Medical Imaging (EL582/BE620/GA4426)

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On behalf of
Prof. Daniel Turnbull

Outline

1. Second part of the class lecture as provided by Prof. Turnbull:
   - Will skip 4 slides with equations

- Small break

2. Active ultrasound research topic at Riverside Research
   - Annular-array imaging at high frequencies
   - Small animal and ophthalmologic applications
   - Photoacoustics imaging (if time allows)

Medical Imaging (EL582/BE620/GA4426)

Ultrasound Imaging

Reference

Prince and Links, Medical Imaging Signals and Systems, Chapters 10 & 11

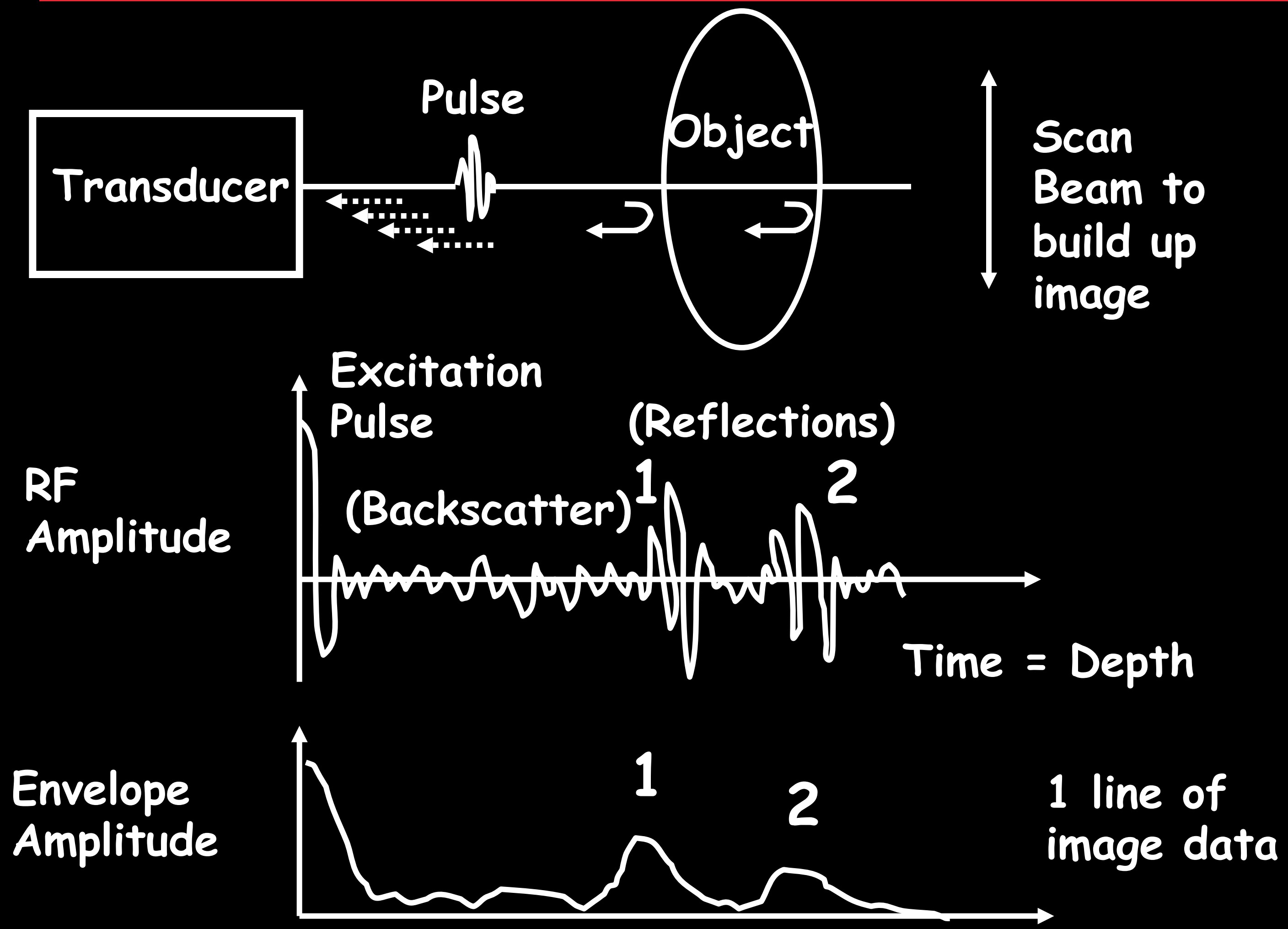
Acknowledgement

Thanks to Professor Yao Wang for use of her course materials!

In vivo microimaging in mice

E10.5 embryo

Pulse-Echo Ultrasound Imaging



Pulse-echo Signal (Complex)

- We will represent the input signal as the Real part of a complex signal

- Complex signal:

$$\mathtt{n}(t) = n_e(t)e^{j\phi}e^{-j2\pi f_0 t}$$

- Complex envelope is $\tilde{n}(t) = n_e(t)e^{j\phi}$
- The pulse is

$$n(t) = \mathrm{Re}\{\mathtt{n}(t)\}$$

- The envelope is

$$n_e(t) = |\mathtt{n}(t)|$$

Plane Wave Approximation

- Excitation pulse envelope arrives at all points at a given range simultaneously.
- Mathematically,

$$\mathtt{n}(t - c^{-1}r_0 - c^{-1}r_0') \approx \mathtt{n}(t - 2c^{-1}z)e^{jk(r_0-z)}e^{jk(r_0'-z)}$$

where wavenumber is

$$k = 2\pi f_0 c^{-1}$$

and range equation gives

$$ct = 2z$$

Field Pattern and Pulse-Echo Equation

- Define field pattern as

$$\boxed{q(x, y, z) = \iint s(x_0, y_0) \frac{z}{r_0^2} e^{jk(r_0 - z)} dx_0 dy_0}$$

- Then received signal (from single scatterer) is

$$\mathtt{r}(x, y, z; t) = KR(x, y, z)\mathtt{n}(t - 2c^{-1}z)[q(x, y, z)]^2$$

General Pulse-Echo Equation

- Define

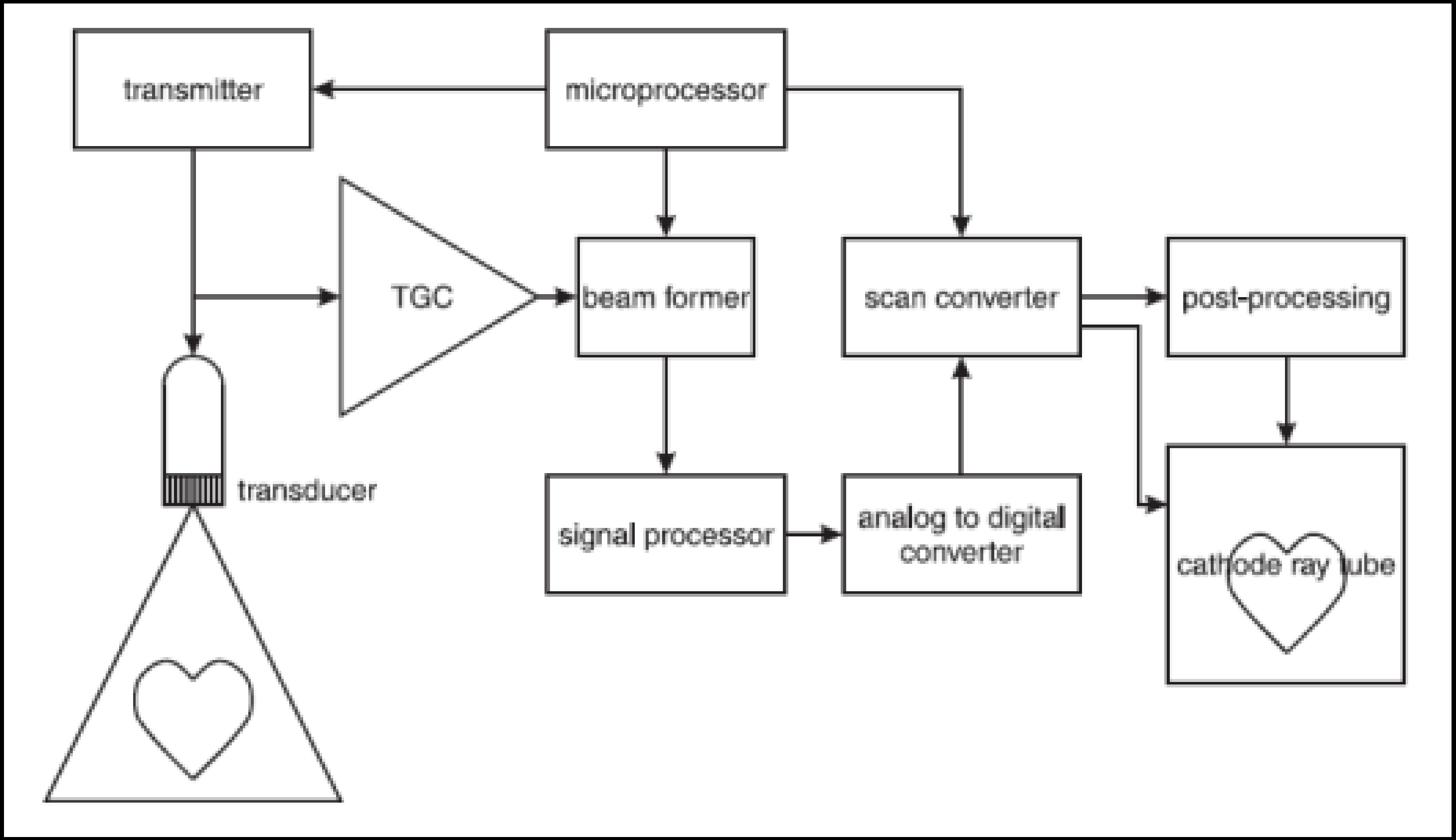
Transducer field pattern

$$\tilde{q}(x,y,z) = zq(x,y,z)$$

- Fresnel or Fraunhofer satisfies

$$\boxed{\begin{aligned} \mathtt{r}(t) = K\frac{e^{-\mu_a ct}}{(ct)^2} \quad & \textbf{TGC} \qquad \textbf{Plane wave assumption} \\ \iiint R(x,y,z)\mathtt{n}(t-2c^{-1}z)\tilde{q}^2(x,y,z)\,dx\,dy\,dz & \end{aligned}}$$

