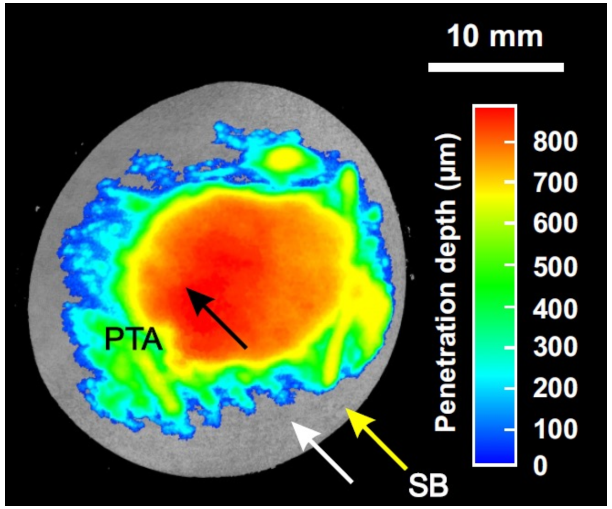
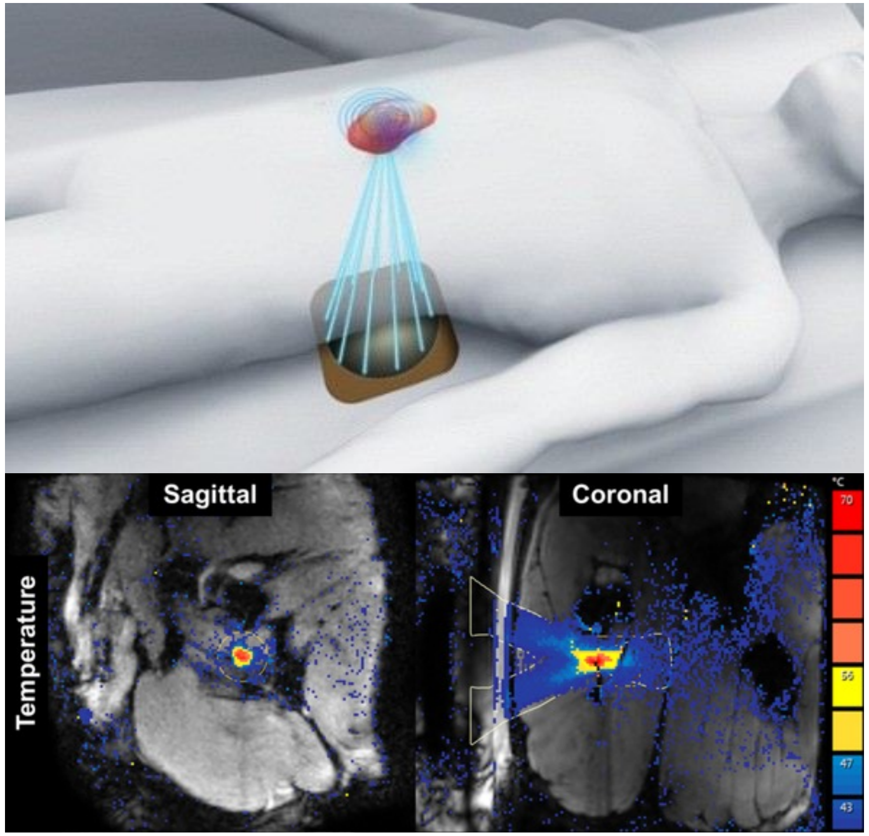
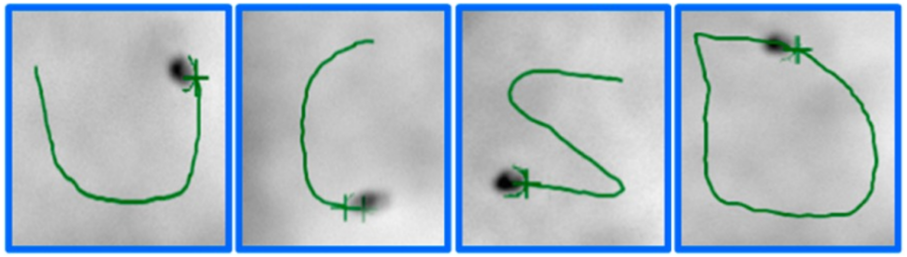
Biomedical Ultrasonics, 5 cr

Heikki Nieminen

13.9.-7.12.2023







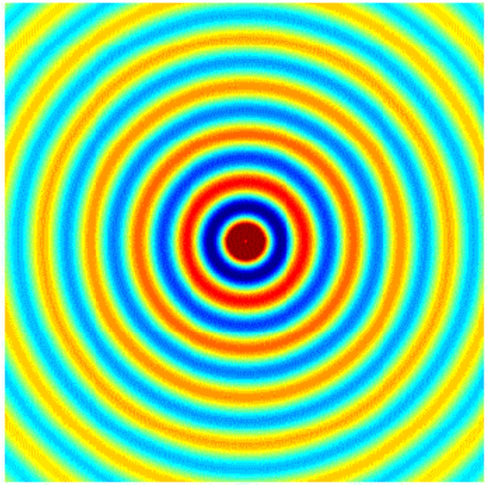
Reading in Duck et al.

- Ultrasound basics & measurements: p. 57-83
- Ultrasound imaging: p. 91-111
- Elastography: p. 263-269

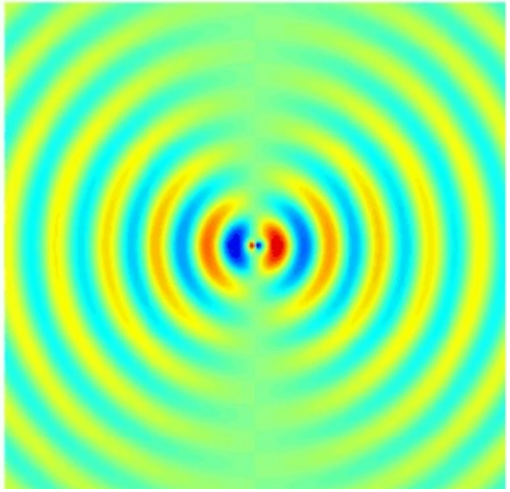
Sources

Monopole vs. dipole

Acoustic monopole

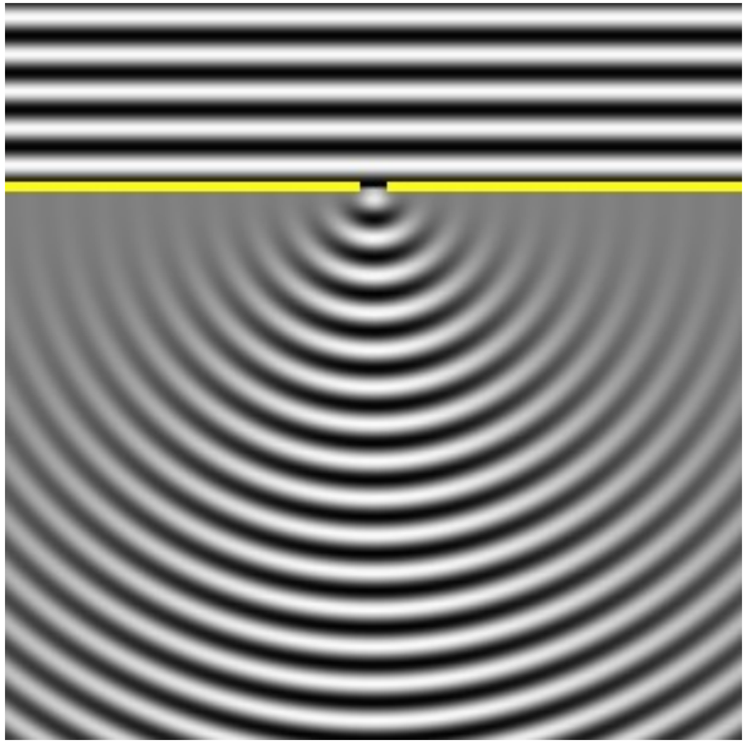


Acoustic dipole



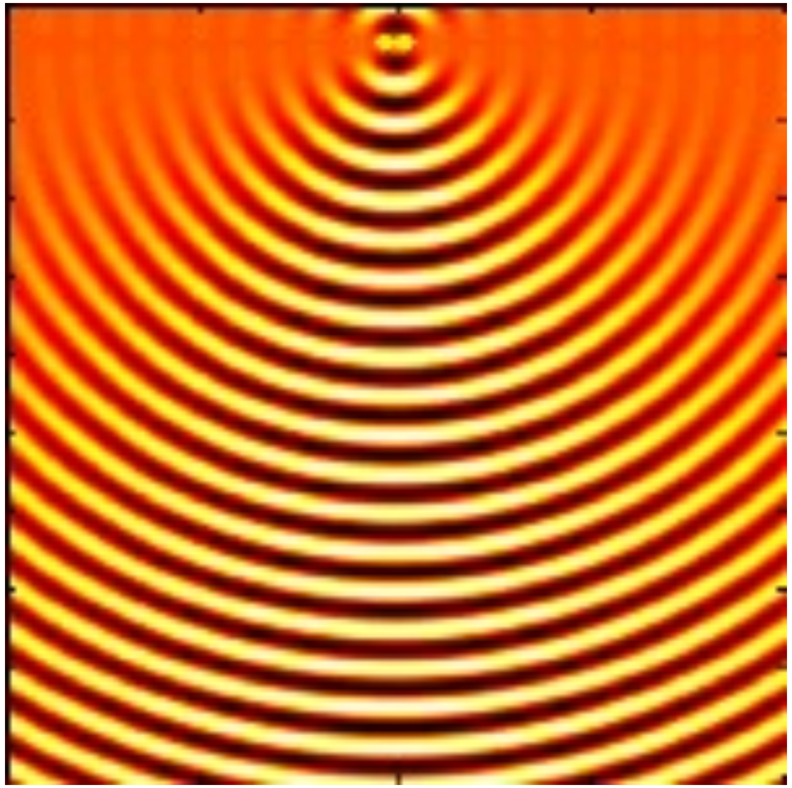
Huygens-Fresnel principle

- Every point on a wavefront is a source of a wavelet.



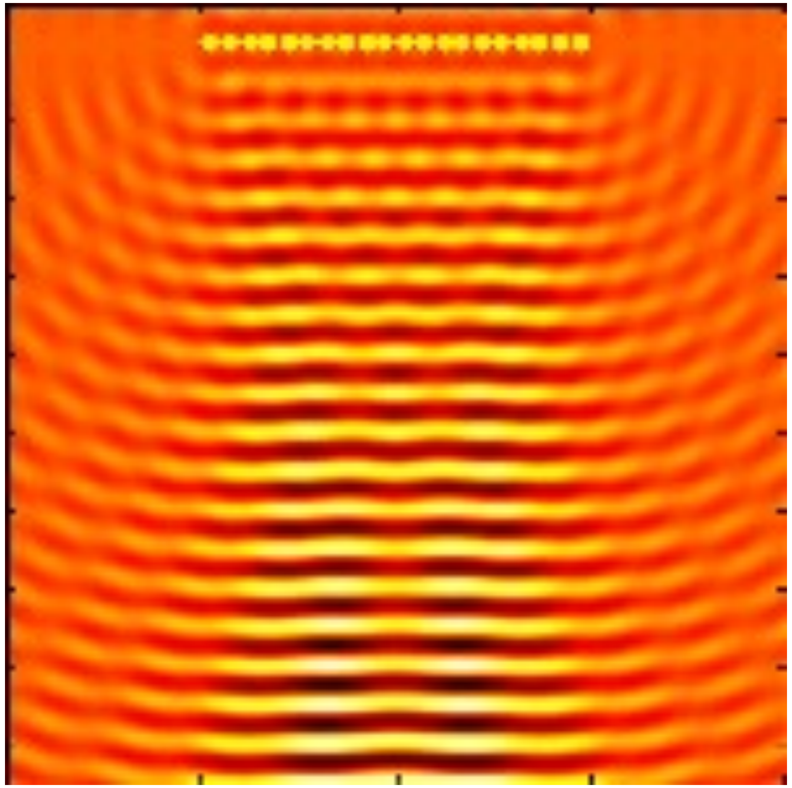
Point source (monopole)

Two adjacent point sources

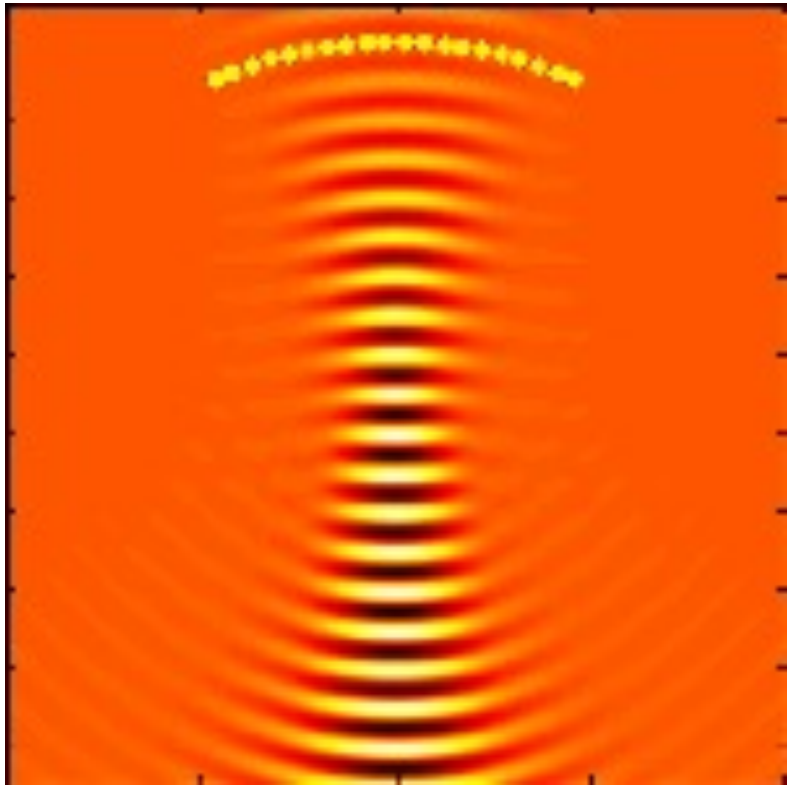


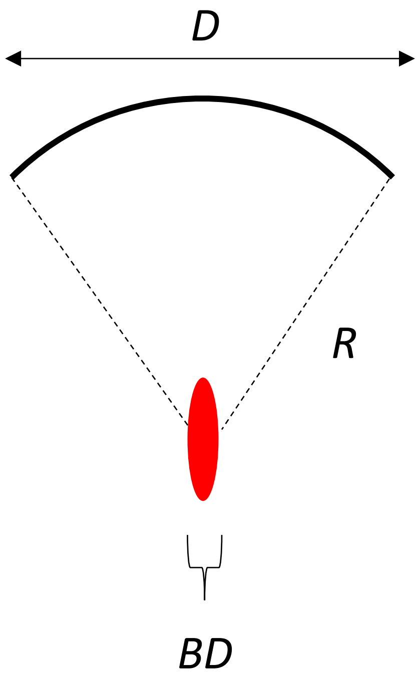
What is the spacing of the two monopole sources in the horizontal direction?

