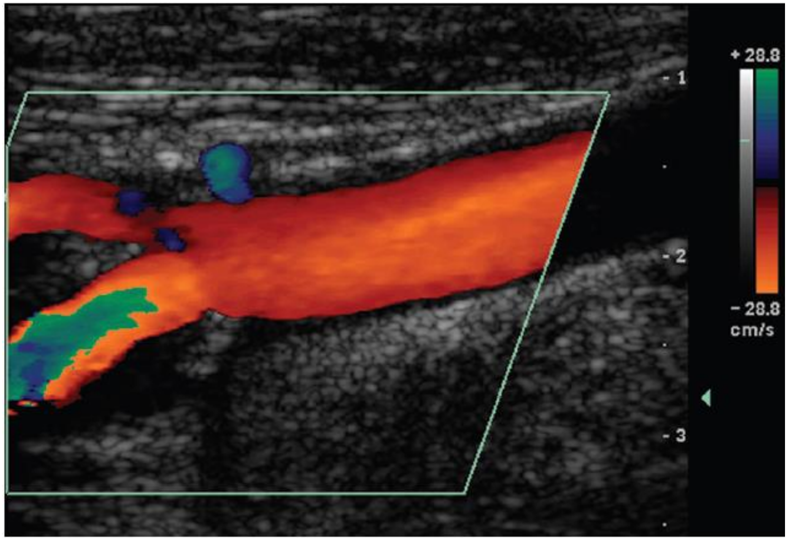


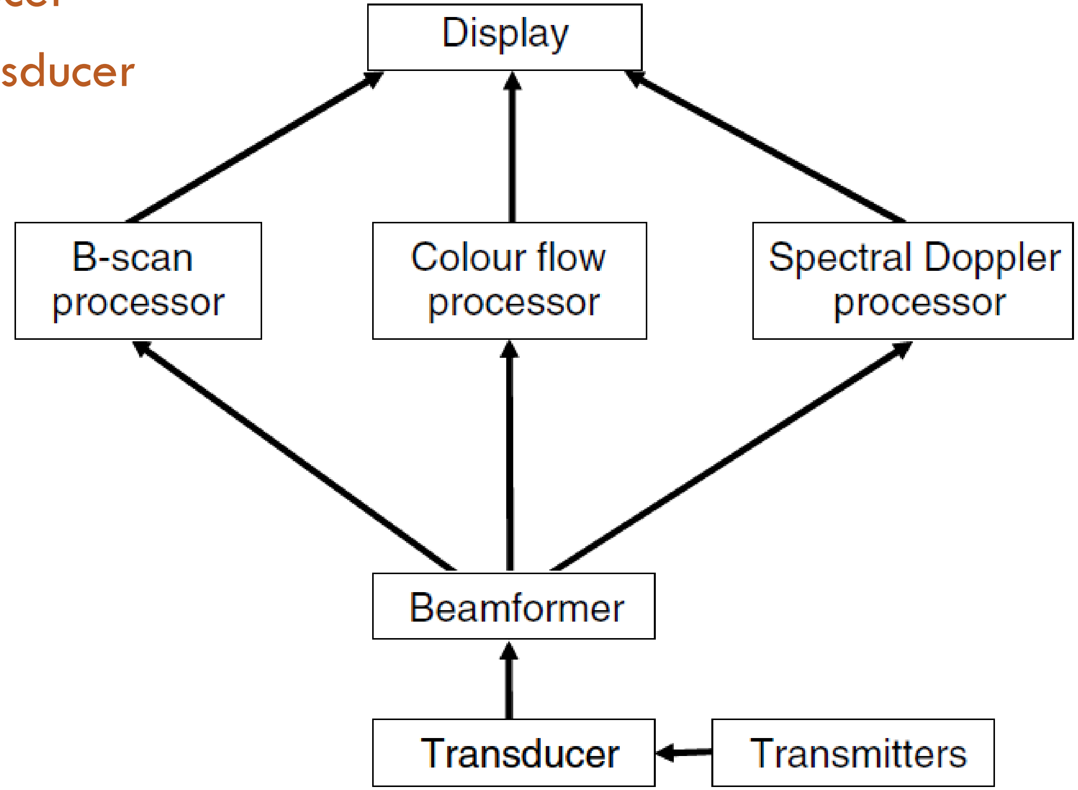
Doppler Ultrasound

- Aliasing
  - Highest Doppler frequency shift that can be measured is equal to PRF/2
- Angle dependence
  - Estimated Doppler shift is dependent on cosine of the angle between the beam and the direction of motion
- Clutter breakthrough
  - Tissue motion giving rise to Doppler frequencies above wall thump or clutter filter may be displayed on spectral Doppler or color flow systems
- Loss of low Doppler
  - Blood velocities which give rise to low Doppler frequencies (as a result of low velocity or angle near to 90°) will not be displayed if value of Doppler frequency is below the level of wall thump or clutter filter