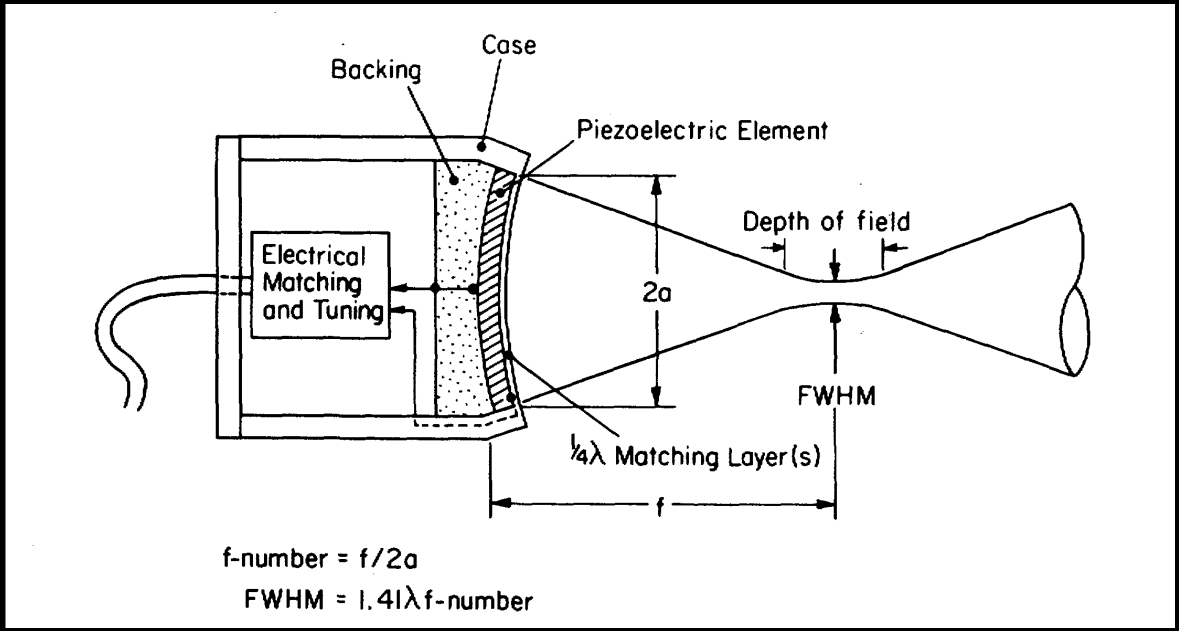
Schematic: Ultrasound Imaging System



Functions of the transducer

- Used both as Transmitter And Receiver
- Transmission mode: converts an oscillating voltage into mechanical vibrations, which causes a series of pressure waves into the body
- Receiving mode: converts backscattered pressure waves into electrical signals

Single Element Transducer



$$DOF = K\lambda\ (f\text{-number})^2$$

From: Hunt *et al*, IEEE Trans BME, 1983

Compromises in ultrasound imaging

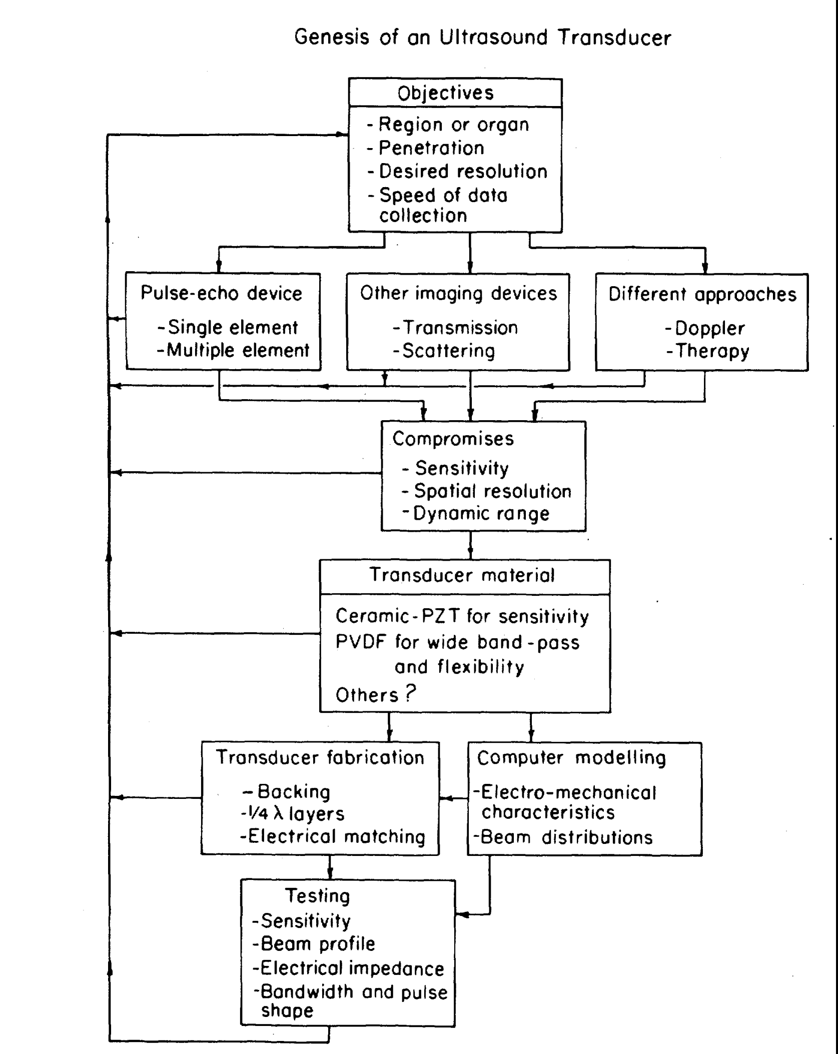
- Resolution (axial and lateral)↑ with ↑frequency
- Penetration↓ with ↑frequency