Multiple adjacent point sources



Multiple adjacent point sources placed at a constant distance from focal point

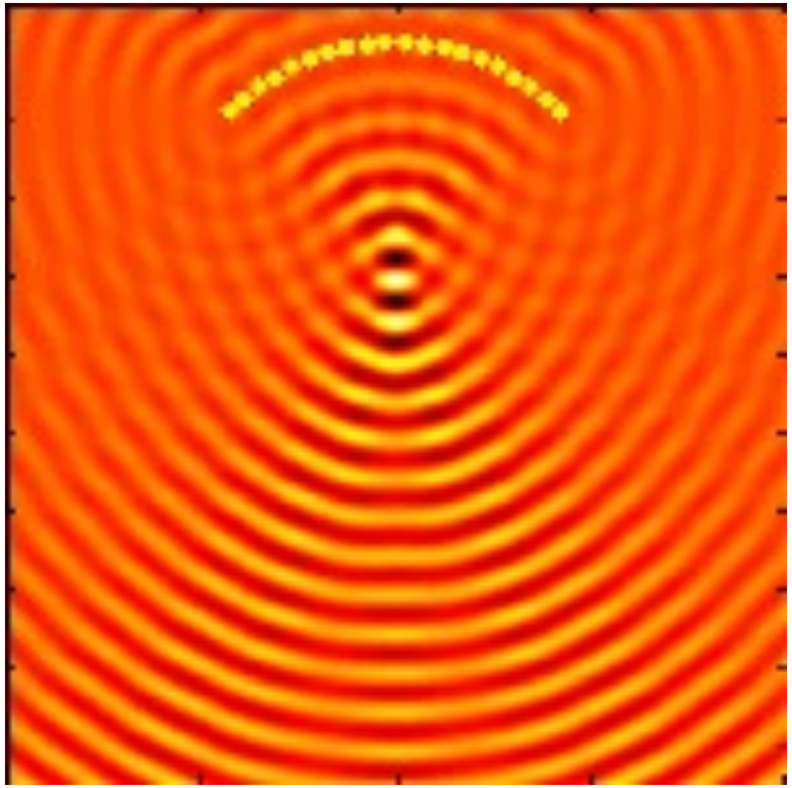


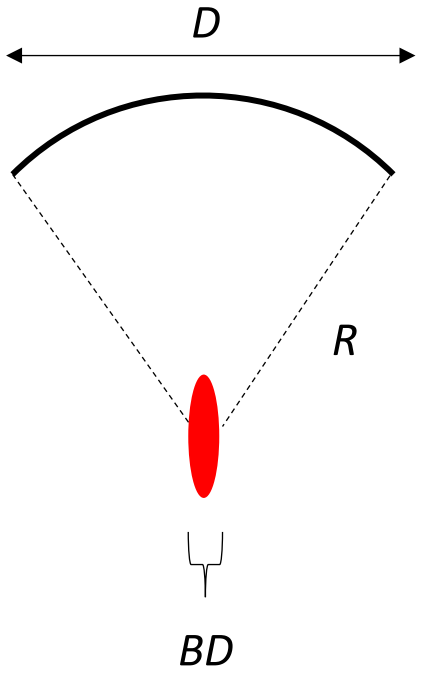


$$BD \approx \frac{\lambda R}{D}$$

BD = beam diameter
λ = wave length
R = radius of curvature
D = aperture (outer diameter of the transducer)

Radius of curvature vs. focusing

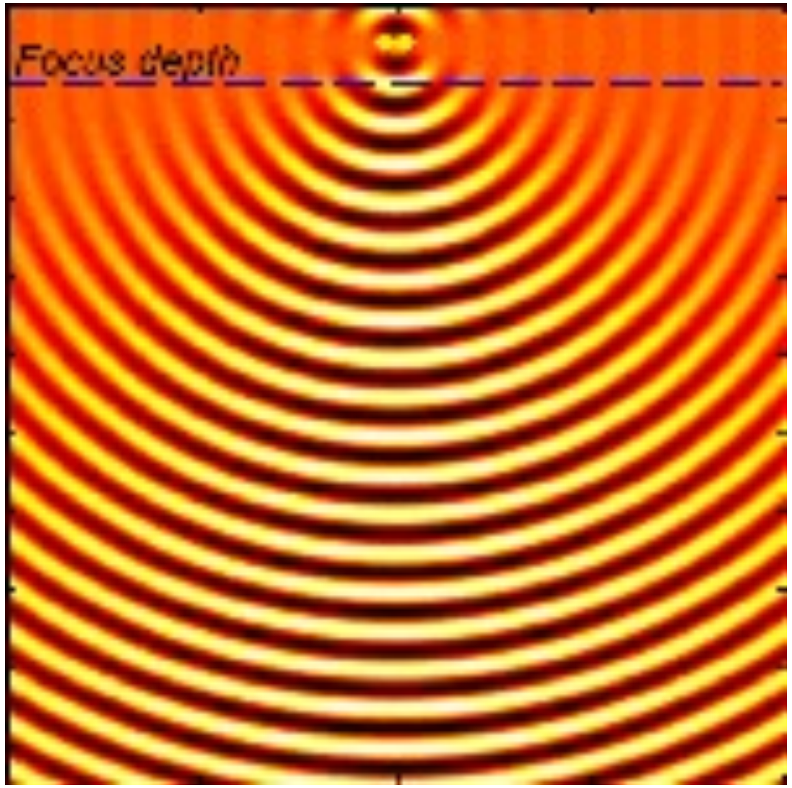


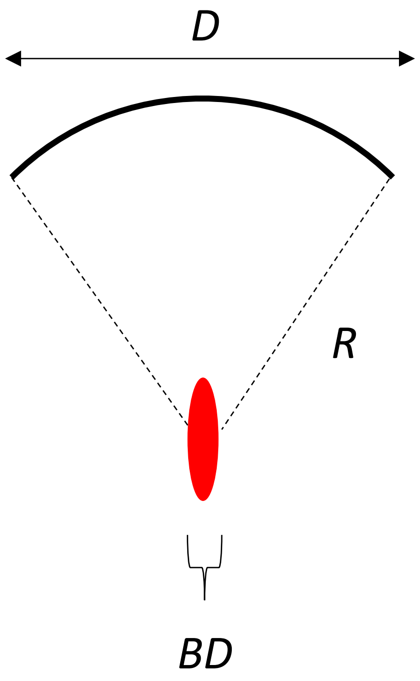


$$BD \approx \frac{\lambda R}{D}$$

BD = beam diameter
λ = wave length
R = radius of curvature
D = aperture (outer diameter of the transducer)

Aperture vs. focus dimensions





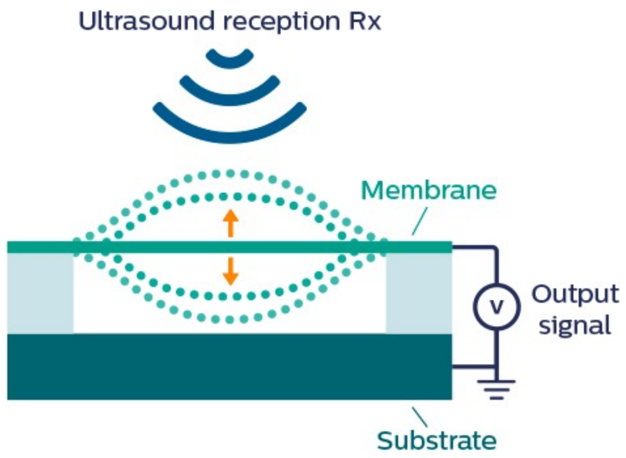
$$BD \approx \frac{\lambda R}{D}$$

BD = beam diameter
λ = wave length
R = radius of curvature
D = aperture (outer diameter of the transducer)

Ultrasound sources

- **Piezoelectric transducers**
- Piezoelectric Micromachined Ultrasound Transducer (PMUT)
- Electromagnetic Acoustic Transducers (EMAT)
- Capacitive Micromachined Ultrasound Transducer (CMUT)
- Heat
  - Light (laser acoustics, photo-acoustics), flame, plasma (spark, lighting)
- Chemical reaction
  - Explosion
- Mechanical shocks
  - Hammering

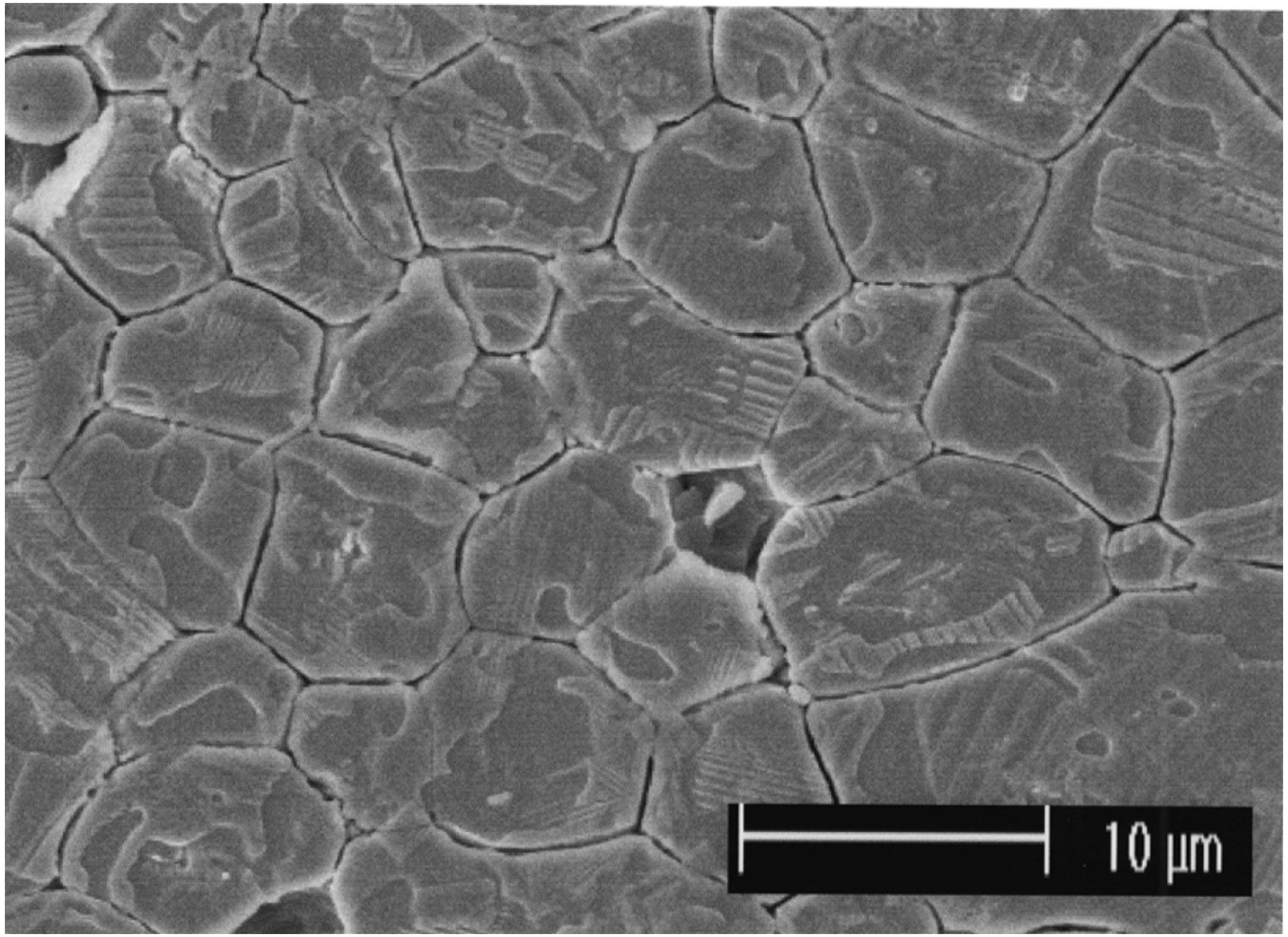
CMUT



Piezo-electric materials

- Natural materials:
  - Quartz, topaz, cane sugar, rochelle salt, and tourmaline
  - Bone, tendon, silk, wood (weak effect)
- Polymers
  - Polyvinylidene fluoride (PVDF)
  - Electromechanical film (EMFIT)
    - 70-80 µm thick film
    - Flat voids separated by thin polyolefin layers
- Synthetic materials (Ferroelectric)
  - Barium titanate (BaTiO3)
  - Lead titanate ($PbTiO_3$)
  - **Lead zirconate titanate, a.k.a. PZT**
  - Lithium niobate (LiNbO3)

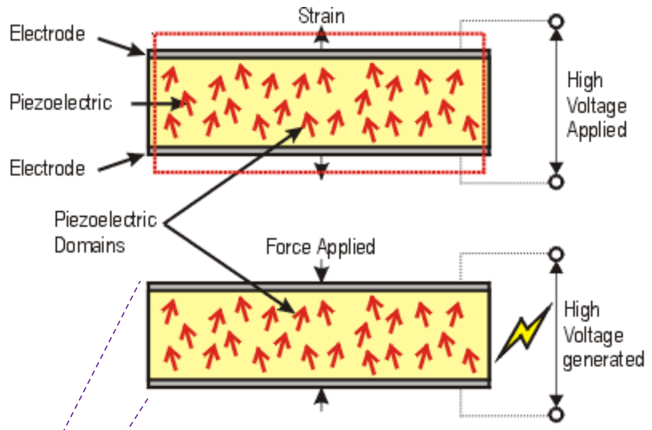
Lead zirconate titanate, a.k.a. PZT

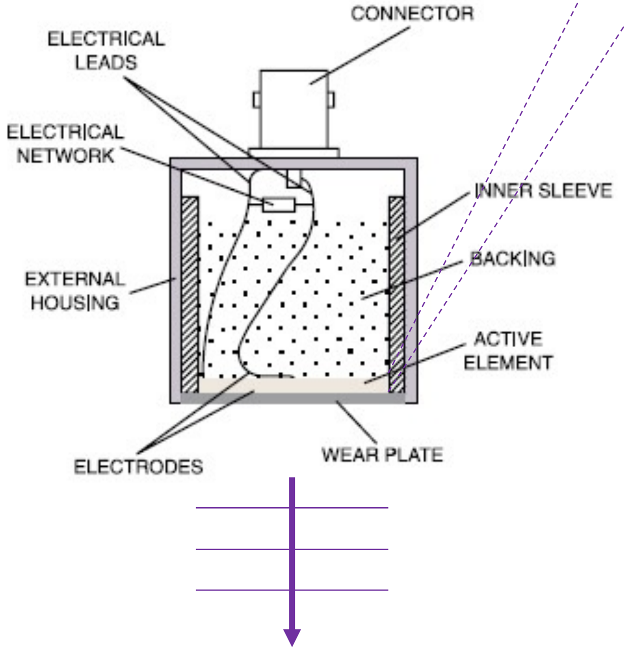


Ultrasound generation & detection

Sound generation:

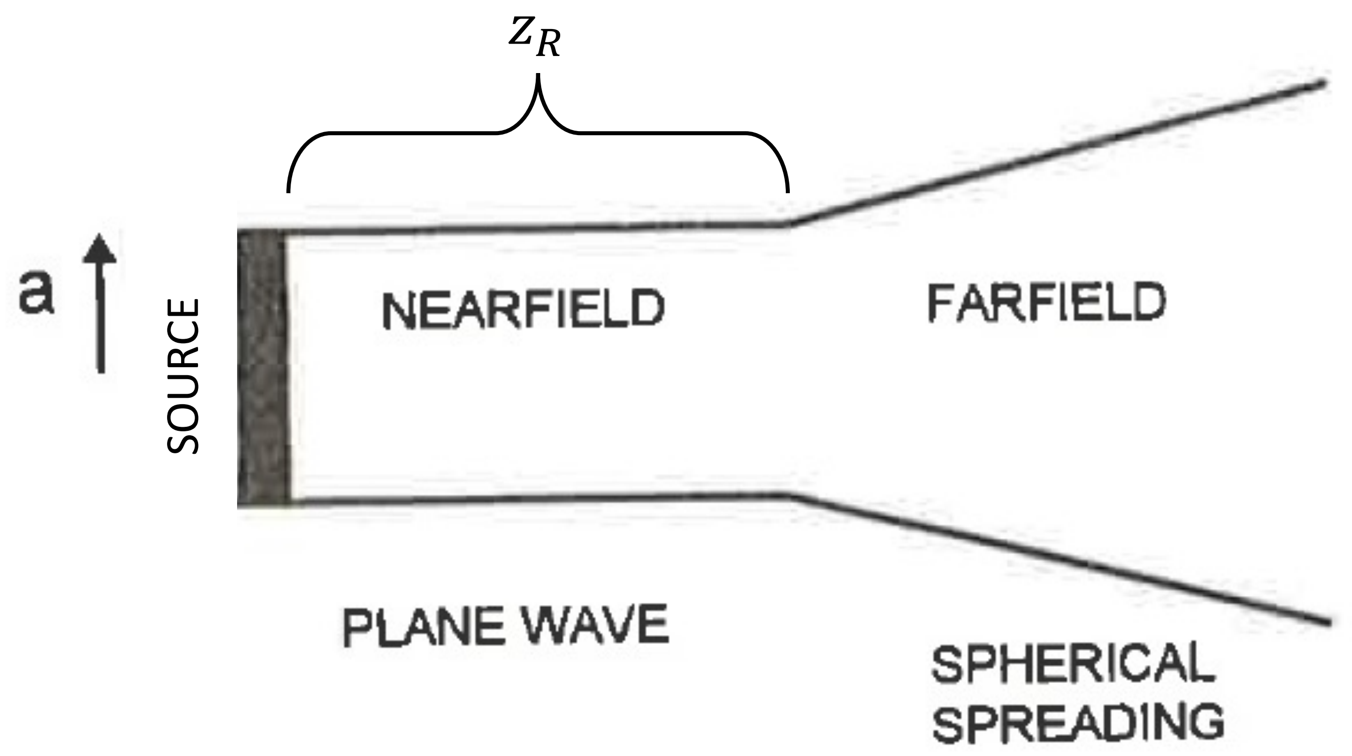
Detection:





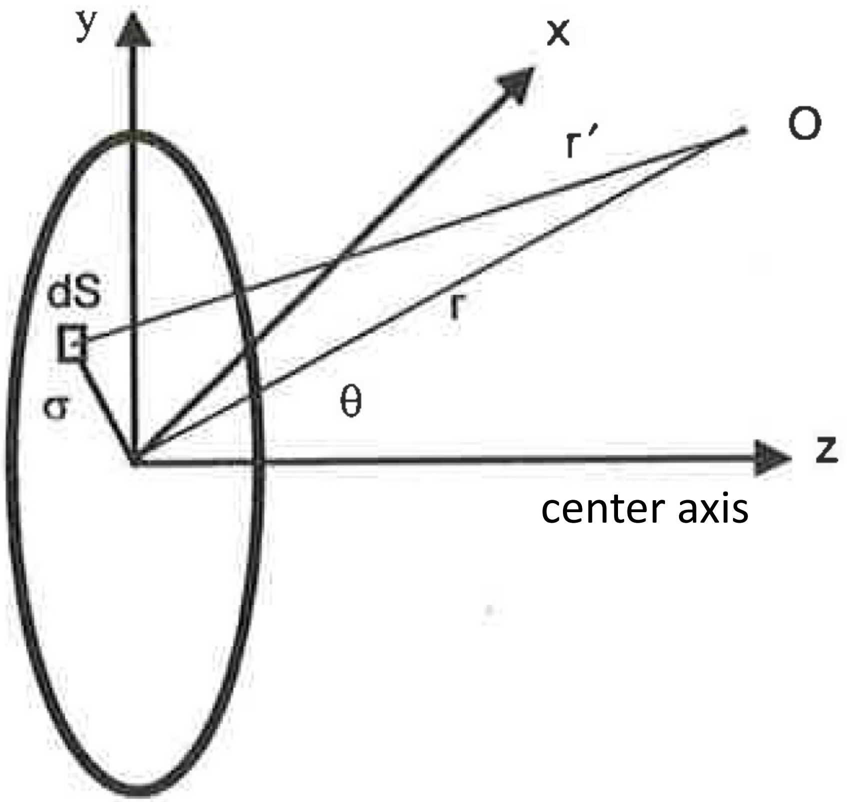
- **Backing/dampening: broad band**
  - Typically used in characterization
  - Permits short bursts
  - Dampening could start generating heat at high intensity, not typically appropriate for high-intensity applications
- **No backing/dampening: narrow band**
  - Typically used in therapeutic applications

Ultrasonic fields



$$z_R = \frac{\pi a^2}{\lambda} = \frac{ka^2}{2}$$

Field of circular transducer



Rayleigh integral:

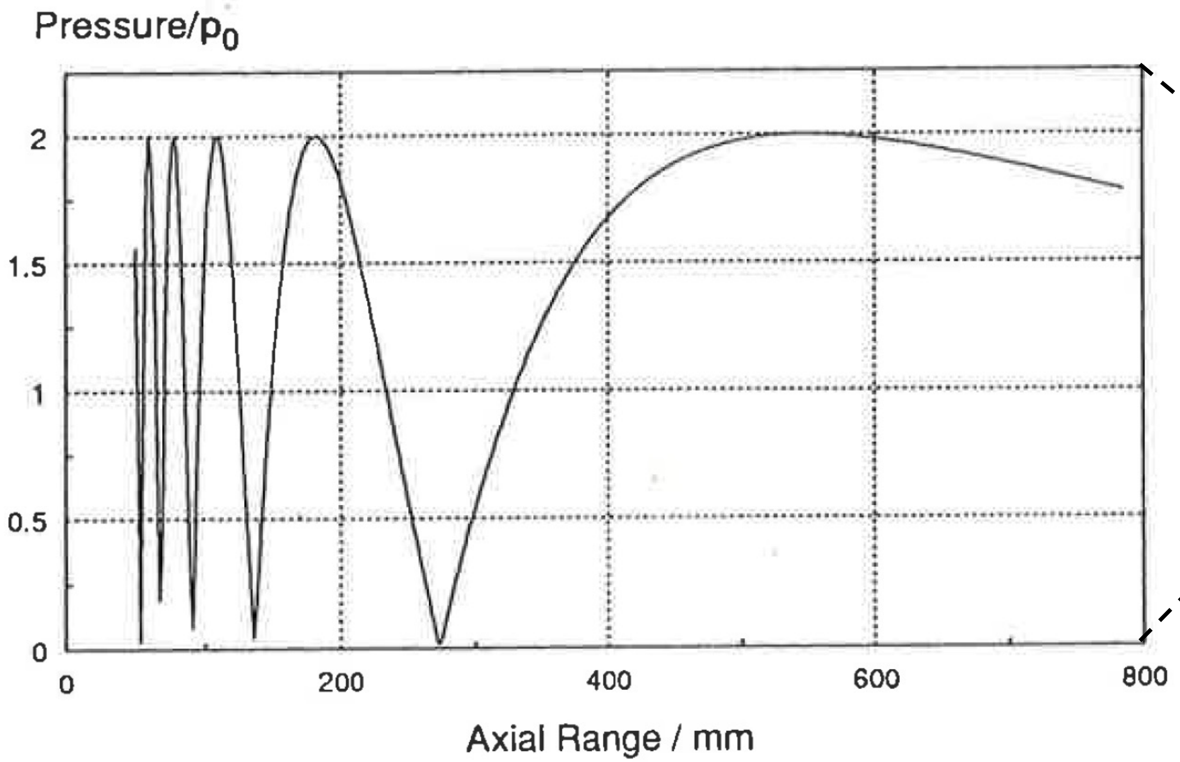
$$p(r,\theta,t) = \mathrm{i}\frac{\rho_0 ck}{2\pi}u_0 \int_{\text{Surface}} \frac{\mathrm{e}^{\mathrm{i}(\omega t - kr')}}{r'}\,\mathrm{d}S$$

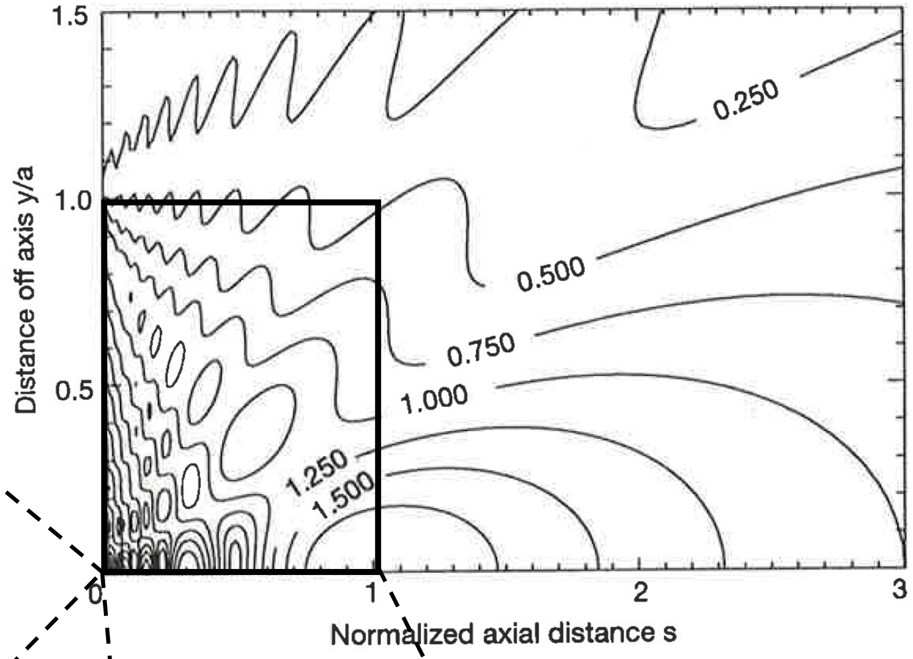
Pressure at center axis:

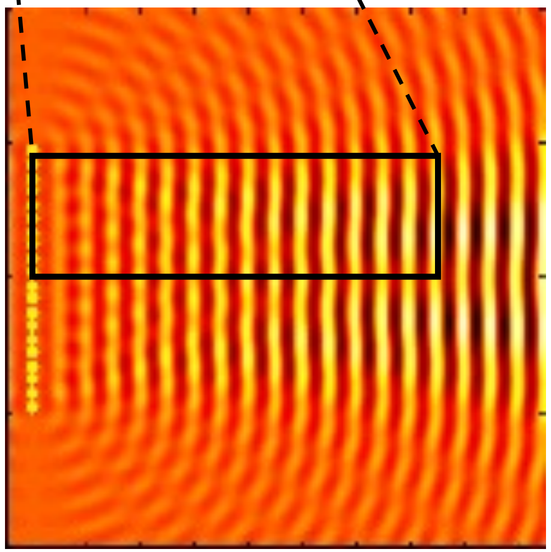
$$p(z) = 2\rho_0 c u_0 \left| \sin\left\{ \frac{kz}{2}\left[\sqrt{1+\left(\frac{a}{z}\right)^2} - 1\right]\right\}\right|$$

Field of circular transducer

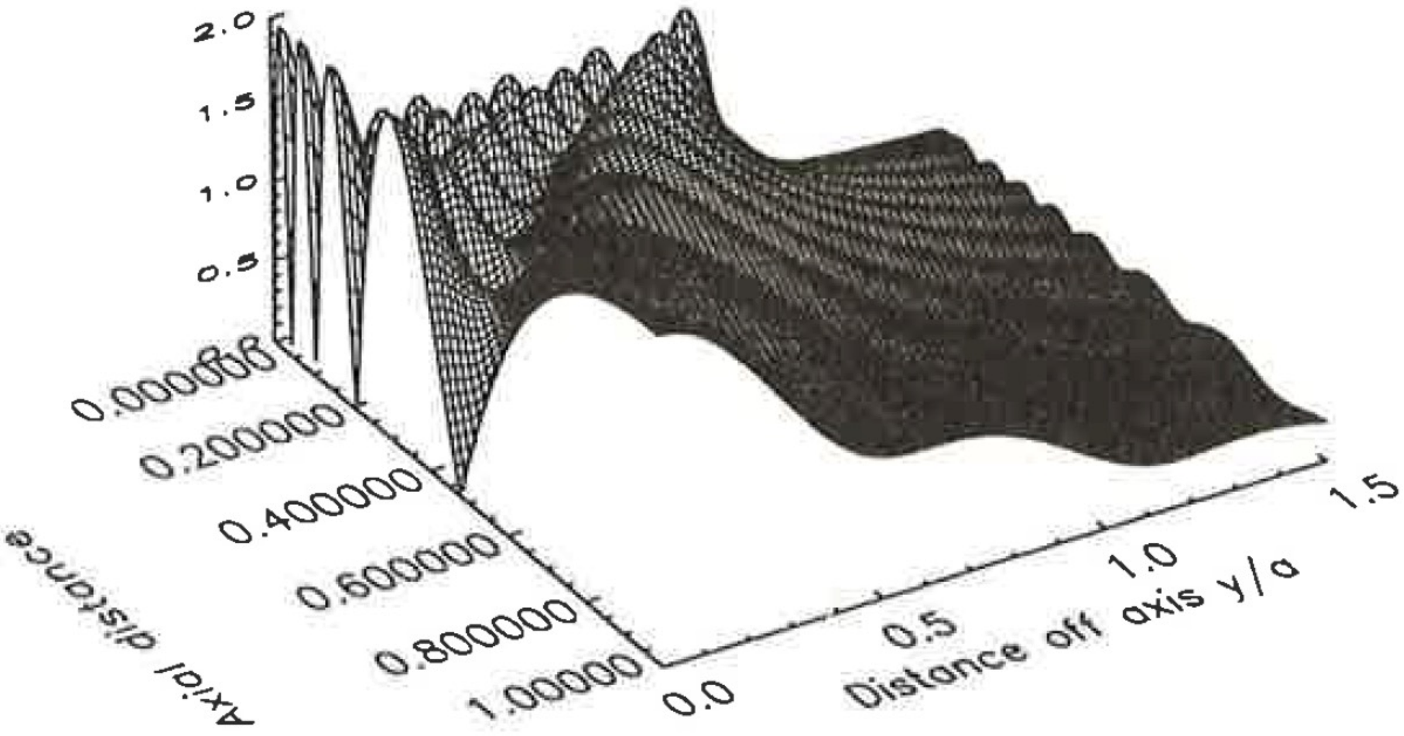
Center axis pressure:







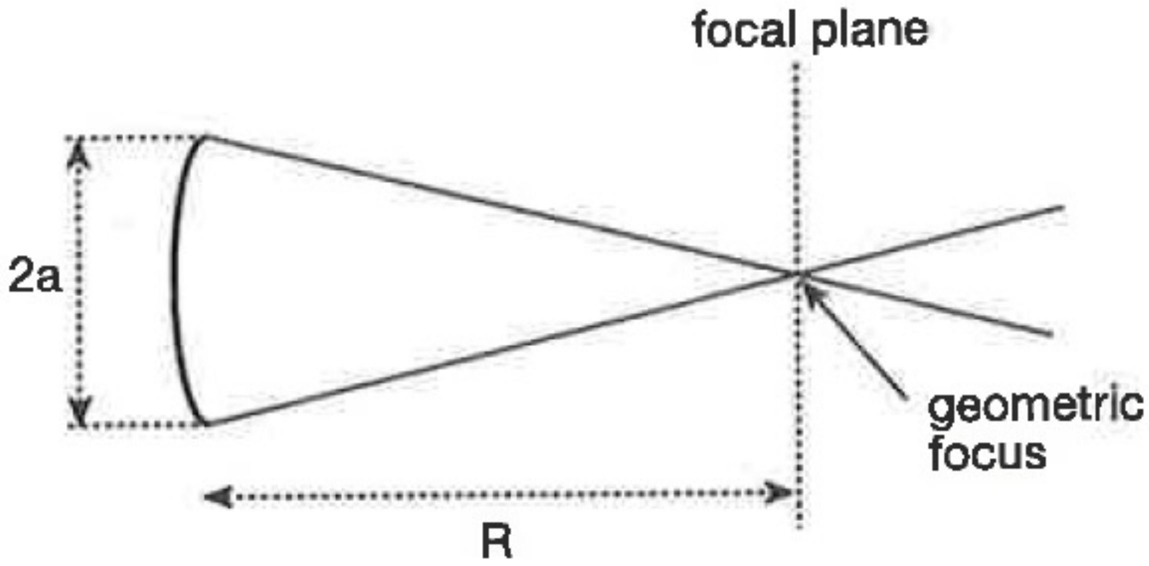
Field of circular transducer



a = 5x the wavelength

Duck p. 13

Amplitude gain



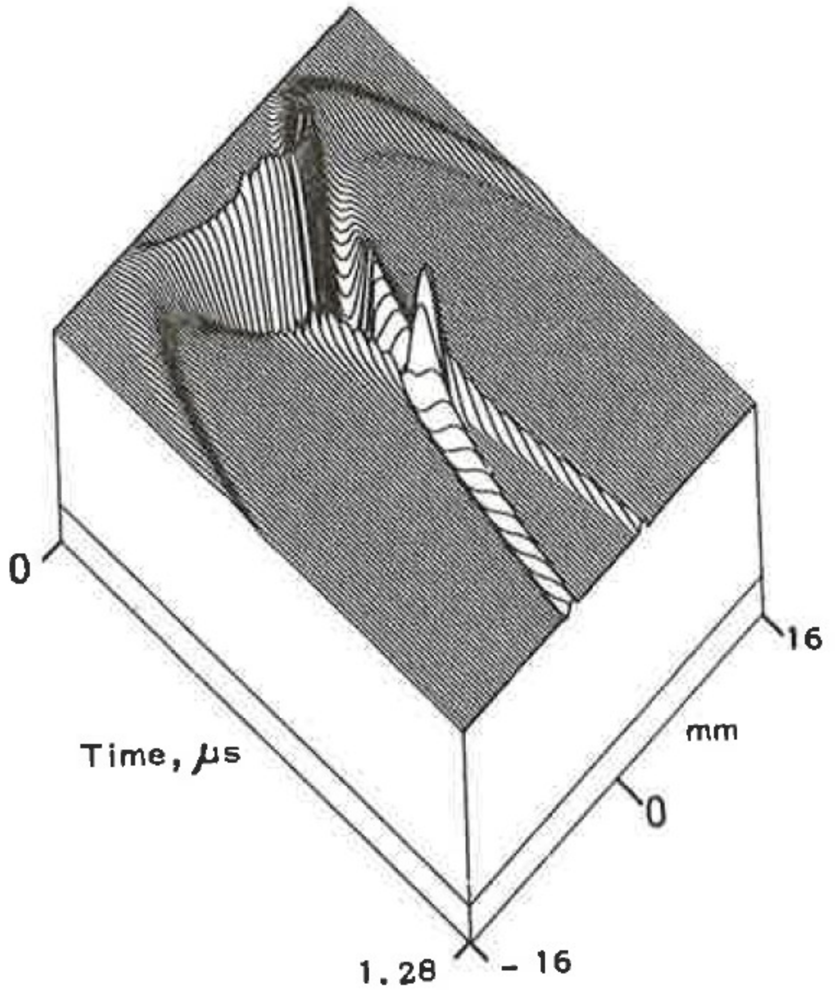
Amplitude gain:

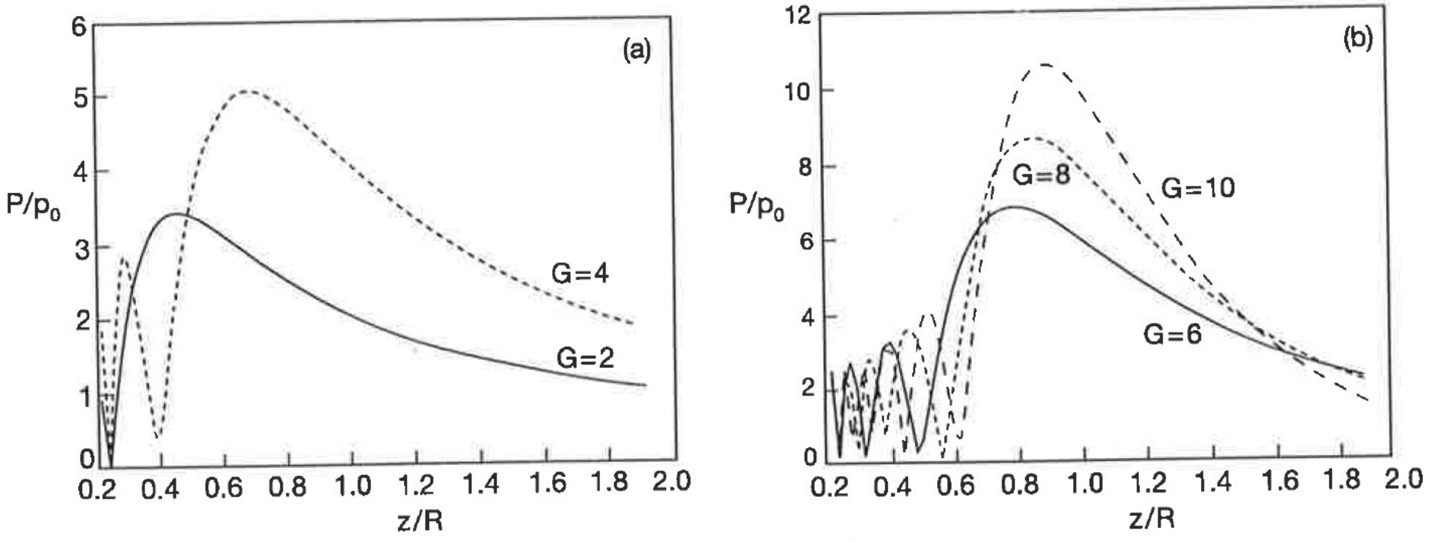
$$G = \frac{z_R}{R} = \frac{\pi a^2}{\lambda R}$$

weak focus: $0 < G \leqslant 2$
medium focus: $2 < G \leqslant 2\pi$
strong focus: $G > 2\pi$

Duck p. 14, 16

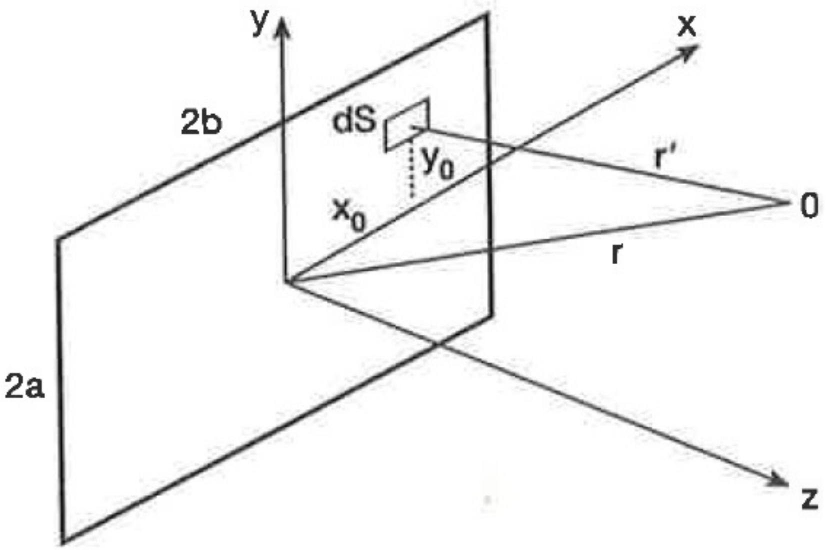
Field of circular focused source





Duck p. 18-19

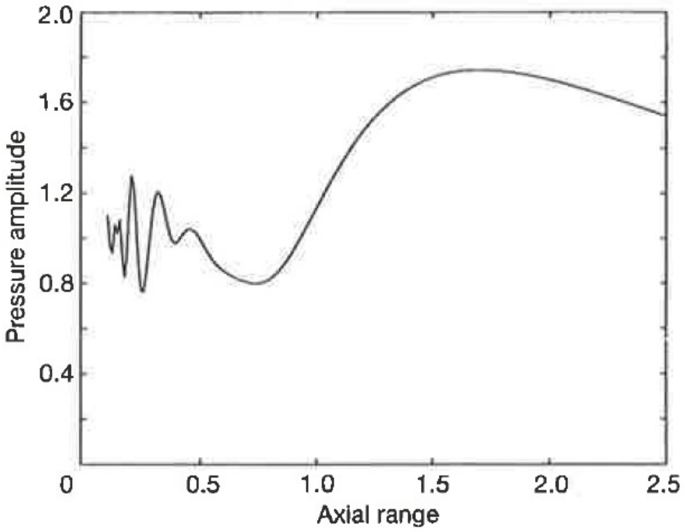
Field of rectangular transducer



Pressure at center axis:

Substituting $g = x_0\sqrt{(2/z\lambda)}$; $g_0 = b\sqrt{(2/z\lambda)}$; $h = y_0\sqrt{(2/z\lambda)}$; $h_0 = a\sqrt{(2/z\lambda)}$; and defining the aspect ratio of the rectangle $N = a/b$ so $h_0 = b/N\sqrt{(2/z\lambda)}$; we have on axis

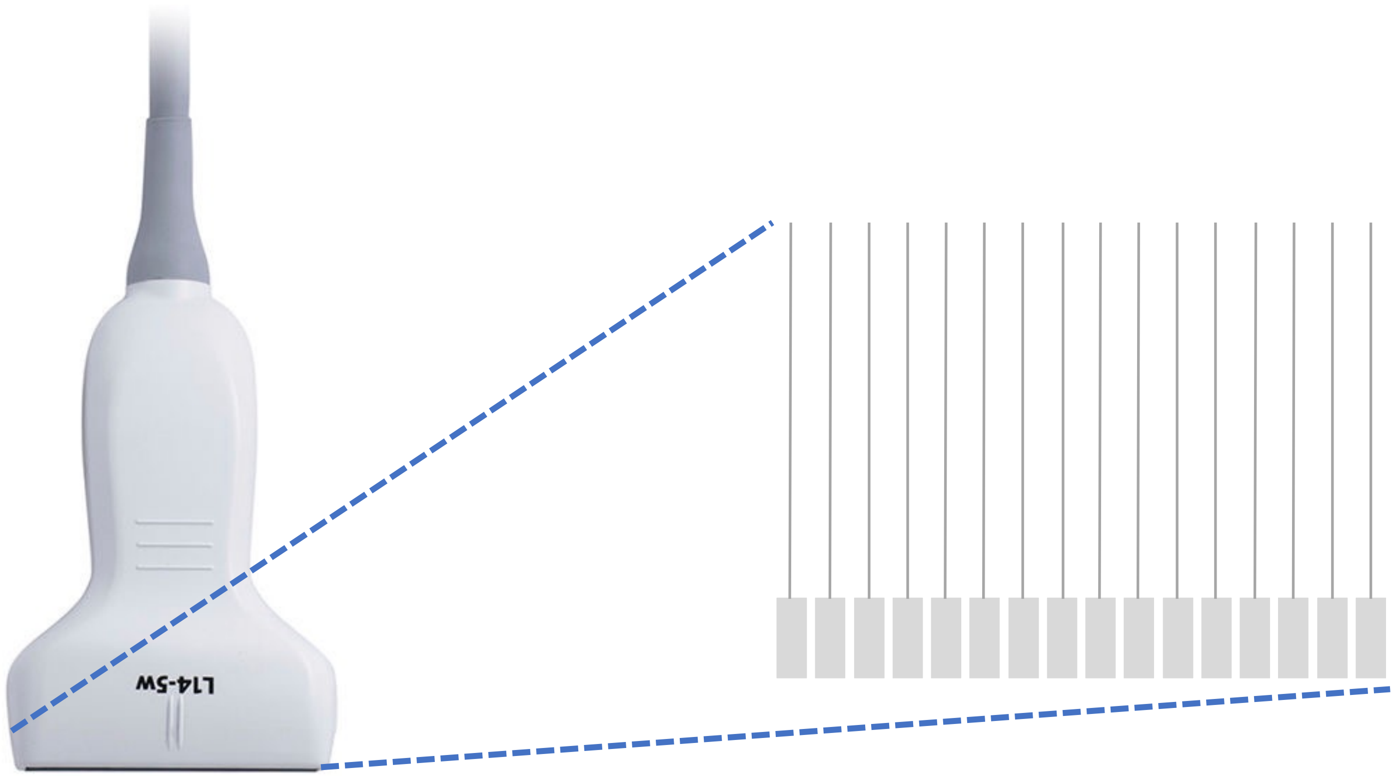
$$p = \frac{\mathrm{i}\rho_0 c u_0}{2}\exp(\mathrm{i}(\omega t - kz))\int_{-g_0}^{g_0}\exp(-\mathrm{i}\pi g^2/2)\,\mathrm{d}g\int_{-h_0}^{h_0}\exp(\mathrm{i}\pi h^2/2)\,\mathrm{d}h.$$