Color Doppler

- Maps mean blood velocity at each points and encodes it in color on the usual B&W ultrasound image
  - Red: flow toward transducer
  - Blue floe away from transducer




Display

B-scan processor

Colour flow processor

Spectral Doppler processor

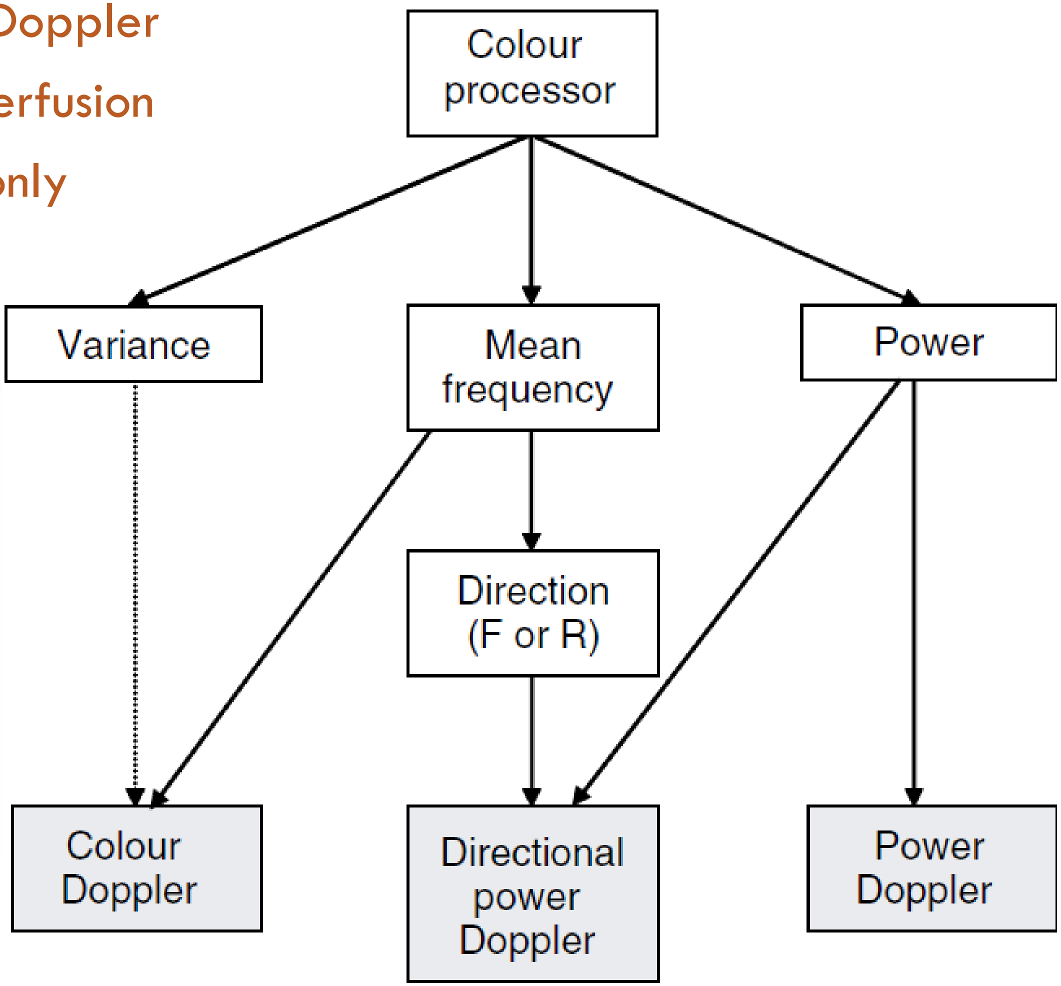
Beamformer

Transducer

Transmitters

Power Doppler

- Estimate of the power of all shifted components
  - Not just mean like in color Doppler
  - Very useful for assessing perfusion
  - Encoded in shades of red only