Compromise between resolution and penetration

- Lateral resolution↓ with↑ f-number
- Depth of field↑ with↑f-number

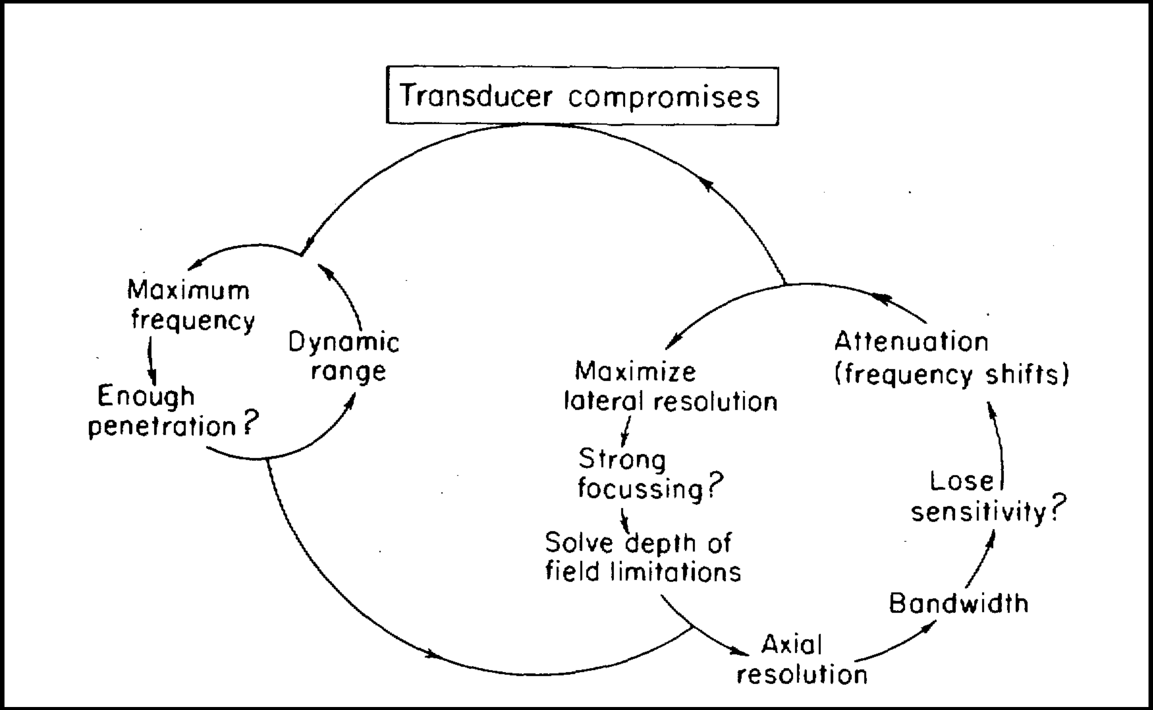
Compromise between focusing and DOF

Transducer Design Concepts



From: Hunt *et al*, IEEE Trans BME, 1983

Transducer Design Concepts



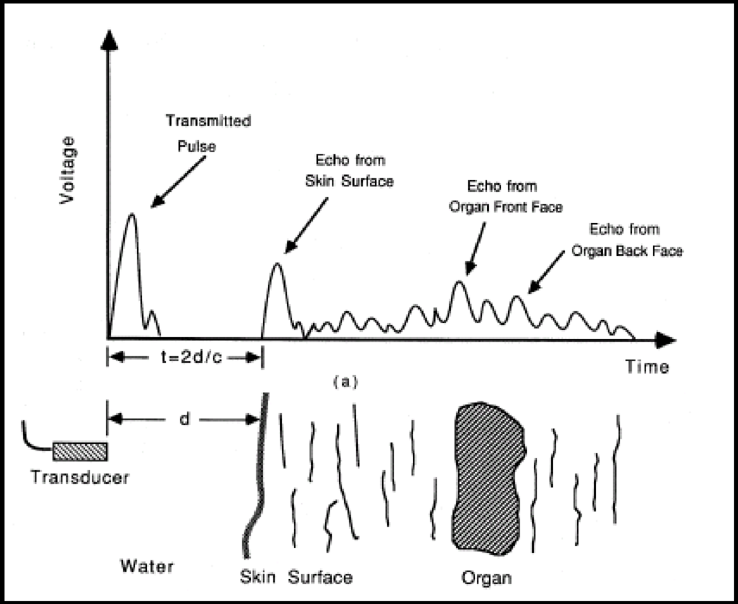
From: Hunt *et al*, IEEE Trans BME, 1983

Ultrasound Imaging Modes

- A-mode
- M-mode
- B-mode

A-Mode Display

- Oldest, simplest type
- Display of the envelope of pulse-echoes vs. time, depth $d = ct/2$
  - Measure the reflectivity at different depth below the transducer position

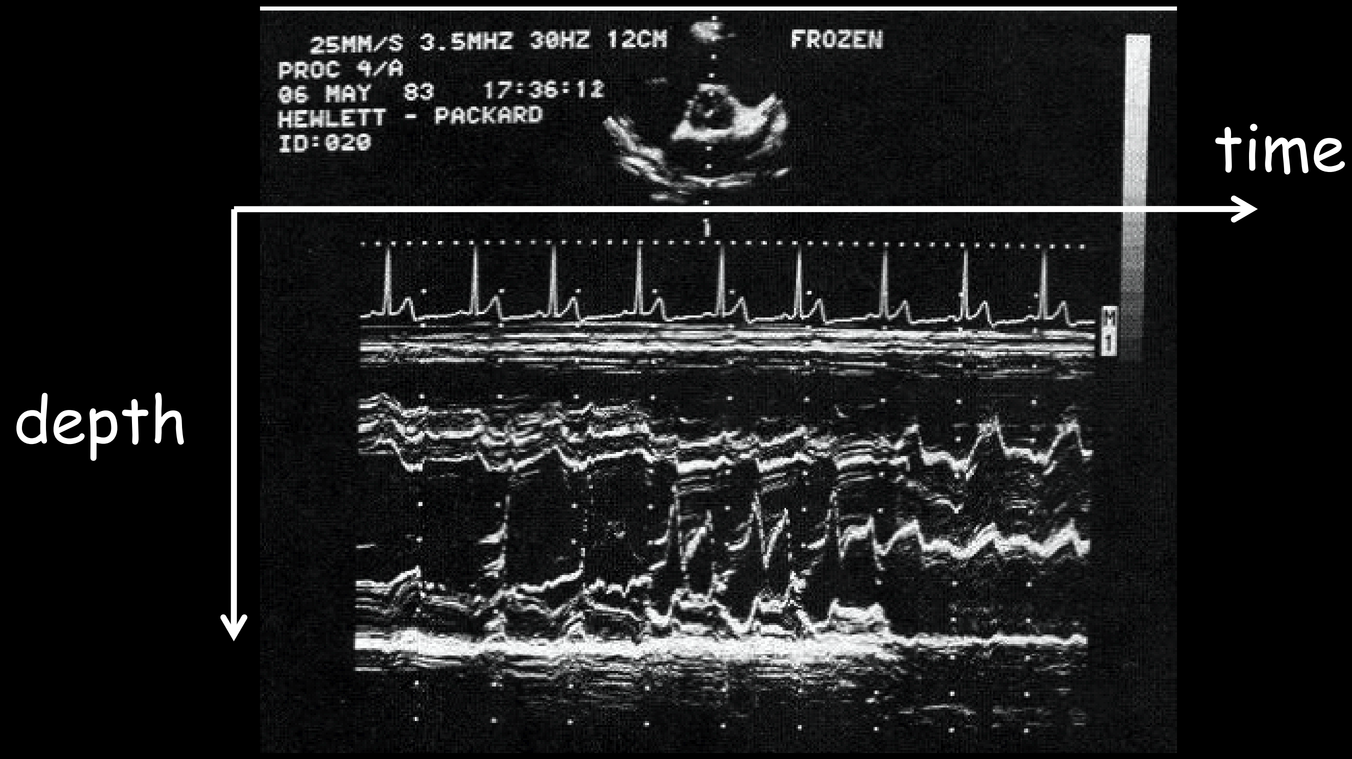


Application of A-Mode

- Applications: ophthalmology (eye length, tumors), localization of brain midline, liver cirrhosis, myocardium infarction
- Frequencies: 2-5 MHz for abdominal, cardiac, brain (lower for brain); 5-20 MHz for ophthalmology, pediatrics, peripheral blood vessels
- Used in ophthalmology to determine the relative distances between different regions of the eye and can be used to detect corneal detachment
  - High frequecy is used to produce very high axial resolution
  - Attenuation due to high frequency is not a problem as the desired imaging depth is small

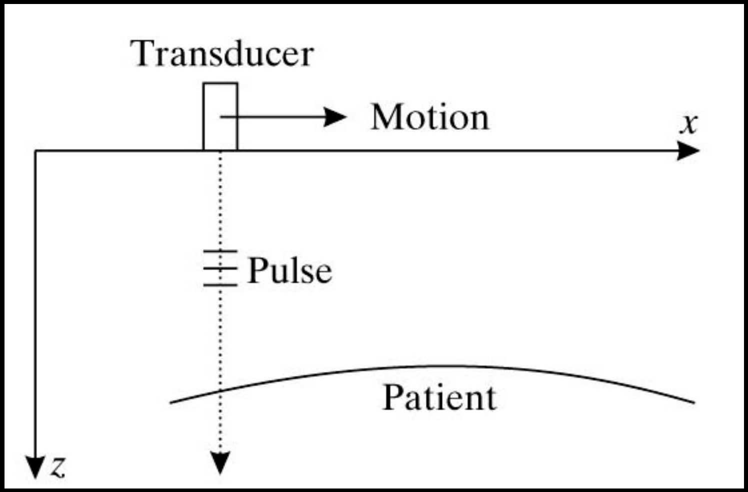
M-Mode

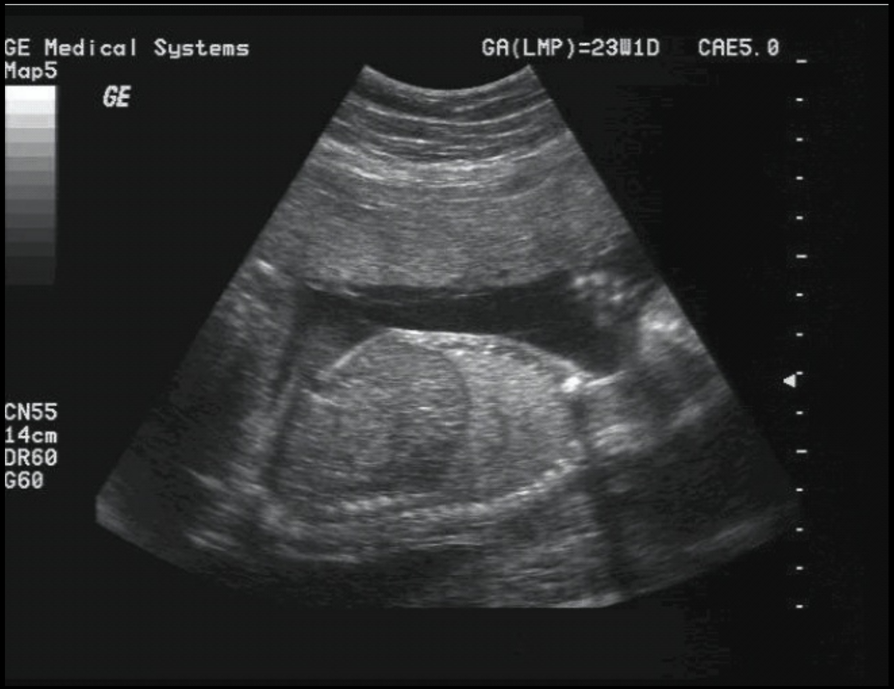
- Display the A-mode signal corresponding to repeated input pulses in separate column of a 2D image, for a fixed transducer position
  - Motion of an object point along the transducer axis (z) is revealed by a bright trace moving up and down across the image
  - Used to image motion of the heart valves, in conjunction with the ECG



B-Mode Display

- Move the transducer in x-direction while its beam is aimed down the z-axis, firing a new pulse after each movement
- Received signal in each x is displayed in a column
- Unlike M-mode, different columns corresponding to different lateral position (x)
- Directly obtain reflectivity distribution of a slice!