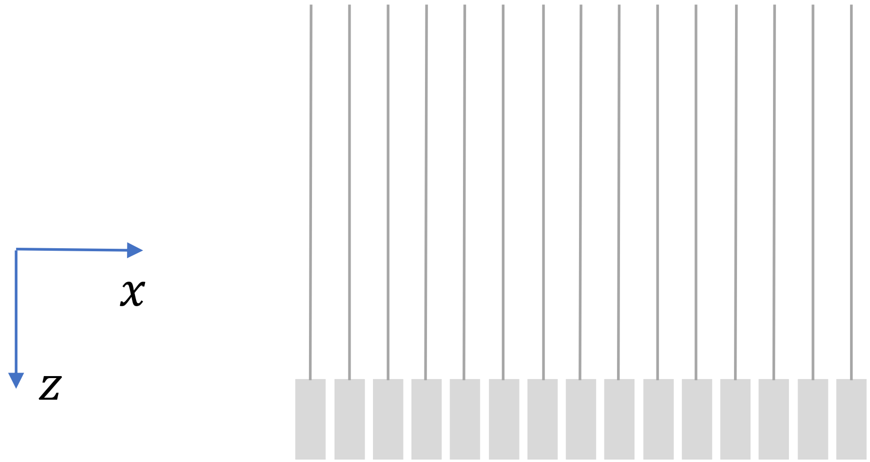
The aspect ratio 1:2

Conventional ultrasound imaging

Multielement array

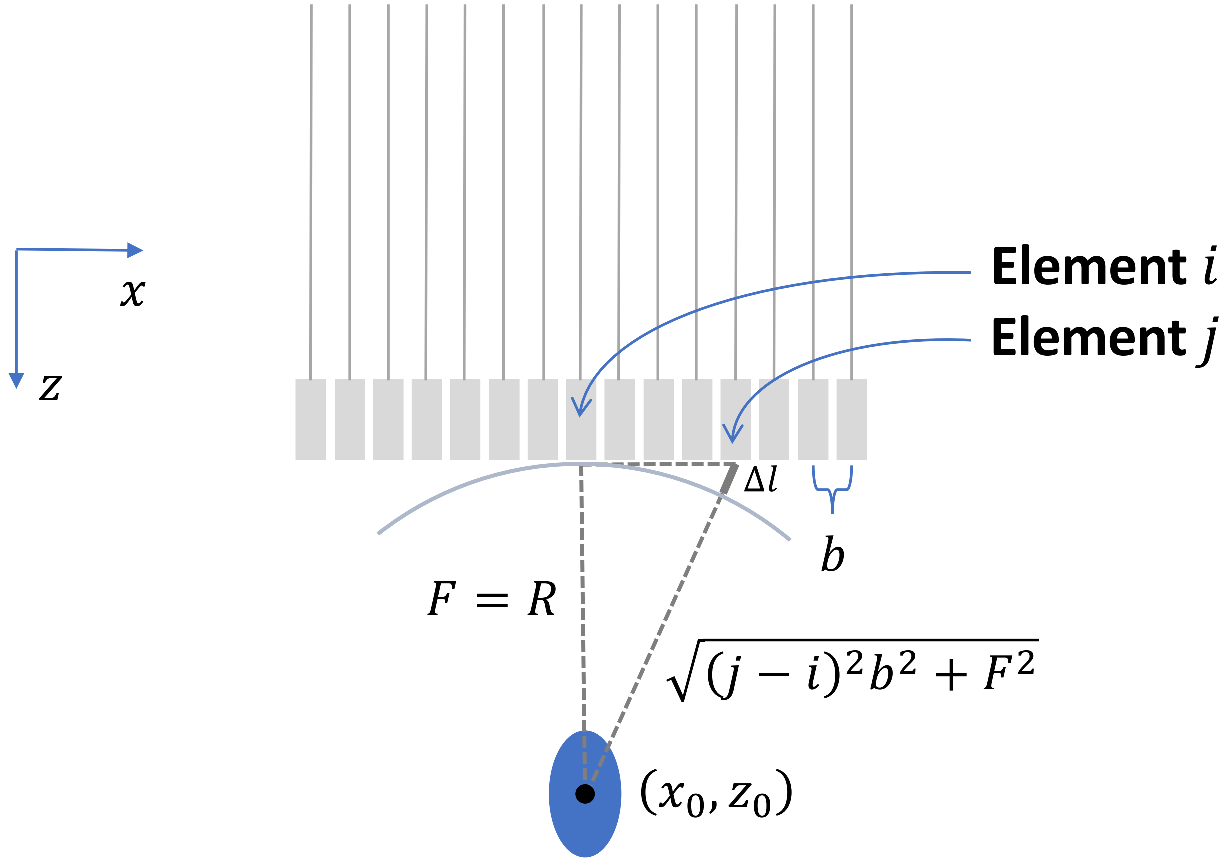


Multielement array



- Commonly 64-256 piezo elements
- Capable of transmission and receiving sound
- One channel per element

Multielement array: focusing

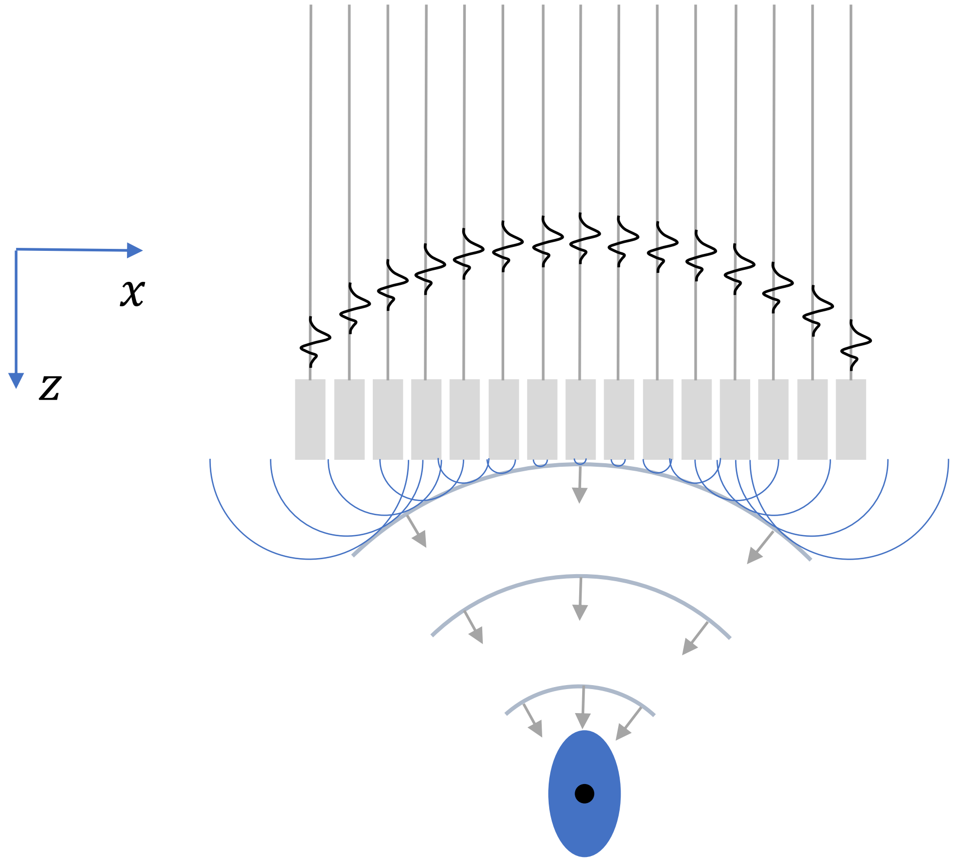


Time delay for the element j is

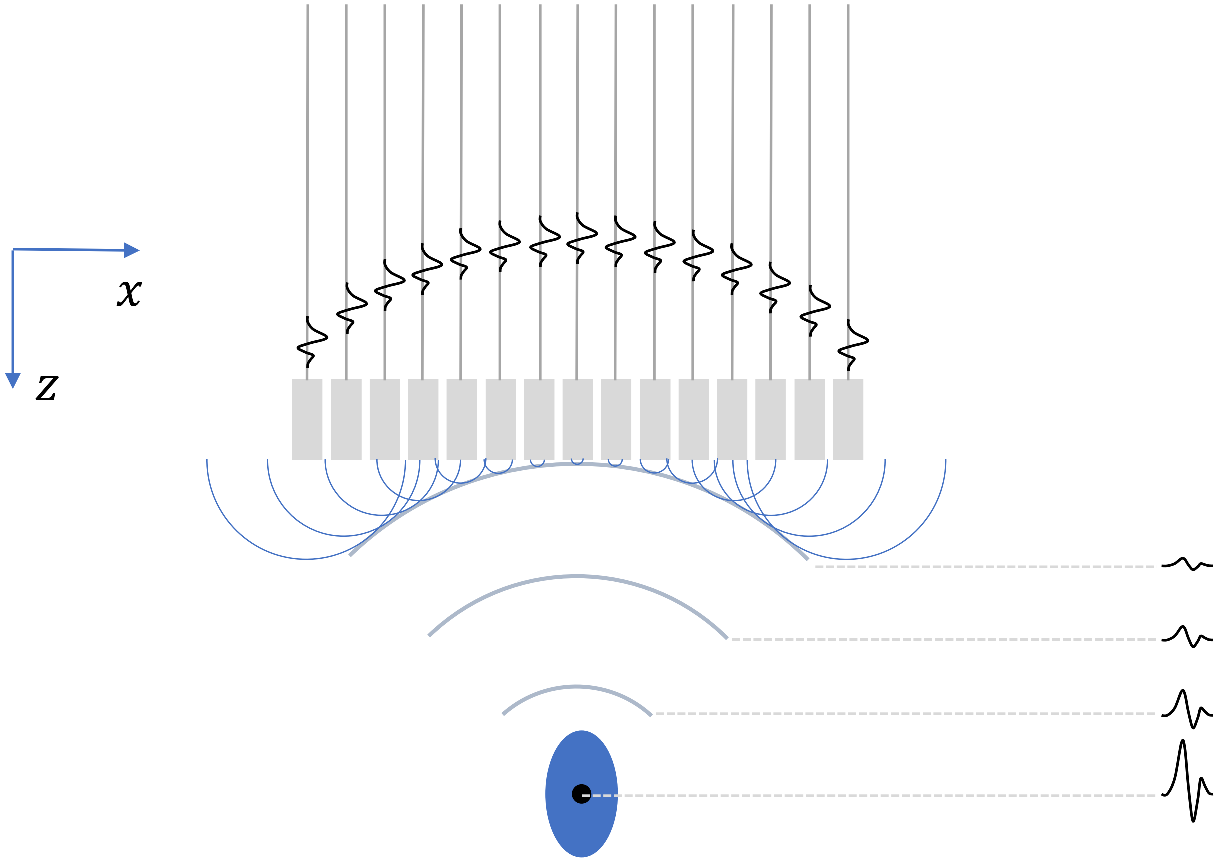
$$\Delta t_i(j) = -\frac{1}{c}\underbrace{\left(\sqrt{(j-i)^2 b^2 + F^2} - F\right)}_{=\Delta l}$$

b **= distance between adjacent elements**
j **= element number**
i **= element number at x_0**
F **= focal distance**
R **= radius of curvature**
c **= speed of sound**