Colour processor

Variance

Mean frequency

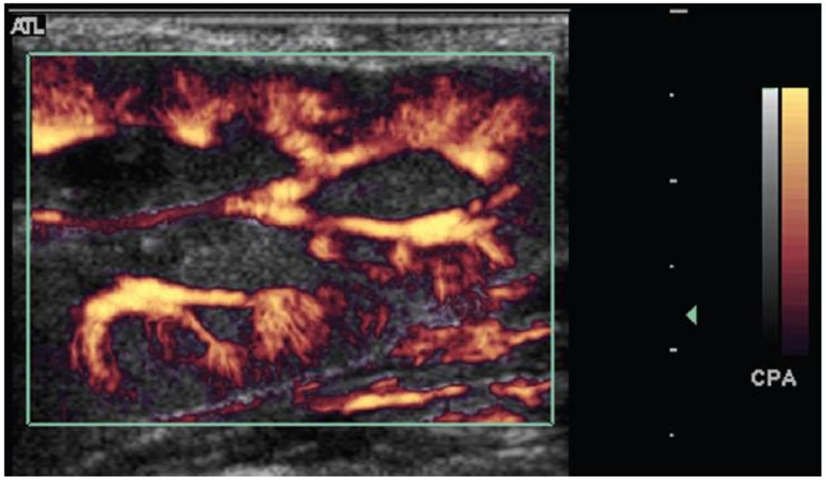
Power

Direction (F or R)