Application of B-Mode

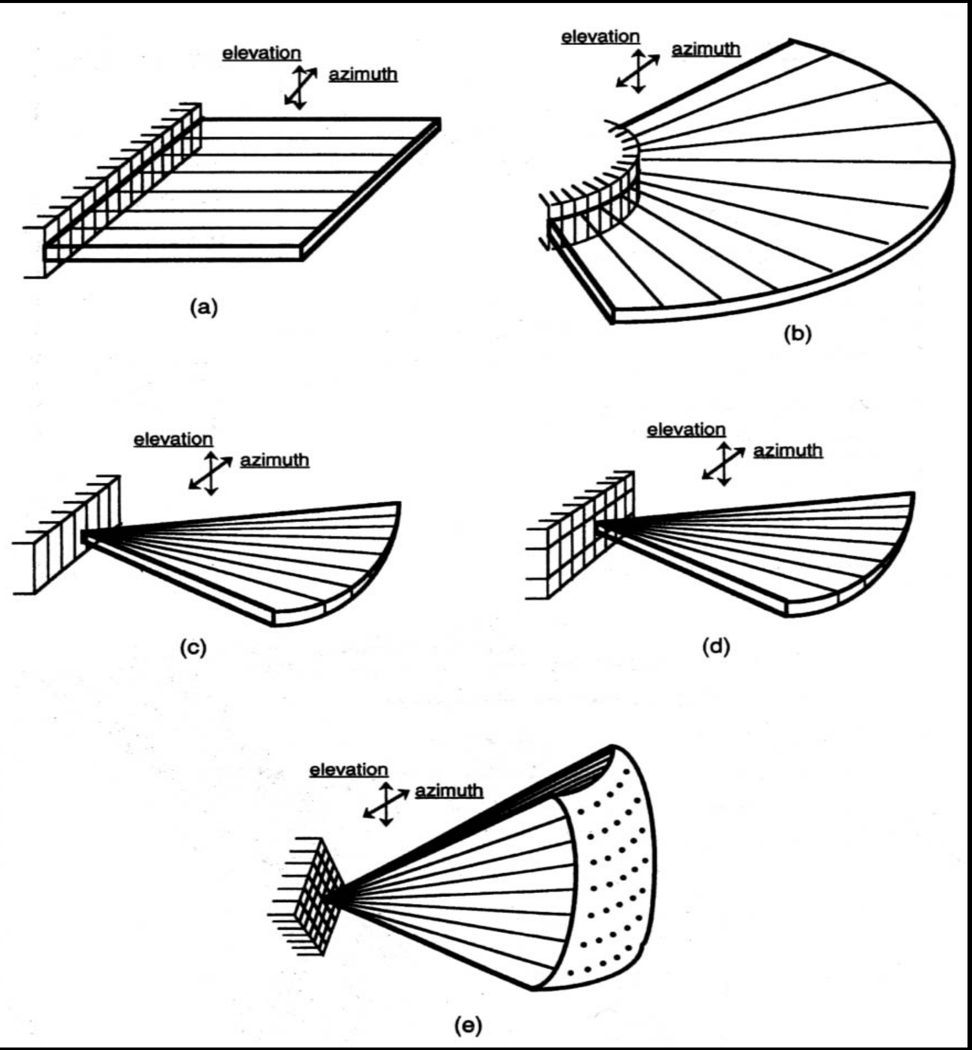
- Can be used to study both stationary and moving structures
- High frame rate is needed to study motion
- Directly obtain reflectivity distribution of a slice
  - No tomographic measurement and reconstruction is necessary!

Transducer Array

- With a single crystal, manual or mechanical steering of the beam is needed to produce a two-dimensional image
- Practical systems today use an array of small piezoelectric crystals
  - Allow electronic steering of the beam to optimize the lateral resolution

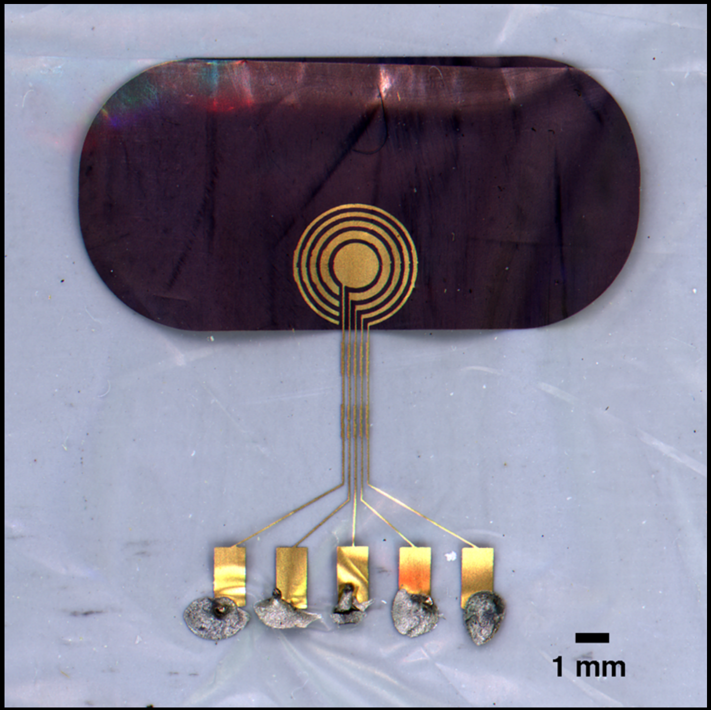
Array types

a) Linear Sequential (switched)
~1 cm × 10-15 cm, up to 512 elements
b) Curvilinear
similar to (a), wider field of view
c) Linear Phased
up to 128 elements, small footprint → cardiac imaging
d) 1.5D Array
3-9 elements in elevation allow for focusing
e) 2D Phased
Focusing, steering in both dimensions