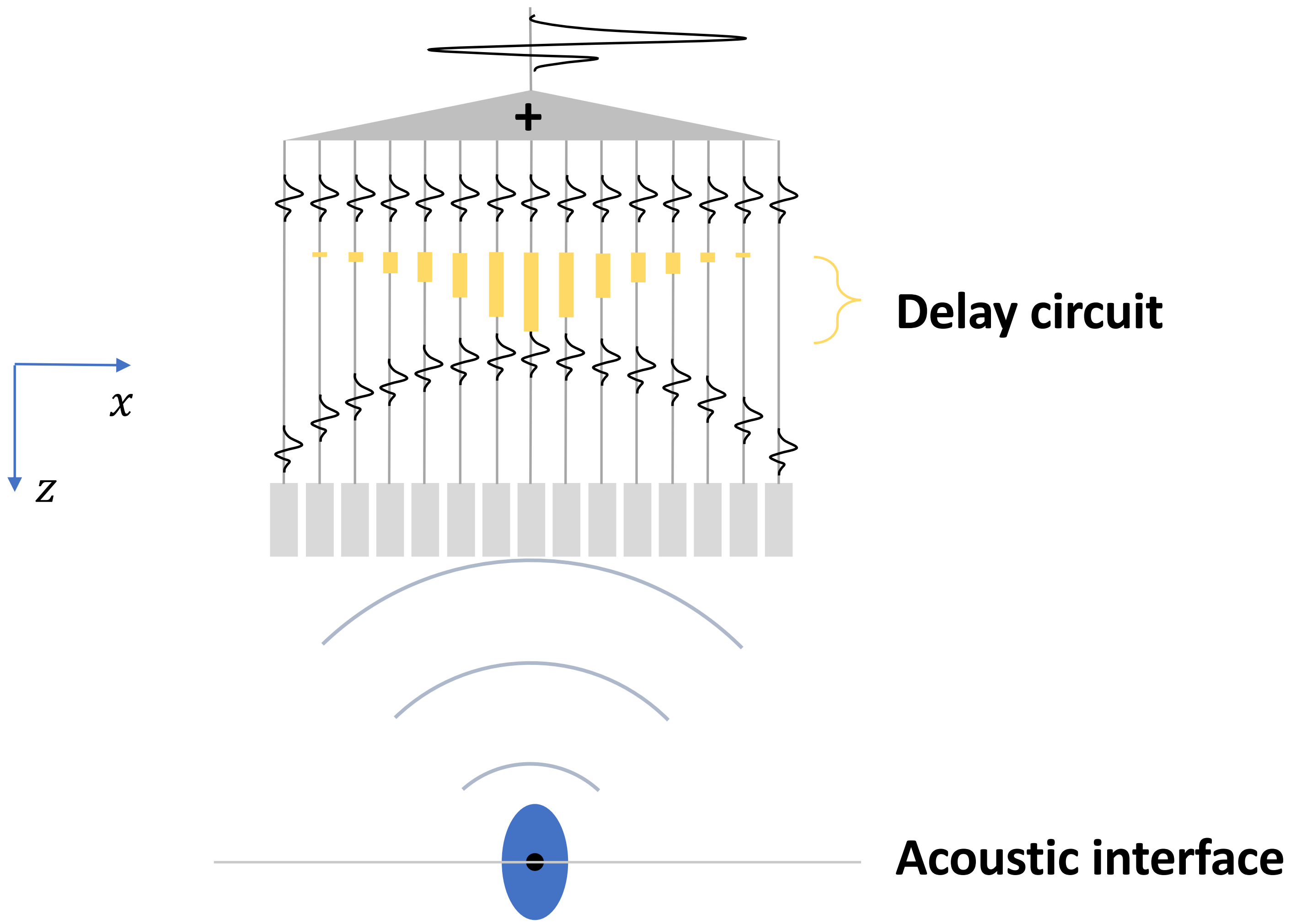
Multielement array: focusing



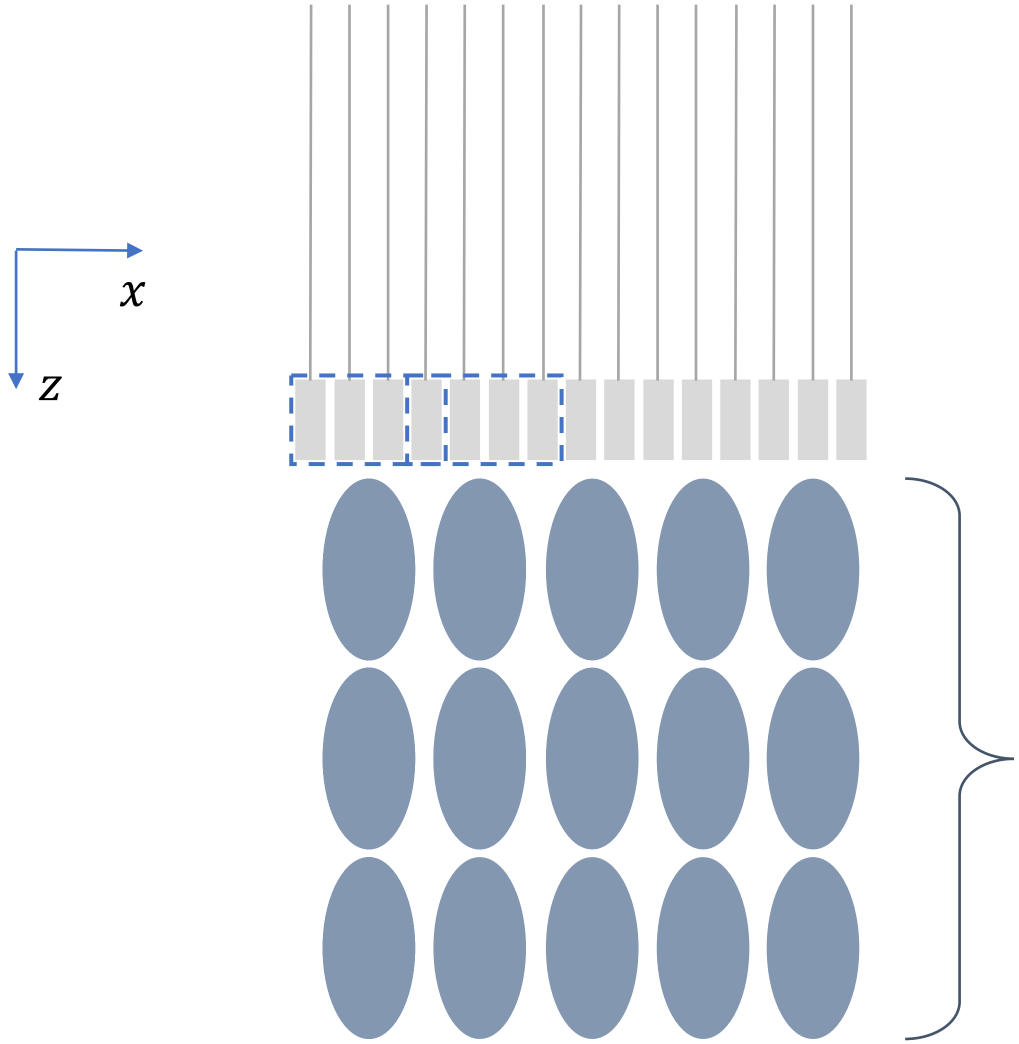
Multielement array: focusing



Transmission & receiving



Sequential imaging



5 “shots” per
3 focal depths
= 15 shots

Sequential imaging: example

Image depth
= 5 cm

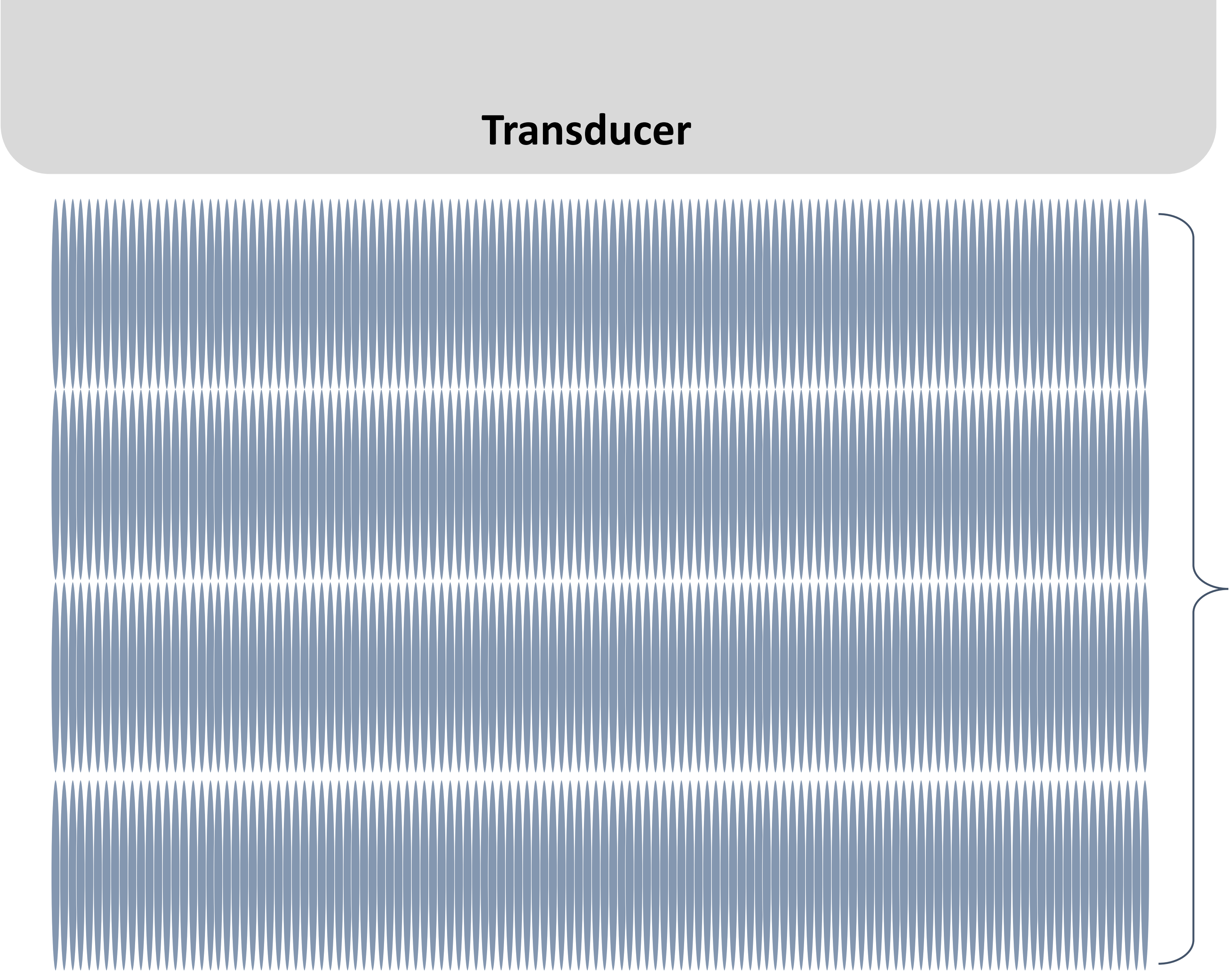
128 shots at 4 focal depths
= 512 shots

Time-of-flight
= 2 x 0.05 m / 1540 m/s
= 65 µs

Time to get one image
= 512 x 65 µs = 33.3 ms

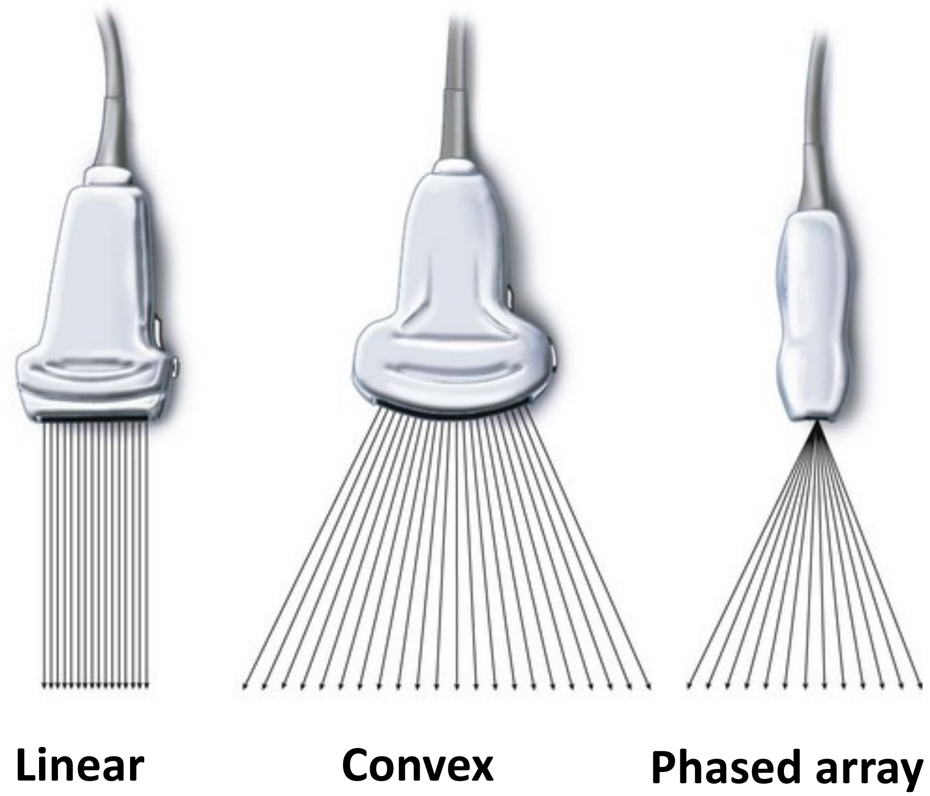
Frame rate
= 1/0.0333 s = 30 fps

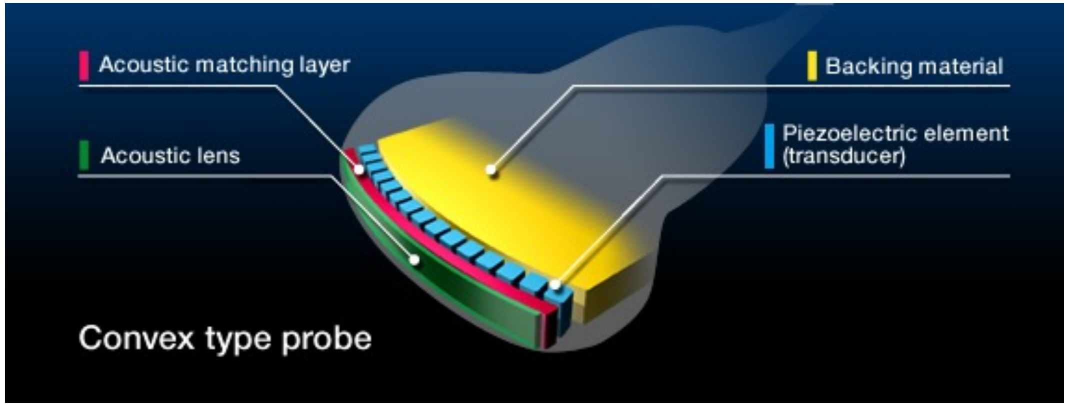
Common range: 25-50 fps



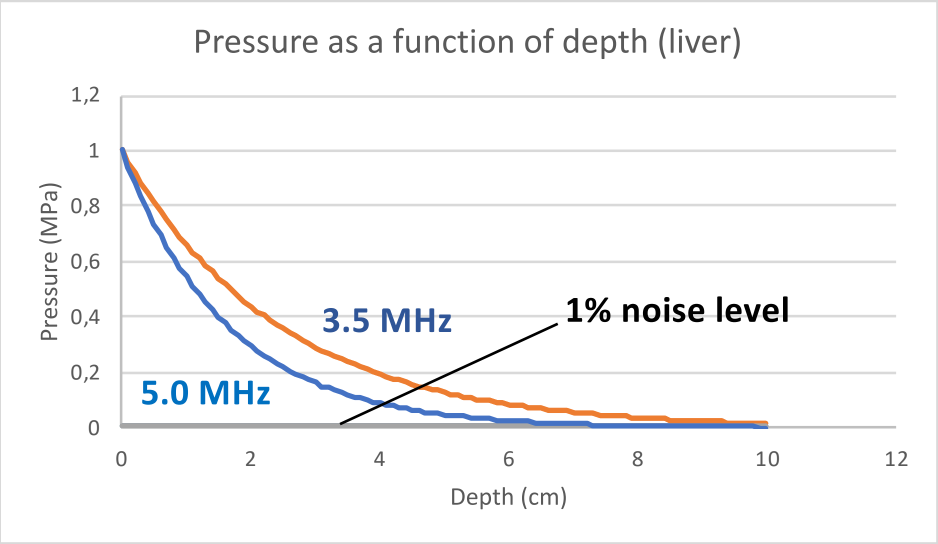
128 “shots” per
4 focal depths
= 512 shots