Colour Doppler

Directional power Doppler

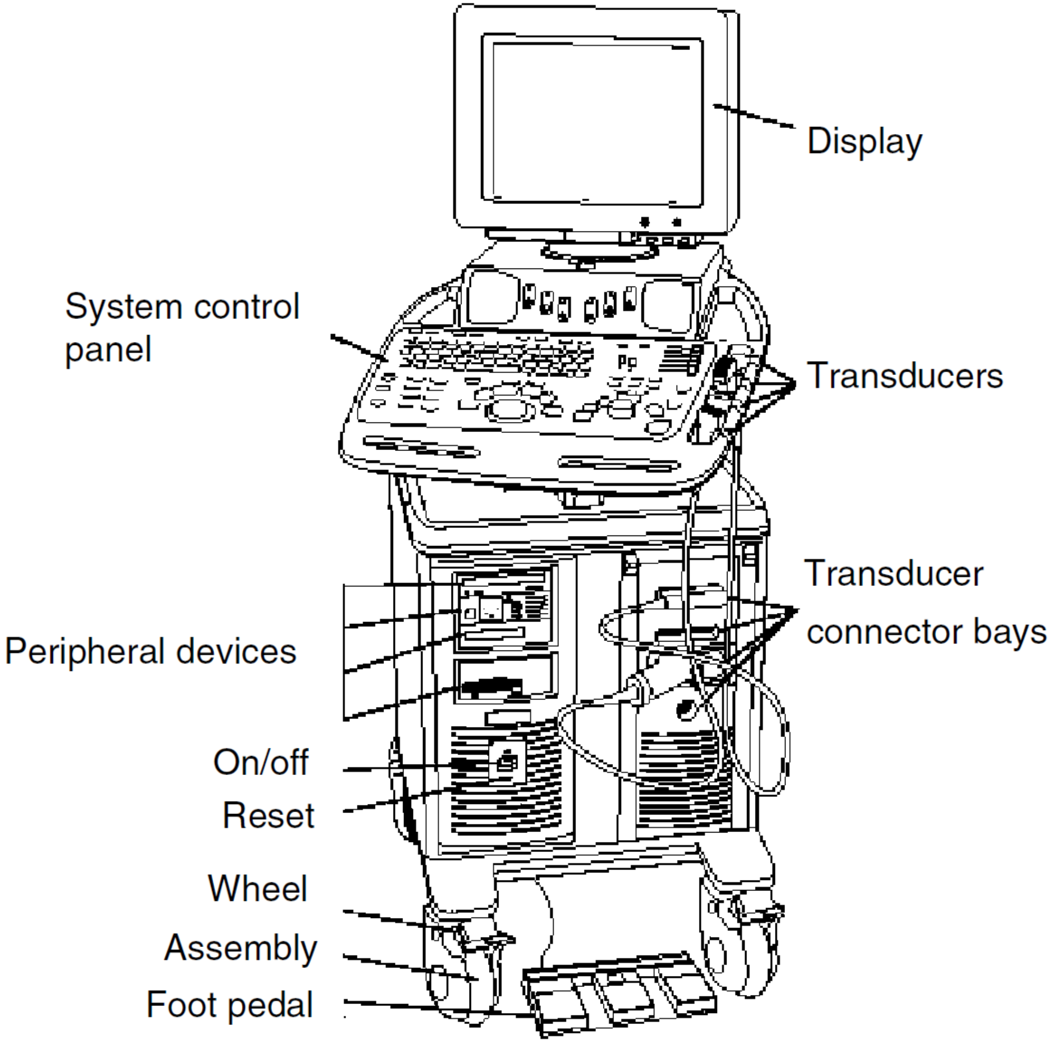
Power Doppler



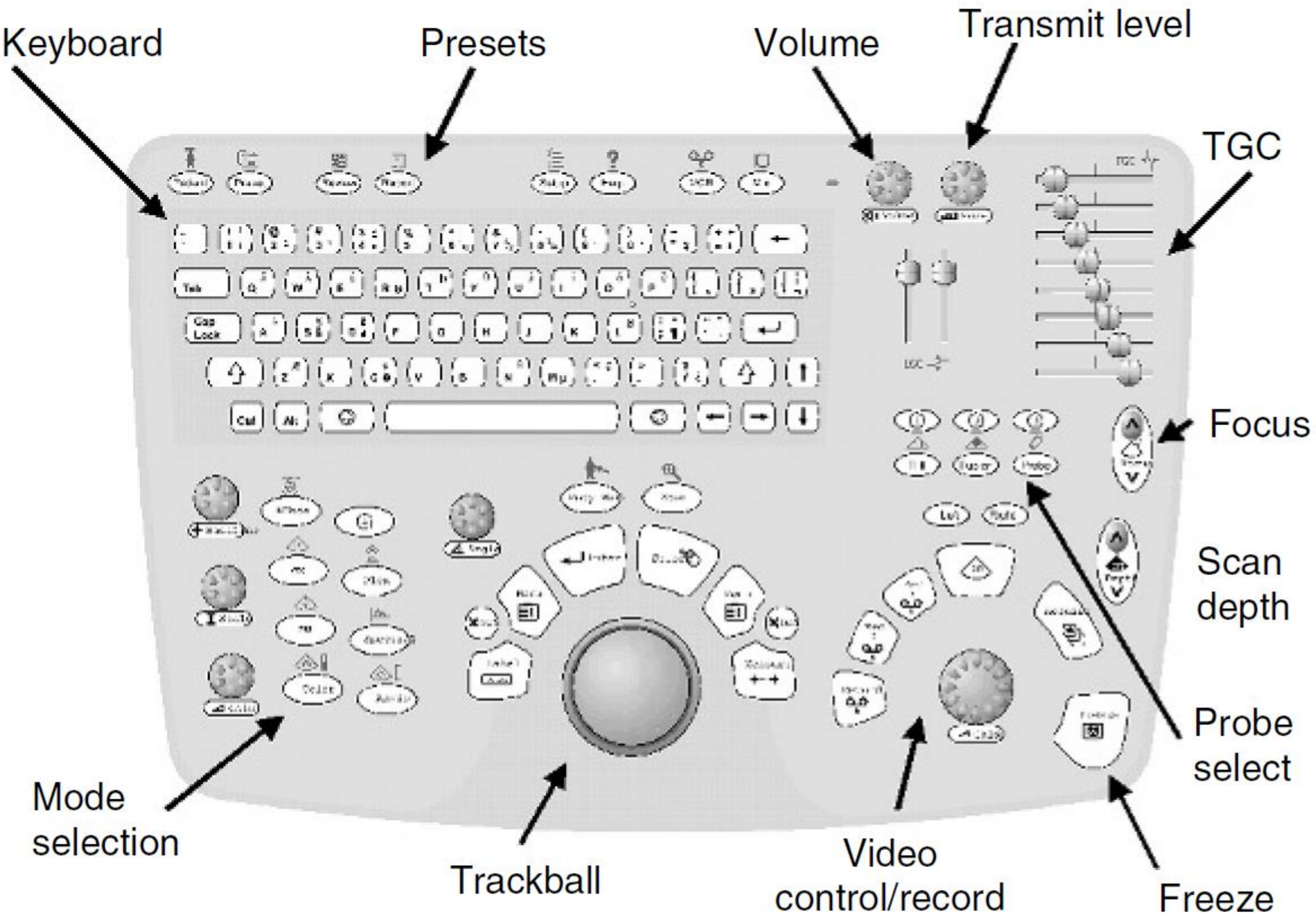
Ultrasound Safety

- A fundamental approach to the safe use of diagnostic ultrasound is to use the lowest output power and the shortest scan time consistent with acquiring the required diagnostic information
  - “ALARA” principle (i.e. as low as reasonably achievable)

Ultrasound Imaging System: External Look



Keyboard Controls



Covered Material and Suggest Problems

- Chapter 2: problems 3, 4, 5, 7, 10
- Chapter 3: problems 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
- Chapter 4: problems 1, 2, 3, 4, 5
- Chapter 7: problems 3, 4, 5, 6, 7, 8
- Consider Doppler blood flow velocity estimation in a vessel at depth of 5 cm and angle of 60°. Find out whether aliasing will occur when estimating blood velocity if the actual velocity in that vessel is 50 cm/s. Let the transmitted signal frequency be 7 MHz.