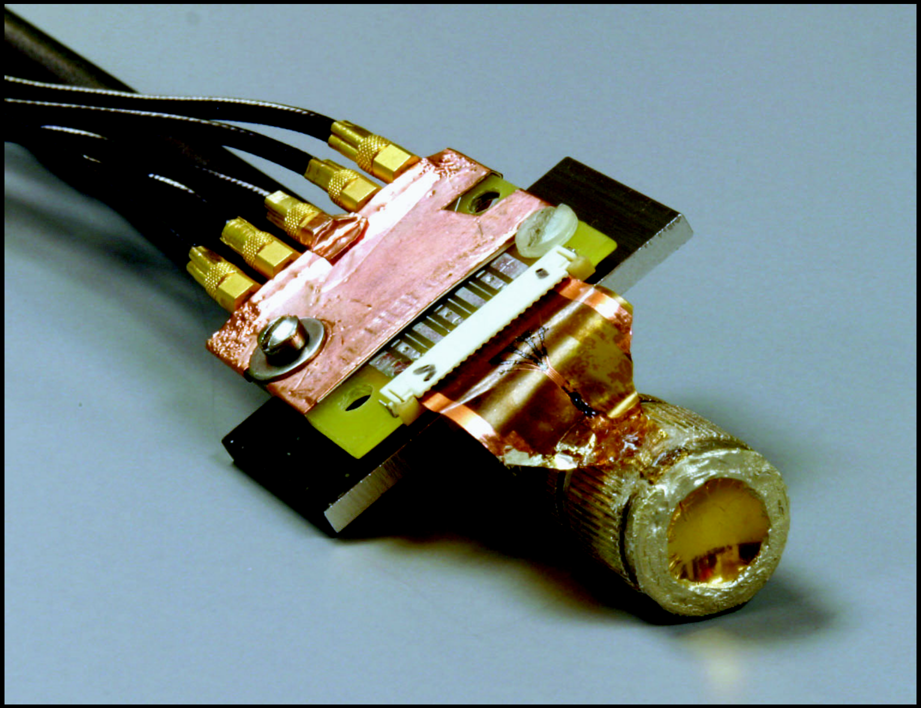


40-MHz annular array transducers for dynamic focusing

5-element array pattern



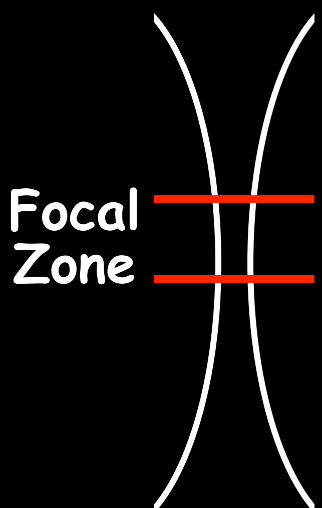
Prototype transducer



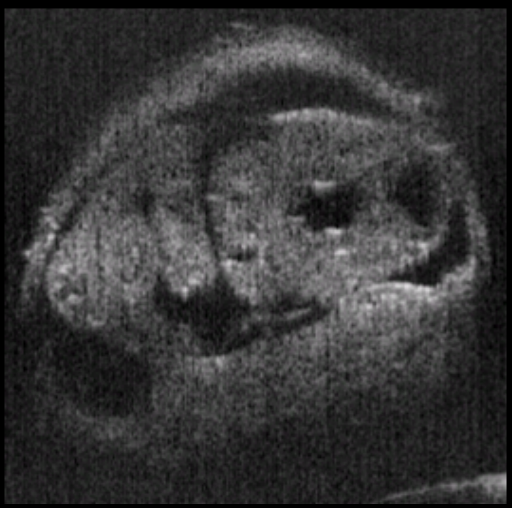
Ketterling et al, IEEE Trans UFFC 2005

Annular array transducer improves focusing in depth

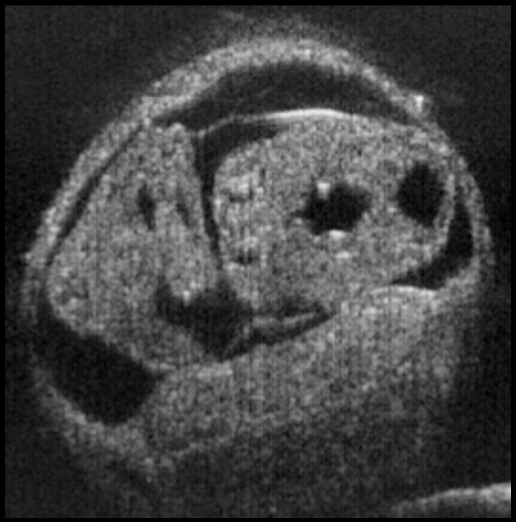
E11.5 Mouse Embryo

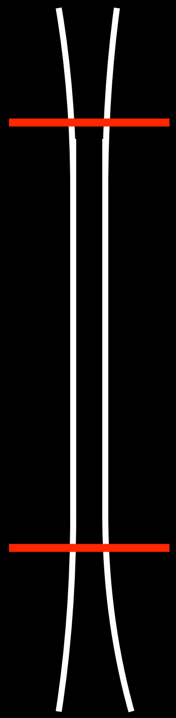


Fixed-Focus



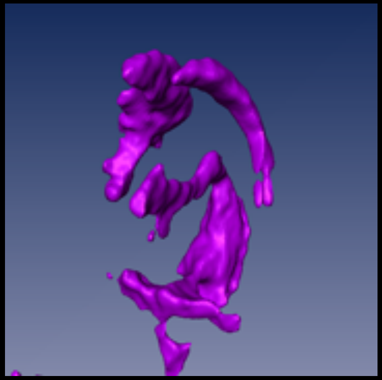
Array-focus





3-D Imaging

- By mechanically or manually scanning a phased array transducer in a direction perpendicular to the place of each B-mode scan
- By electronically steering the beams to image different slices

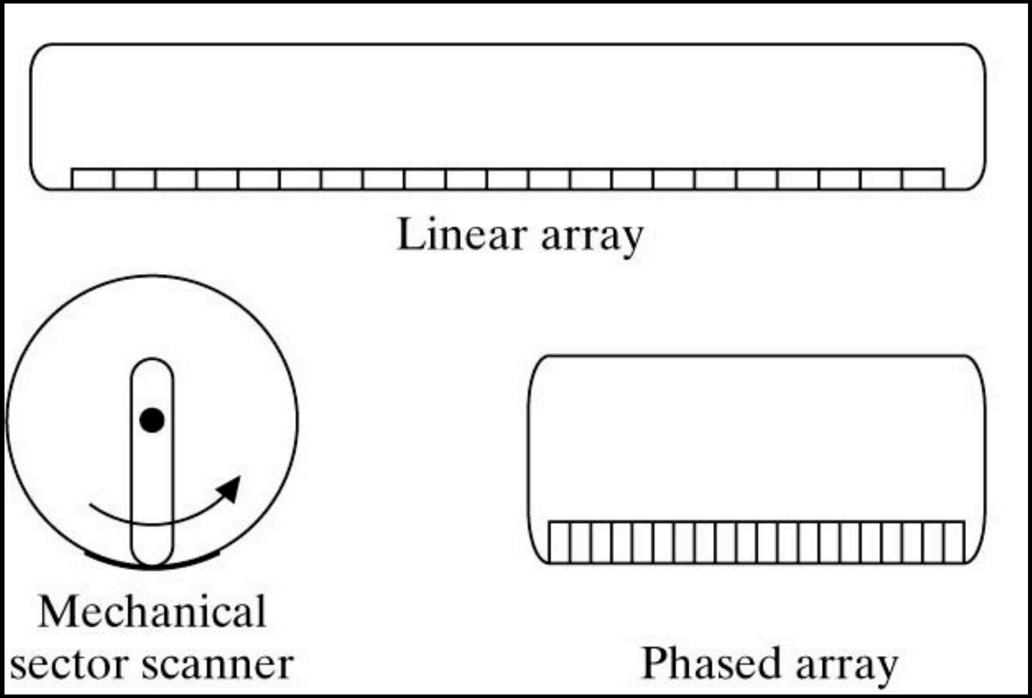


Ventricle Segmentation

Aristizábal et al, Ultrasound Med Biol, 2006

B-mode Scanner Types

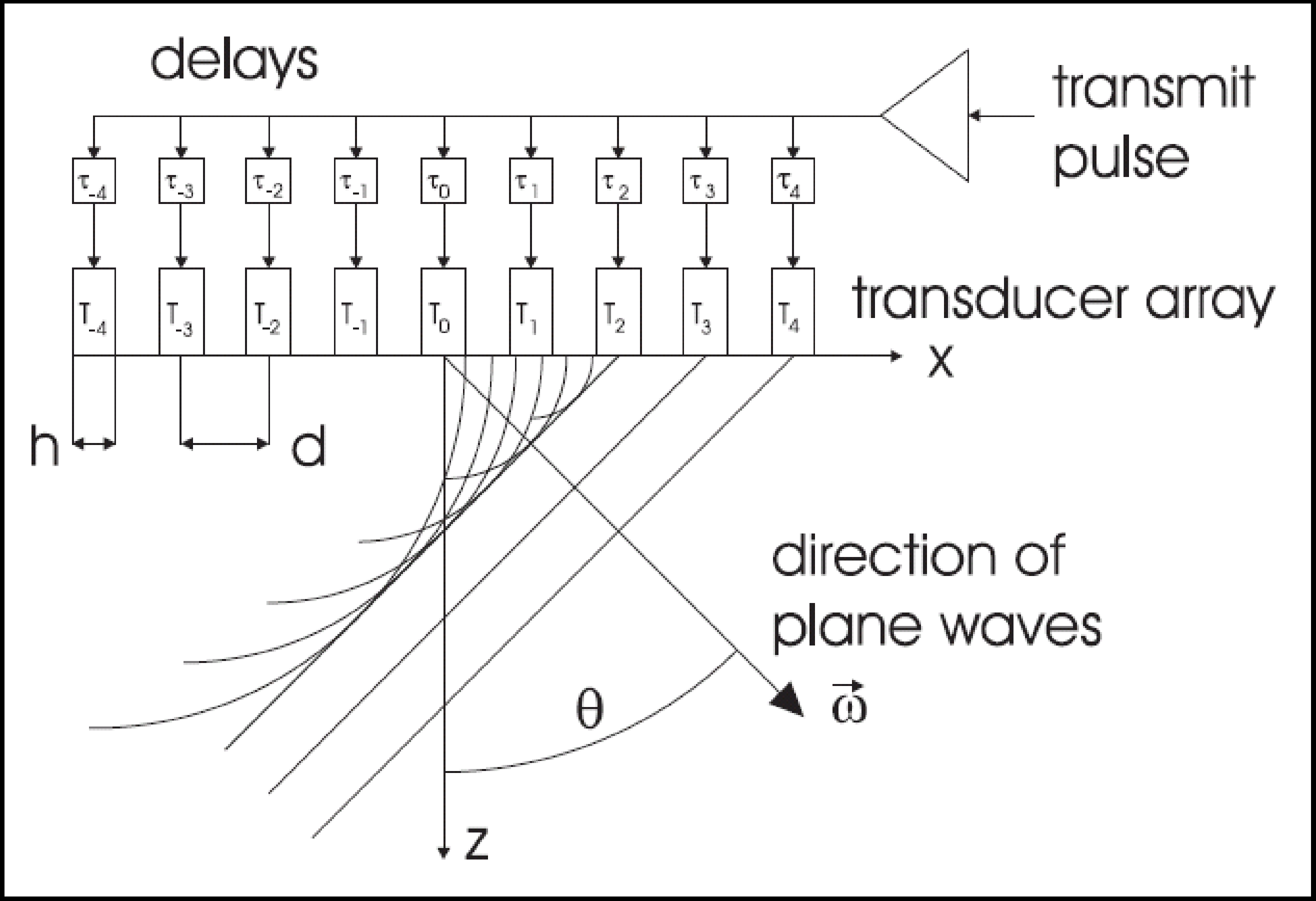
- B-mode scanners use multiple transducers



Phased Arrays

- Phased array:
  - Much smaller transducer elements than in linear array
  - Use electronic steering/focusing to vary transmit and receive beam directions

Beam Steering (Transmit)



Delays for Steering

- Extra distance that T0 travels than T1:

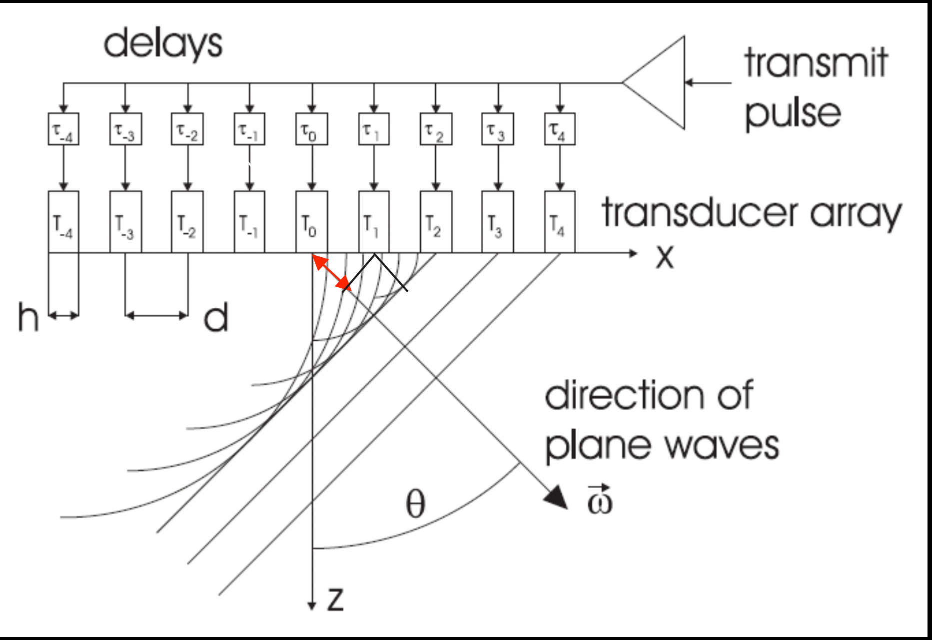
  $$\Delta d = d \sin\theta$$

- For the wave from T1 to arrive at a point at the same time as T0, T1 should be delayed by