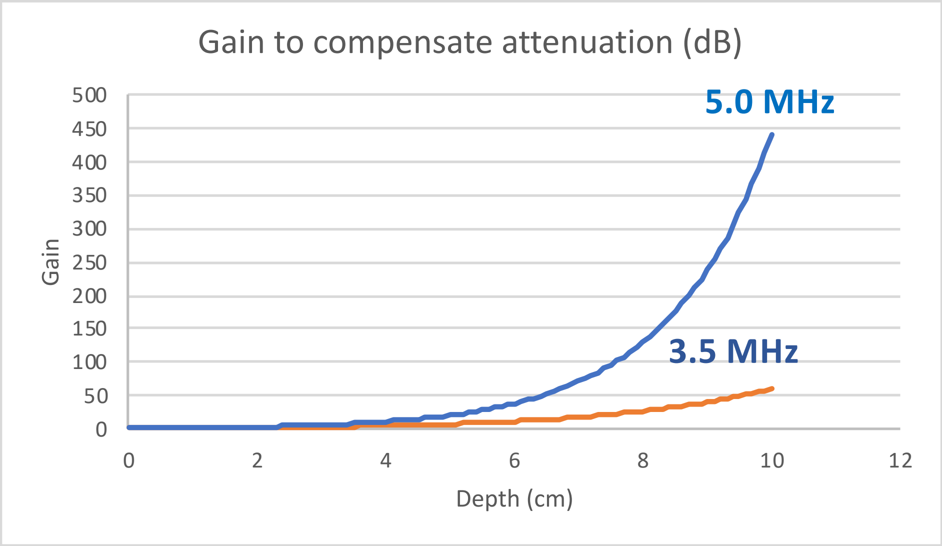
Ultrasound transducers

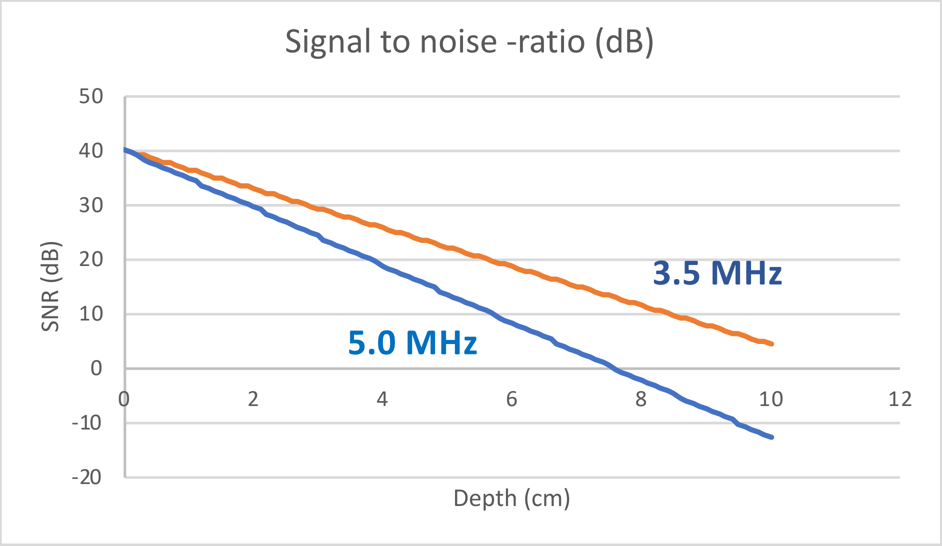




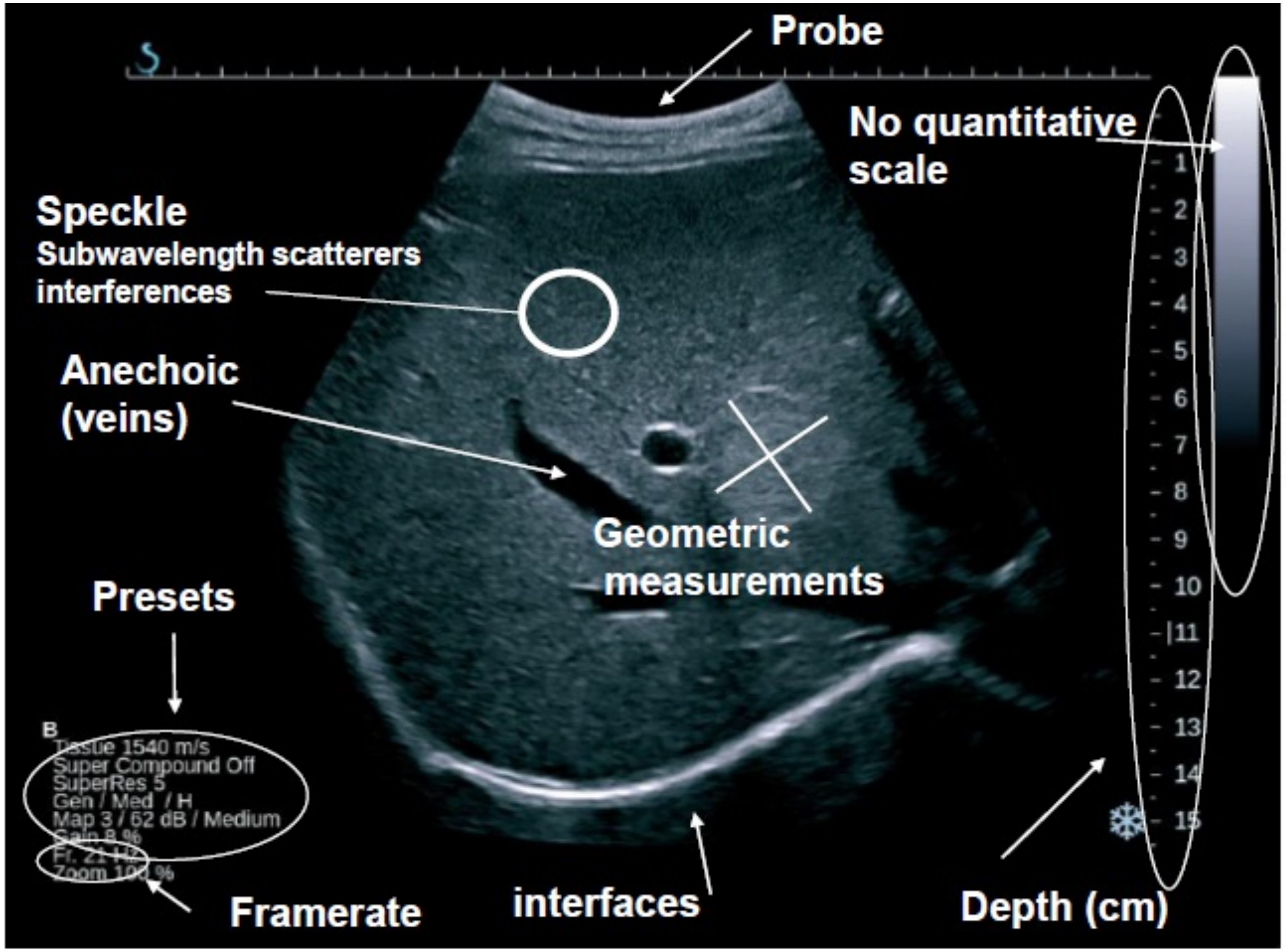
Compensation for attenuation (liver)







Example: device display



Ultrasound devices

Trolley devices

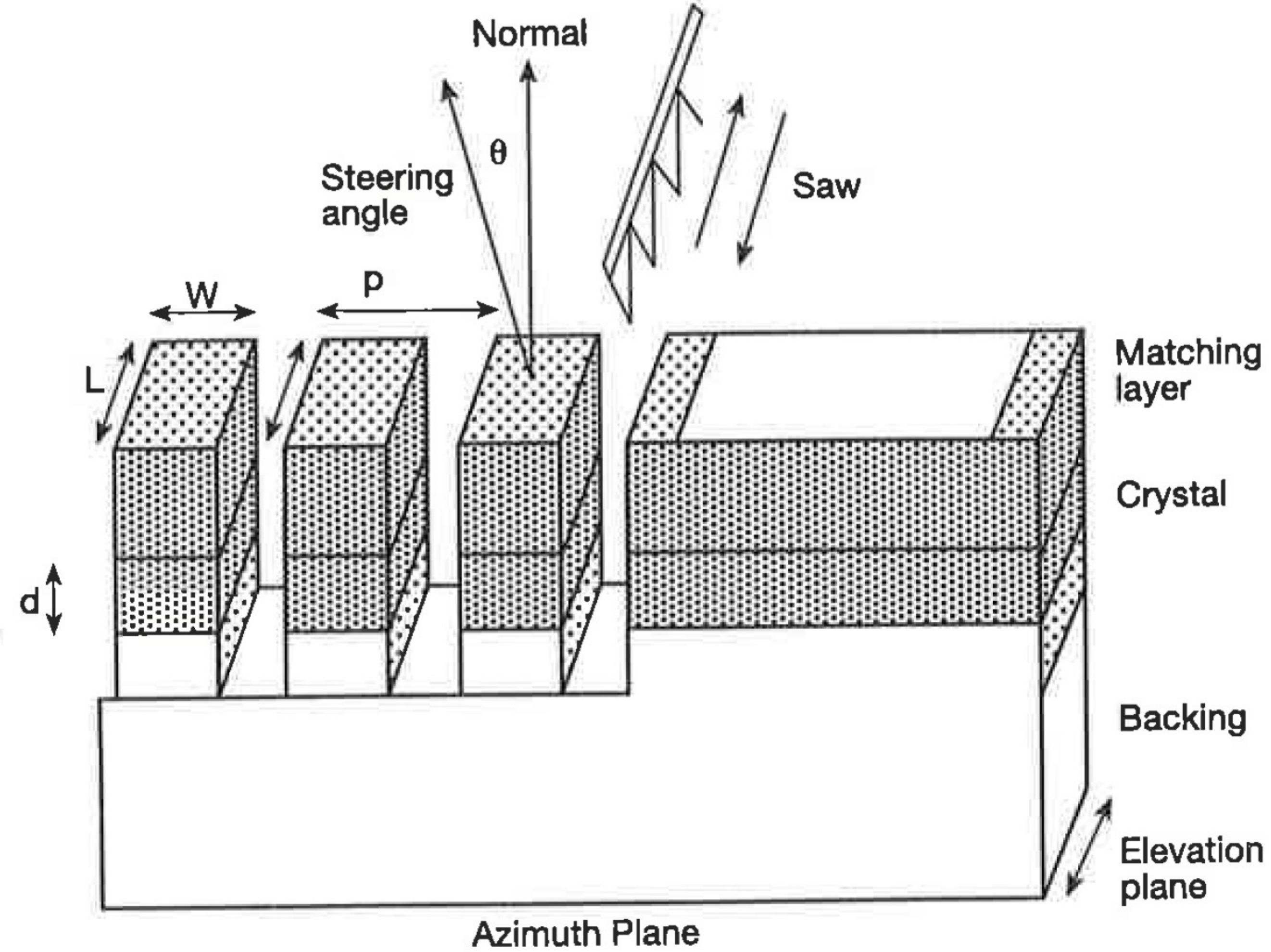
Table-top

Hand-held

Mobile phone

Duck p. 96

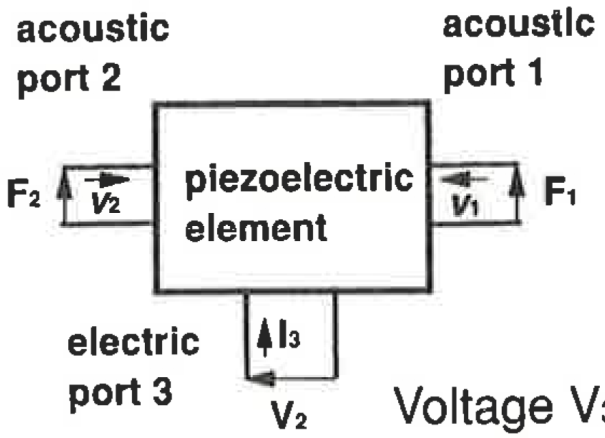
Transducer array



Duck p. 97

Equivalent circuit model

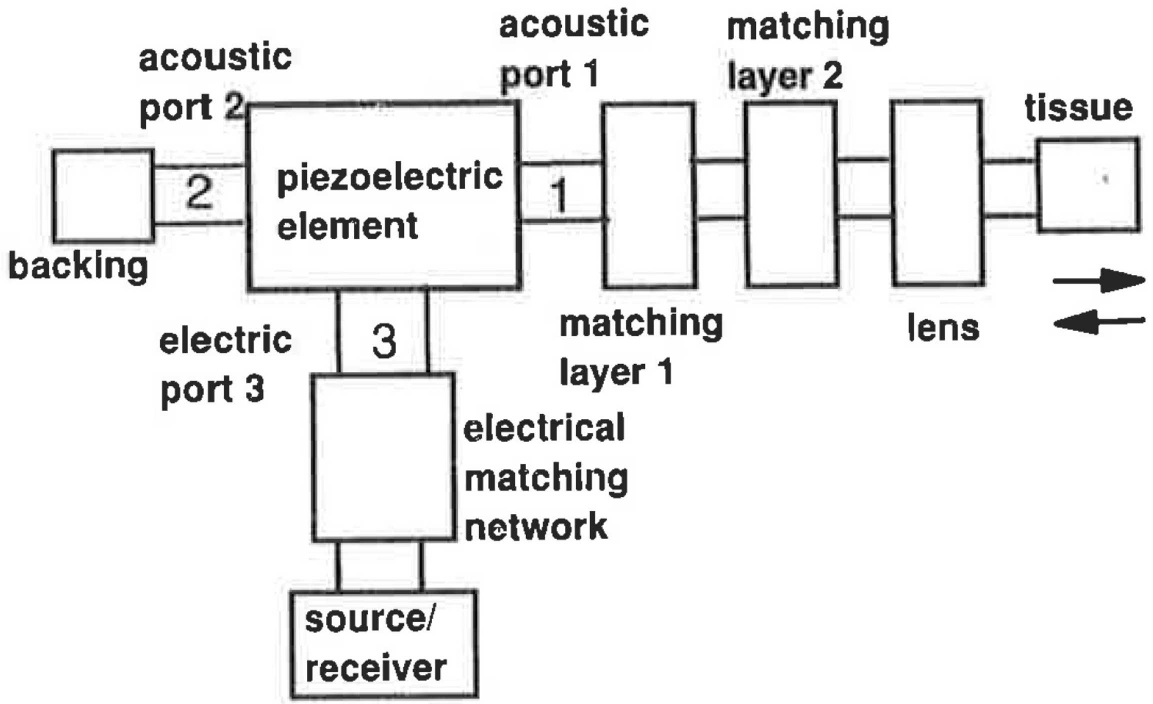
Piezoelectric element



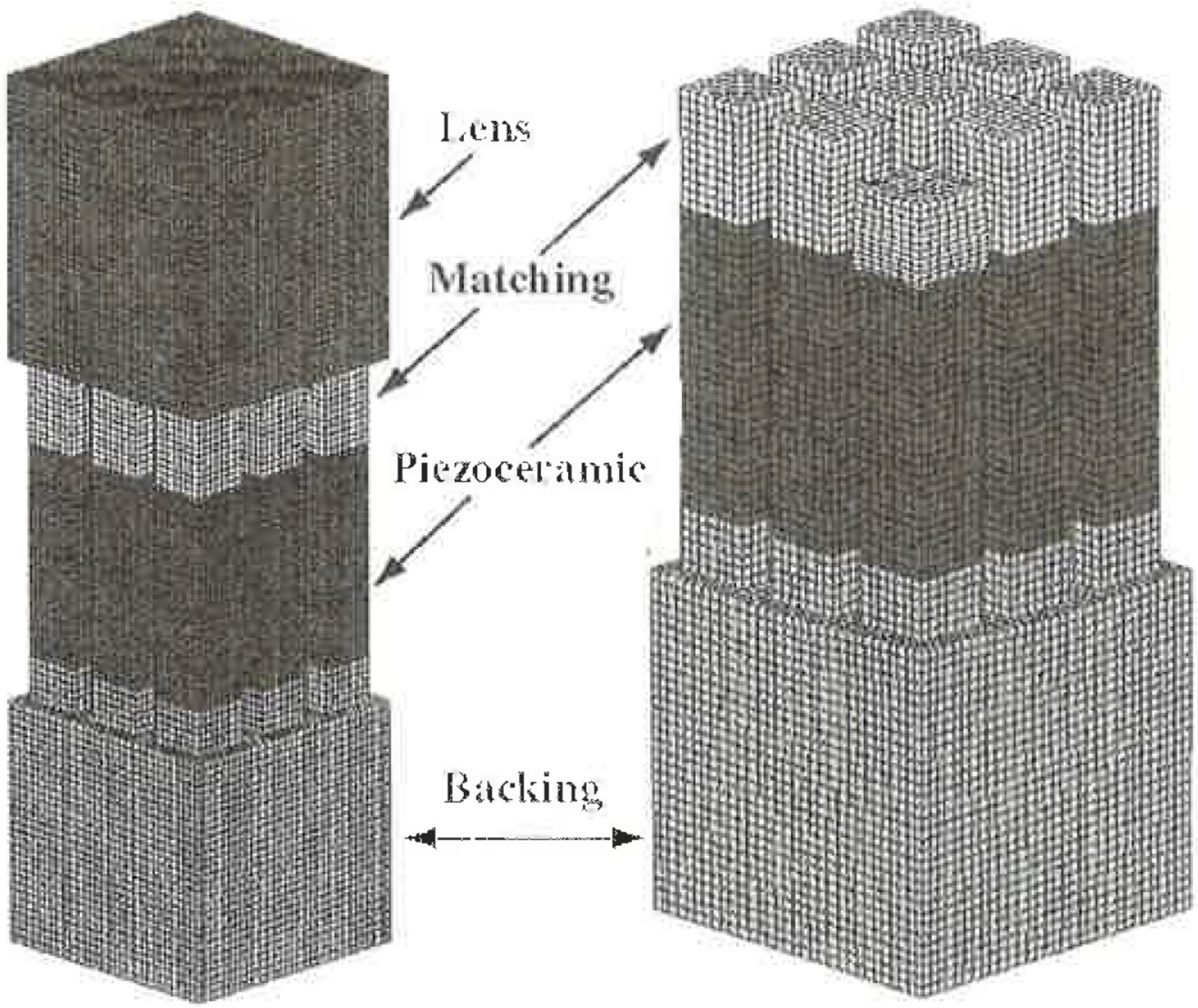
Force F_1
Particle Velocity v_1
Load Impedance Z_1