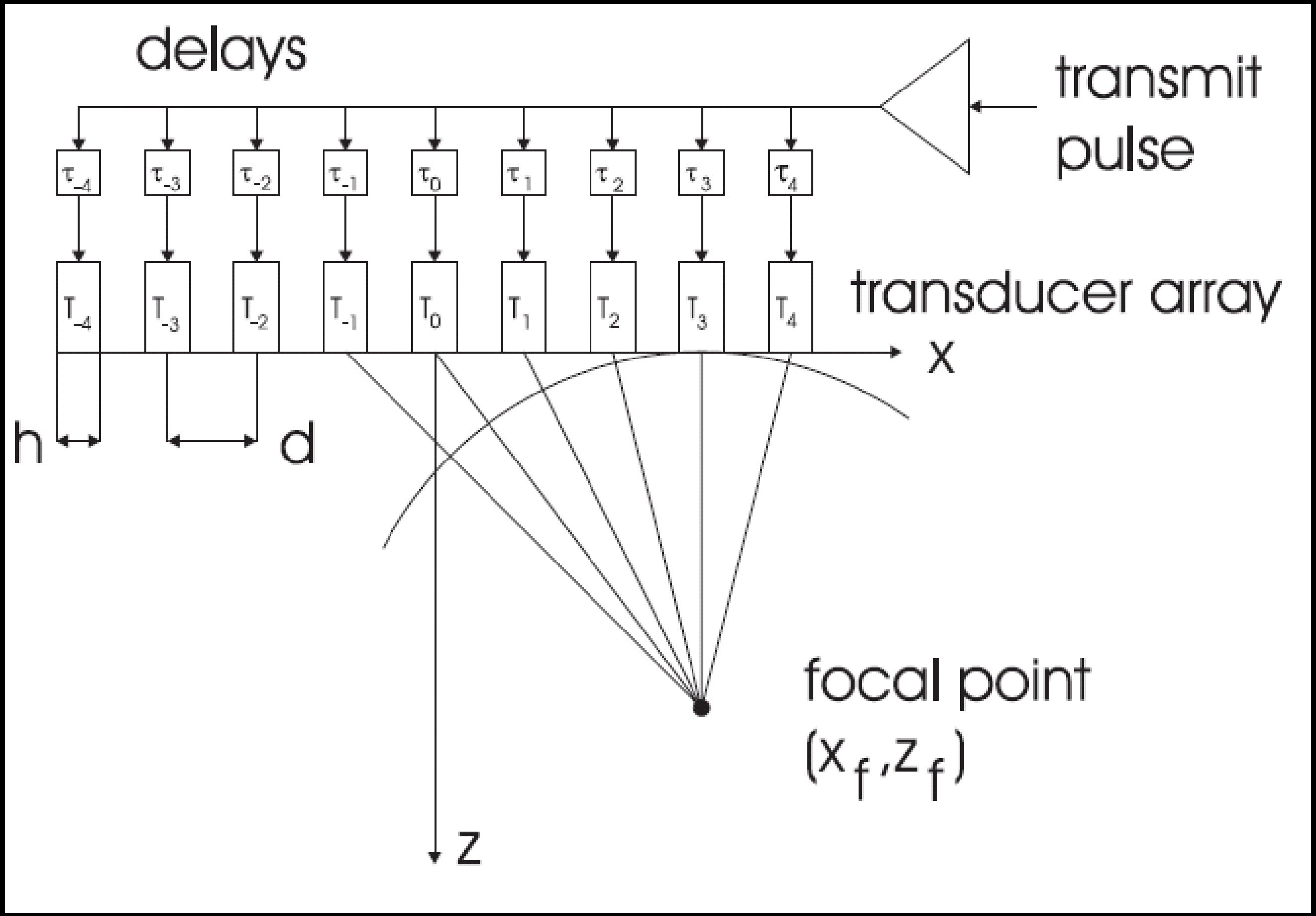
  $$\Delta t = \Delta d/c = d \sin\theta/c$$

- If T0 fires at t=0, Ti fires at

  $$t_i = i\Delta t = id \sin\theta/c$$



Beam Focusing (Transmit)



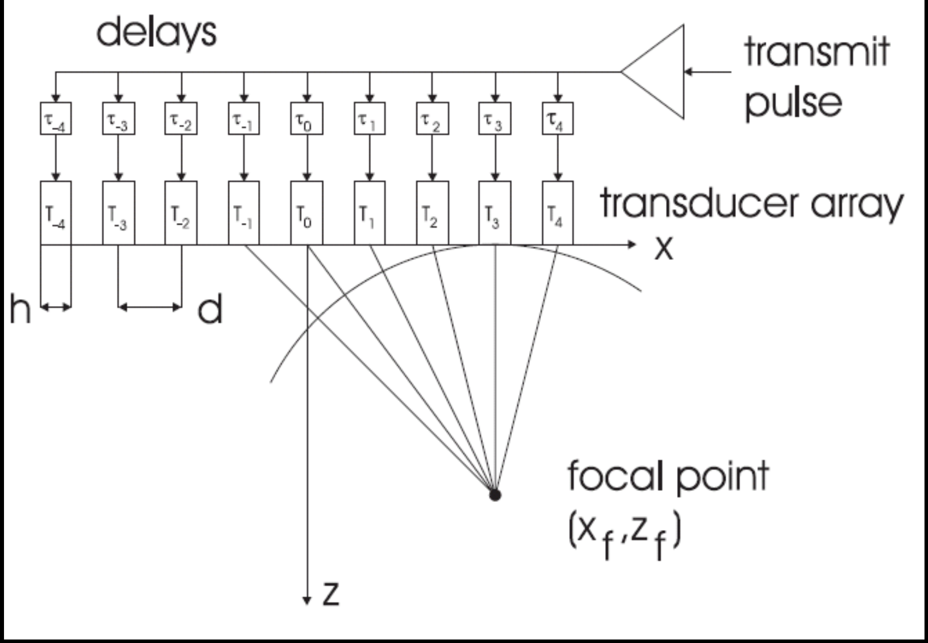
Delays for Focusing

- Focal point at (x_f, z_f)
- T_i is at $(id, 0)$.
- Then range from T_i to focal point is:

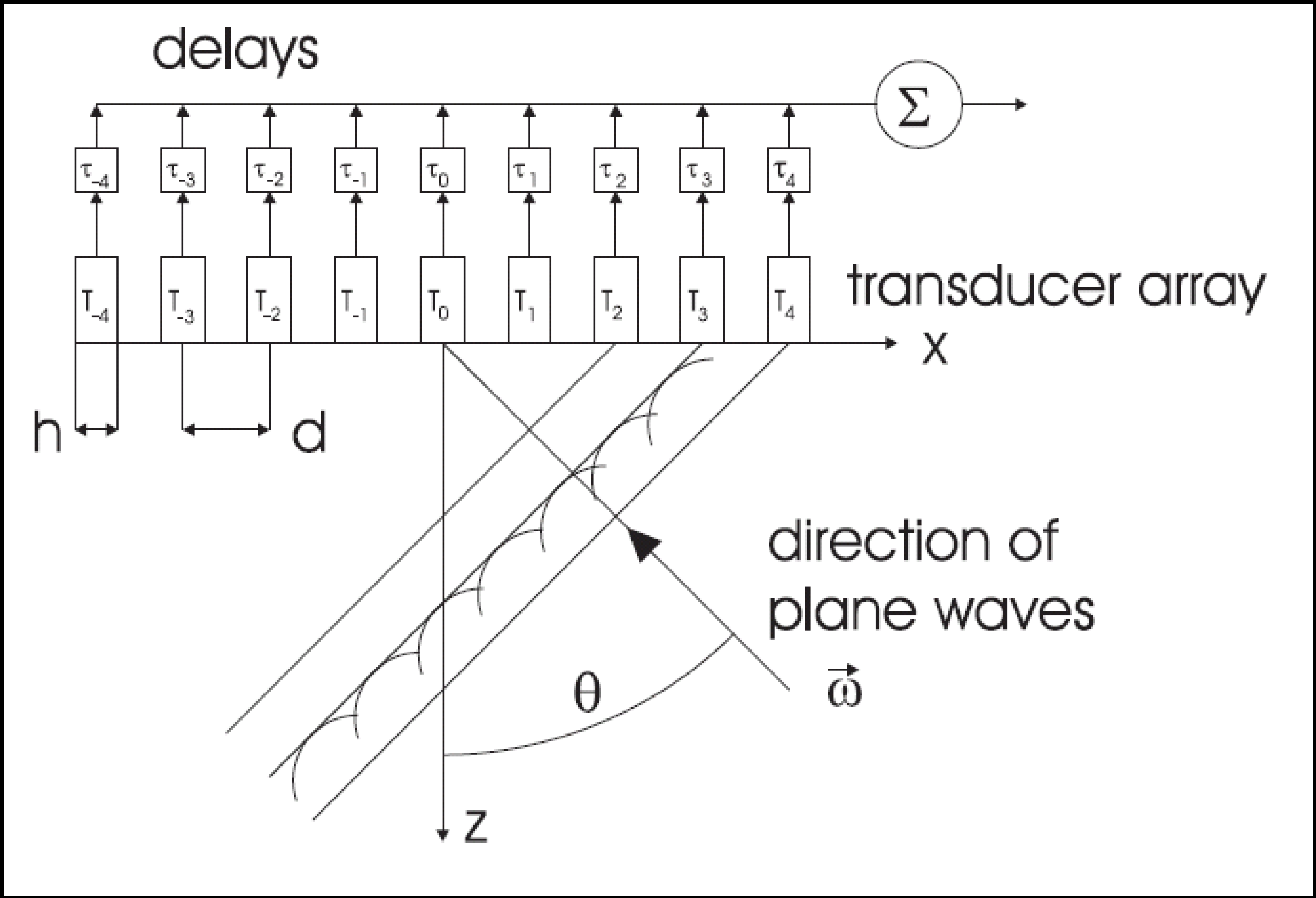
$$r_i = \sqrt{(id - x_f)^2 + z_f^2}$$

- Assume T_0 fires at $t = 0$. Then T_i fires at

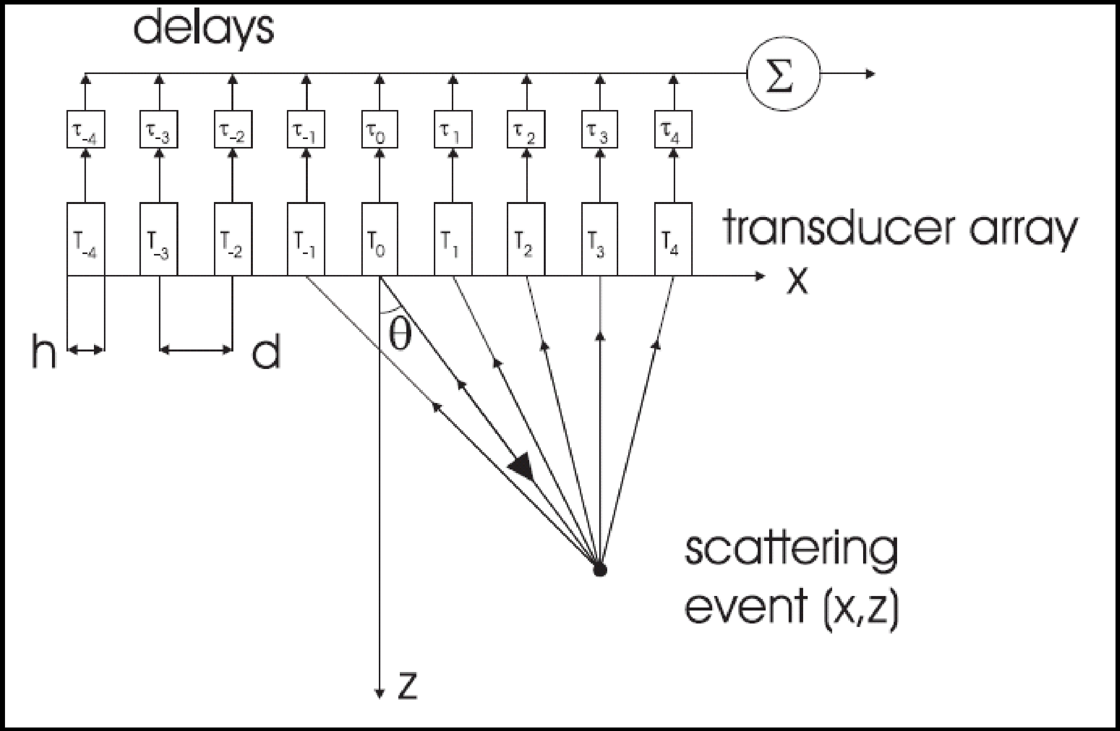
$$\begin{aligned} t_i &= \frac{r_0 - r_i}{c} \\ &= \frac{\sqrt{x_f^2 + z_f^2} - \sqrt{(id - x_f)^2 + z_f^2}}{c} \end{aligned}$$



Receive Beamforming



Receive Dynamic Focusing



T0 fires in direction θ, and all Ti's receive after a certain delay, so that they are all receiving signal from the same point at a particular time

Delays for Dynamic Focusing

- First consider a stationary scatterer at (x,z)
- Time for a wave to travel from T0 to the scatterer and then to Ti is
  $t_i = \{(x^2+z^2)^{1/2} + [(id-x)^2+z^2]^{1/2}\}/c$

- Time difference between arrival time at T0 and at Ti
  $\Delta t_i = t_0 - t_i$

- Desired time delay is a function of t:

$$\tau_i(t) = t - \frac{\sqrt{(id)^2 + (ct)^2 - 2ctid\sin\theta}}{c} + \frac{Nd}{c}$$

Practicalities of dynamic focusing

- Steer and focus the transmit beam in direction θ
- Focus the receive beam dynamically along that direction
- Increment steering direction to $\theta + \Delta\theta$
- Repeat for the new direction / image line

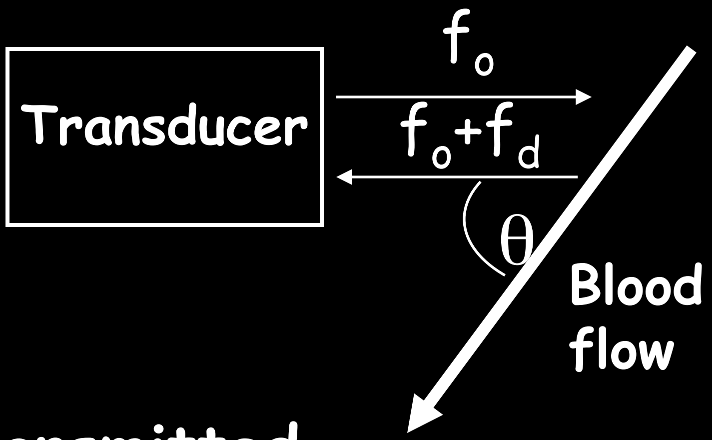
Steering and Focusing: Summary

- Beam steering and focusing are achieved simply by applying time delays on transmit and receive
- The time delays are computed using simple geometrical considerations, and assuming a single speed of sound
- These assumptions may not be correct, and may lead to artifacts

Doppler Ultrasound: Reminder

- Doppler Equation:

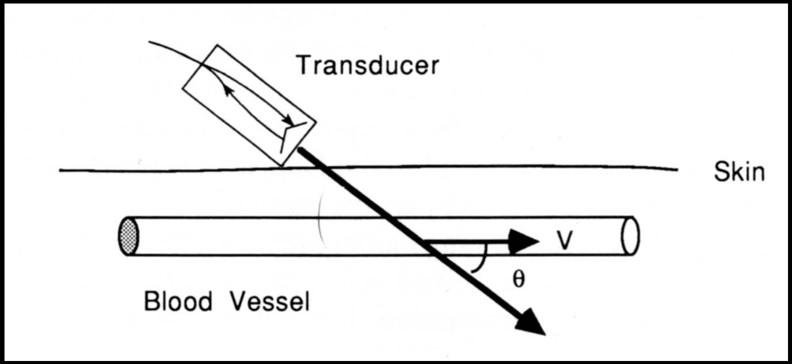
$$f_d = 2f_o . v . \cos\theta / c$$

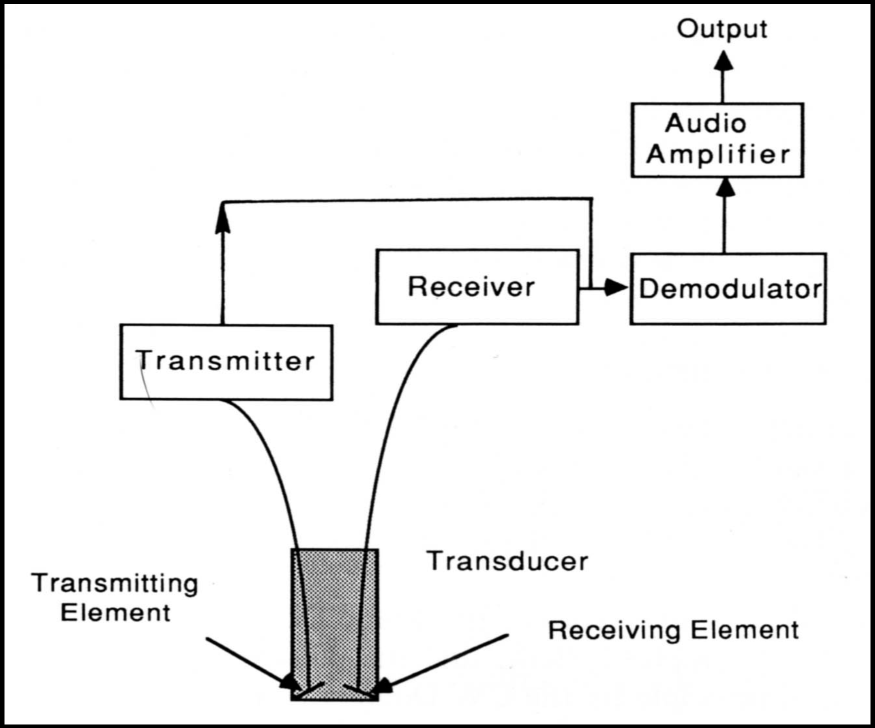


  - f_o is the frequency transmitted
  - v is the velocity of the moving blood
  - c is the sound speed in the medium (blood, ~1600 m/s)

Doppler Ultrasound Instrumentation

CW Doppler (2 transducers)





Pulse Mode Doppler Measurement

- Use only one transducer
  - Transmits short pulses and receives backscattered signals a number of times
- Can measure Doppler shifts at a specific depth

Doppler Imaging via Time Correlation

- Performing correlation of two signals detected at two different times
- Deducing the time shift (correspondingly distance traveled) that yields maximum correlation
- Determine the velocity

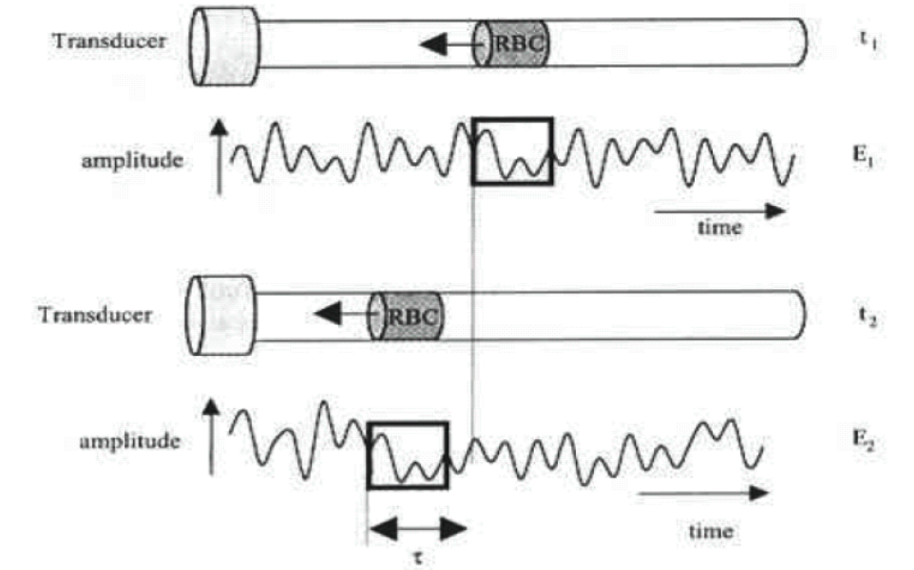
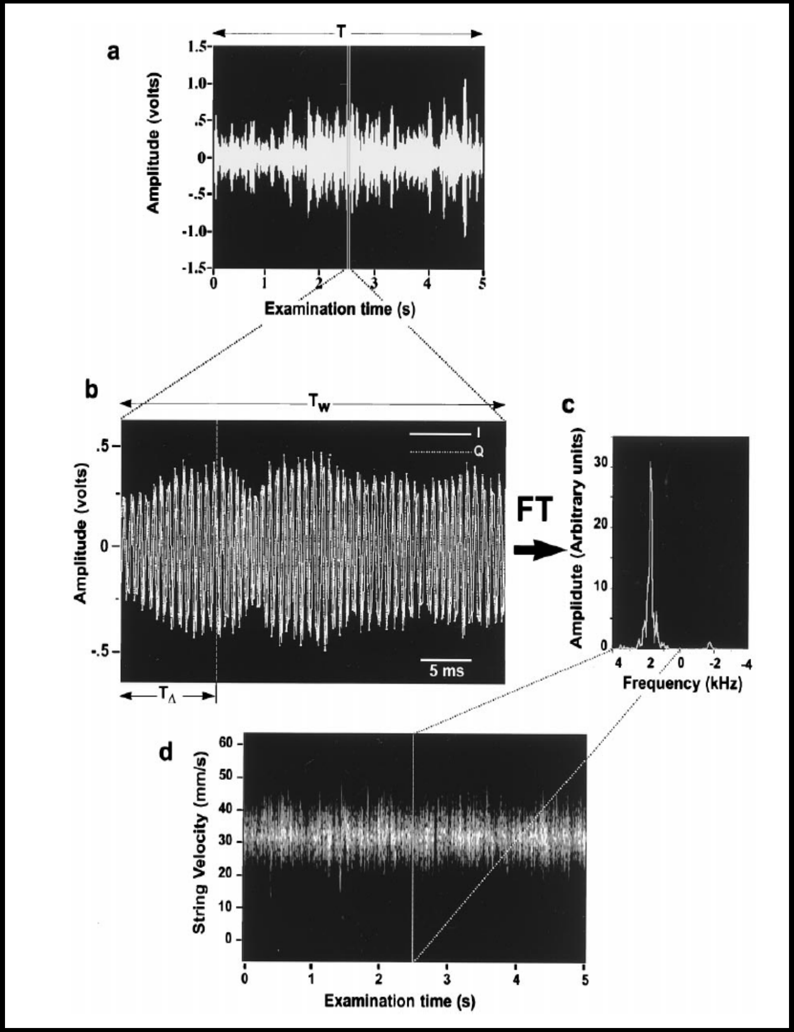


FIGURE 3.26. A diagram showing the basis of time-domain correlation methods for measuring blood velocity. A pulse of ultrasound is transmitted at time t_1 and the backscattered echo E_1 recorded. A second pulse is transmitted at time t_2 and the signature signal from the particular group of RBCs is time-shifted by an amount τ in the corresponding echo E_2. Correlation methods, as described in the text, are used to estimate the value of τ and hence the blood velocity.

Doppler Data Processing

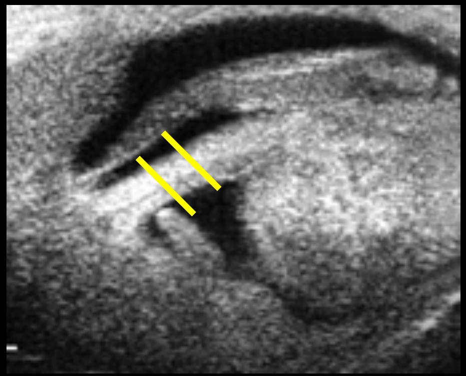


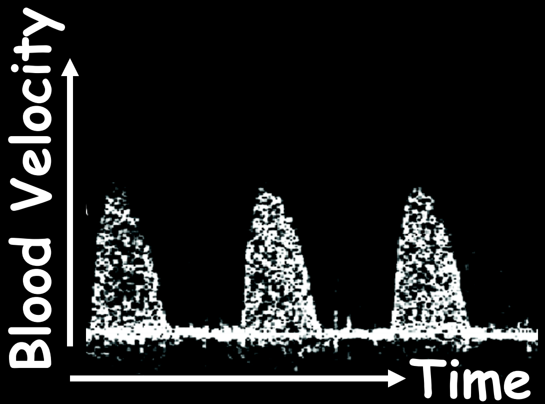
(Aristizabal, Ultrasound in Medicine & Biology 1998)

Duplex Imaging

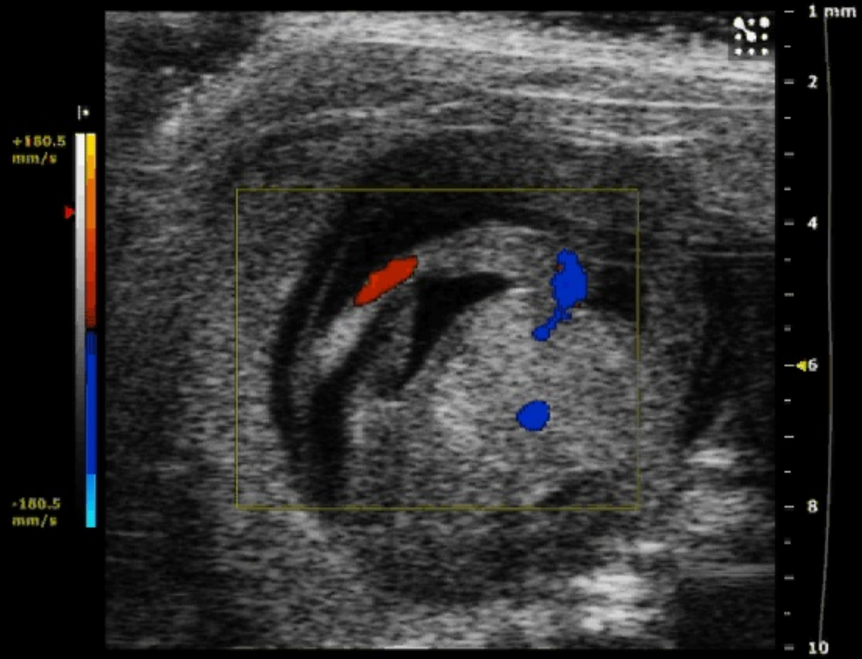
- Combines real-time B-scan with US Doppler flowmetry
- B-Scan: linear or sector
- Doppler: C.W. or pulsed (f_c = 2-40 MHz)
- Duplex Mode:
  - Interlaced B-scan and color encoded Doppler images $\Rightarrow$ limits acquisition rate to 2 kHz (freezing of B-scan image possible)
  - Variation of depth window (delay) allows 2D mapping (4-18 pulses per volume)

Duplex: Imaging + Doppler





Color Doppler of a Mouse Embryo



Color Dopper Imaging Example

Clinical Applications

- Ultrasound is considered safe; instrument is less expensive and imaging is fast
- Clinical applications
  - Obstetrics and gynecology
    - » Widely used for fetus monitoring
  - Breast imaging
  - Musculoskeletal structure
  - Cardiac diseases
- Contrast agents

Homework

- Reading:
  - Prince and Links, Medical Imaging Signals and Systems, Chapters 10 & 11
- Problems:
  - Work through example 11.3 in text (not to be handed in)
  - P11.2
  - P11.3
  - P11.6
  - P11.9
  - P11.14