Voltage V_3
Current I_3
Impedance $Z_3 = V_3/I_3$

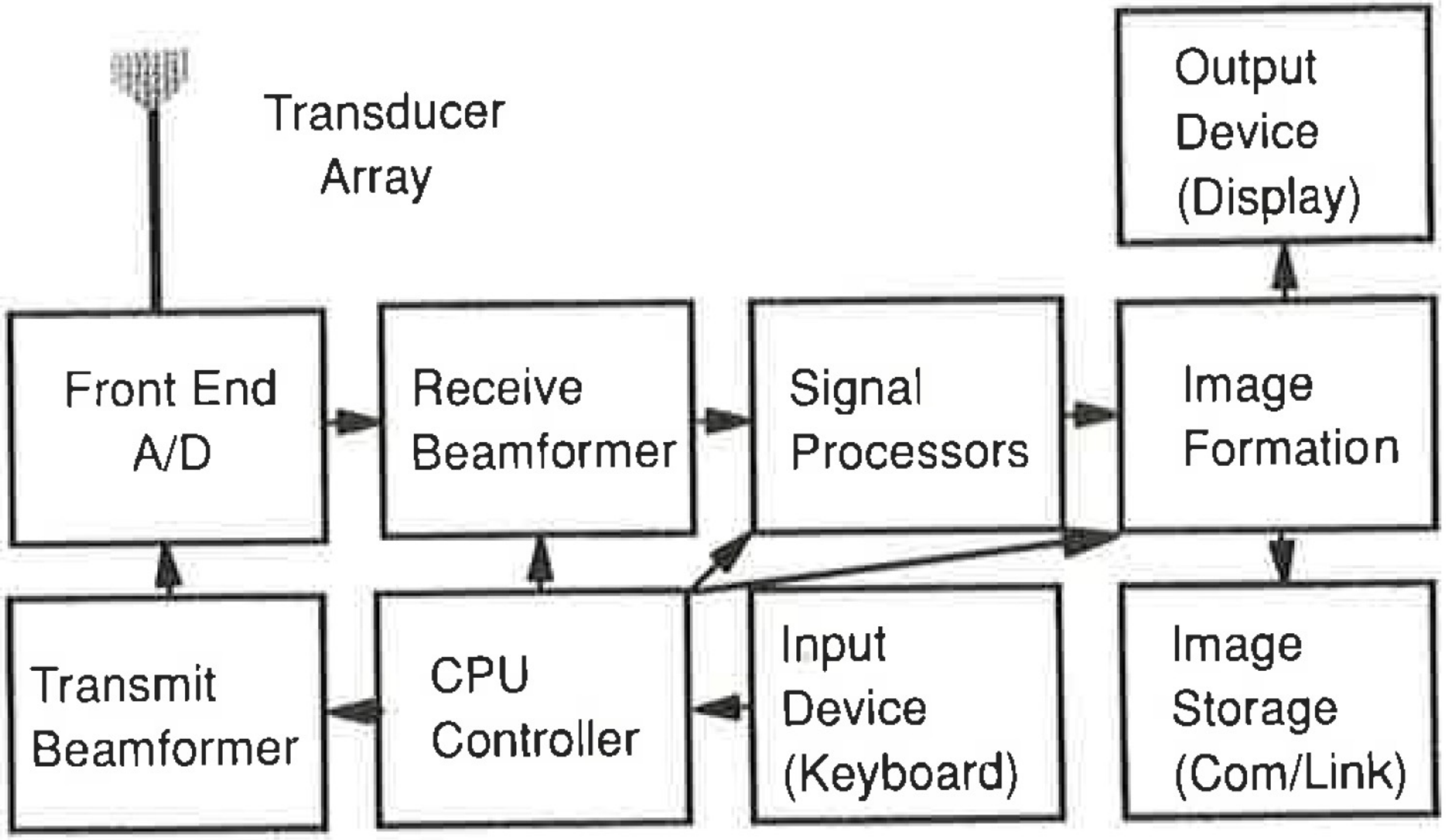
Ultrasound imaging transducer



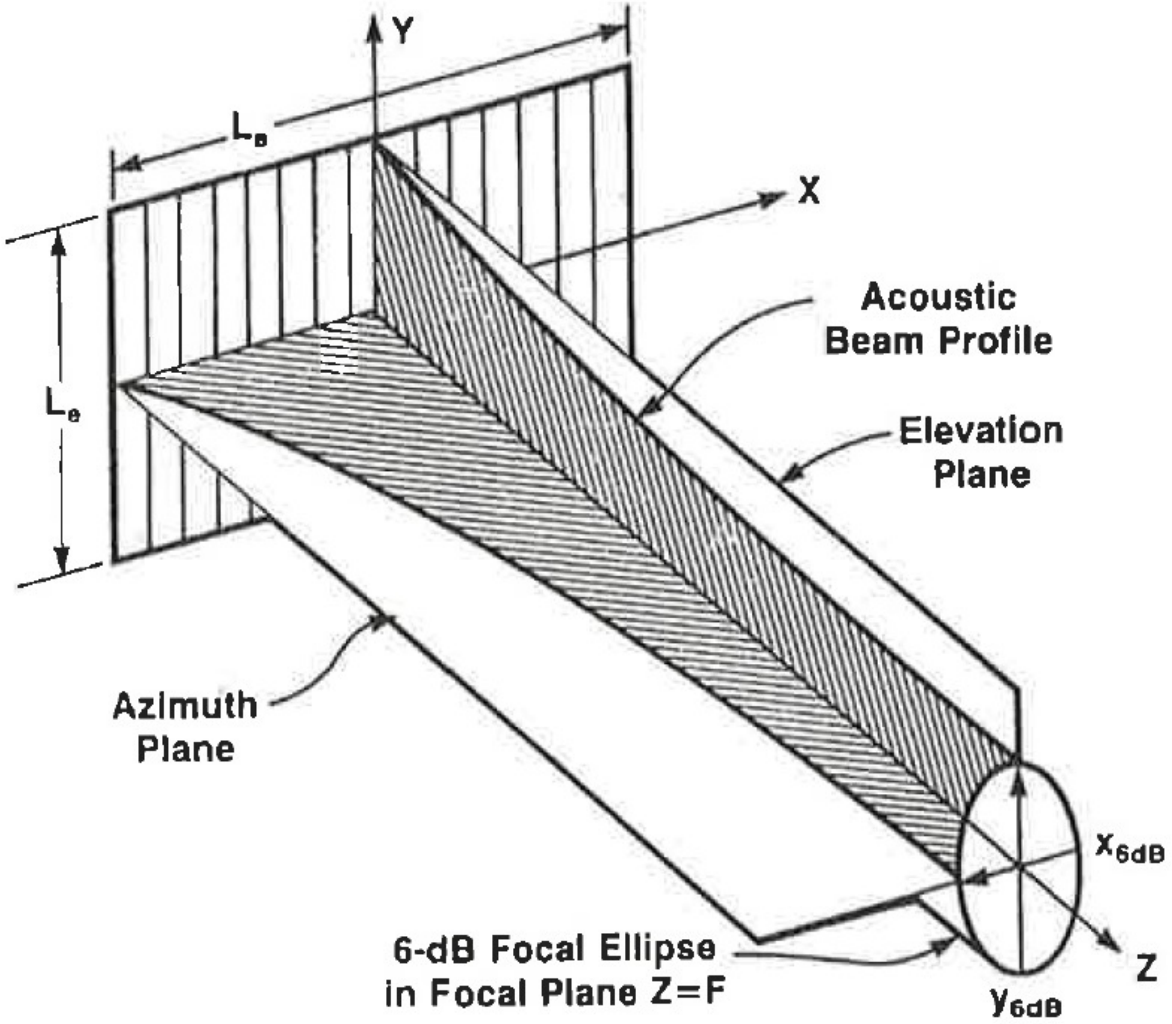
Ultrasound transducer array



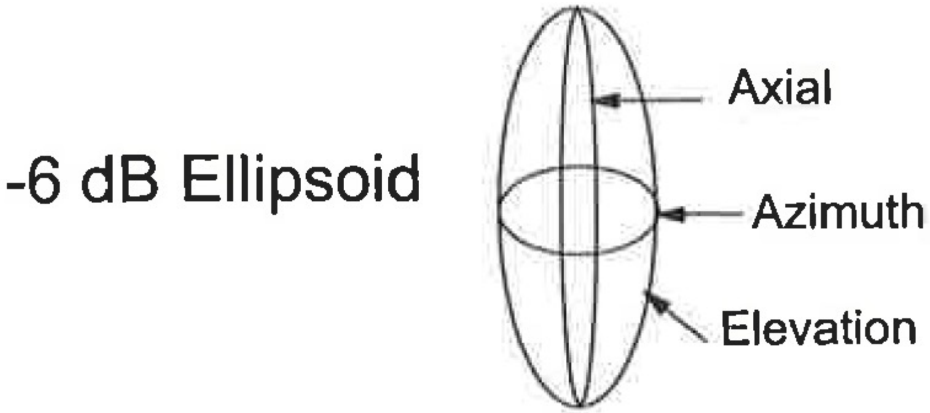
Block diagram of a diagnostic imaging system



Beam



Spatial resolution

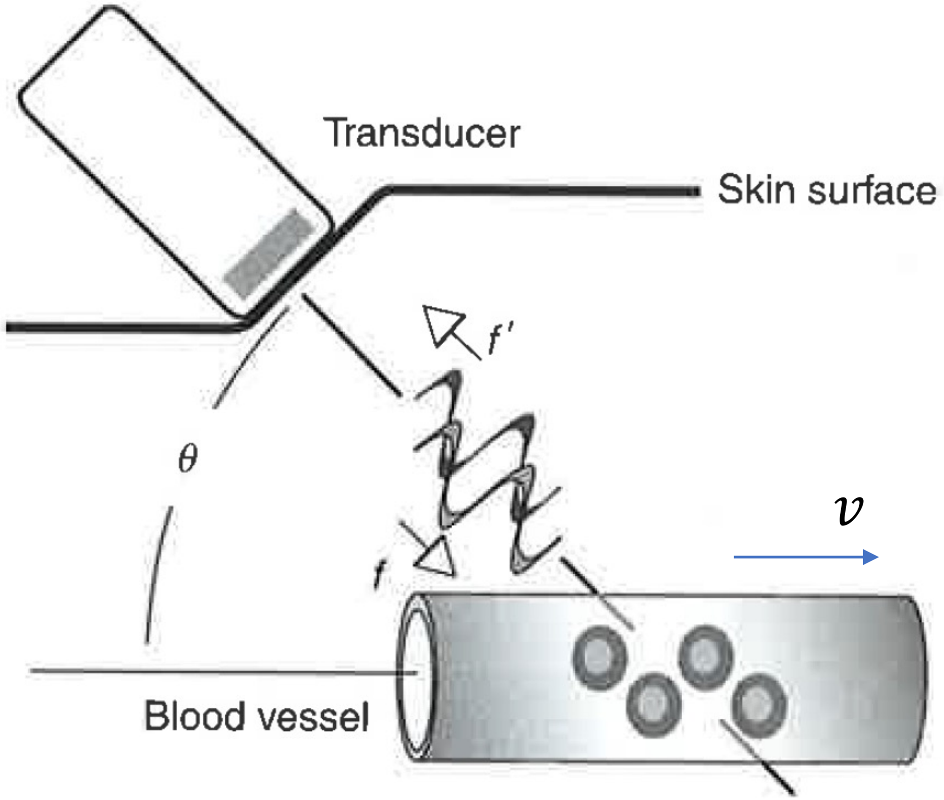


Doppler ultrasound

Doppler ultrasound

- Austrian Physicist Christian Doppler (1803-1853)
- Famous for describing the Doppler effect
  - Shift in wave frequency when the wave source or the observer is moving

Doppler shift

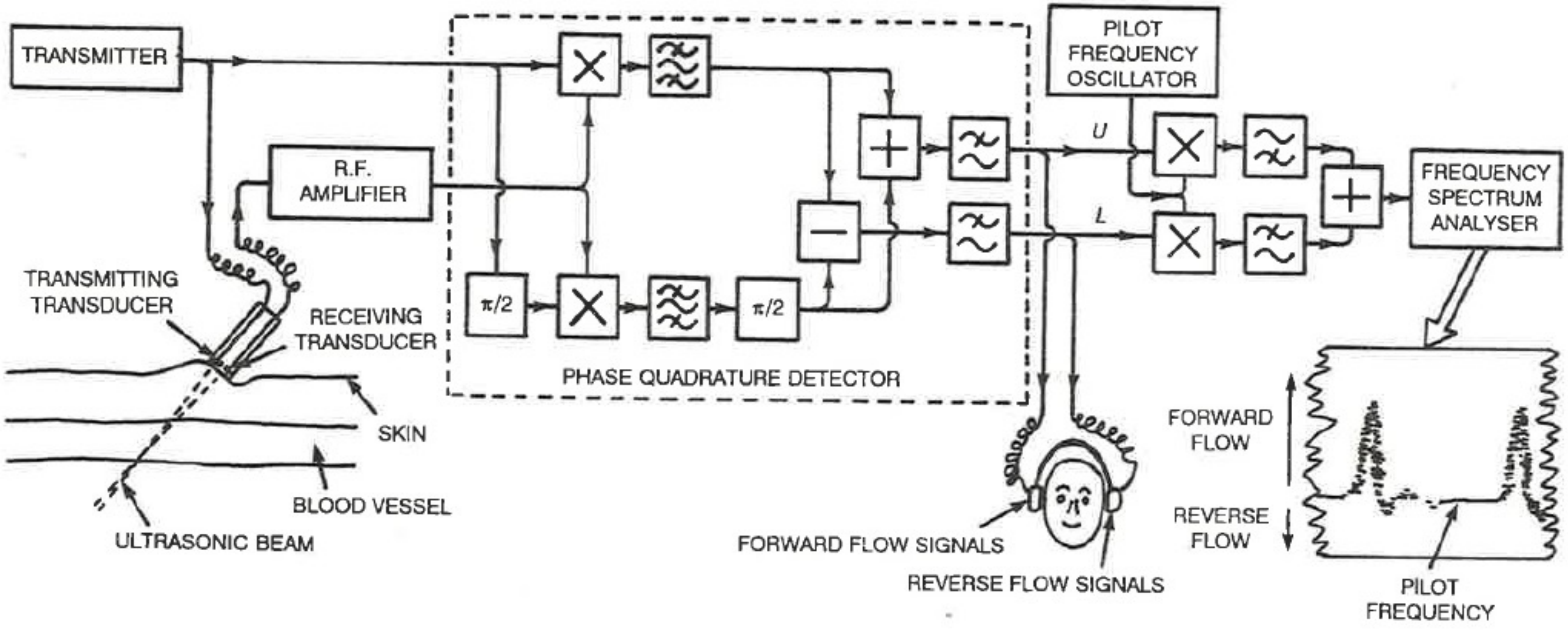


Doppler shift:

$$\Delta f = \frac{2fv}{c}\cos\theta$$

f = change in frequency
Δf = frequency of the incident wave
v = velocity of the flow
c = speed of sound
θ = angle of incidence

Continuous-wave Doppler

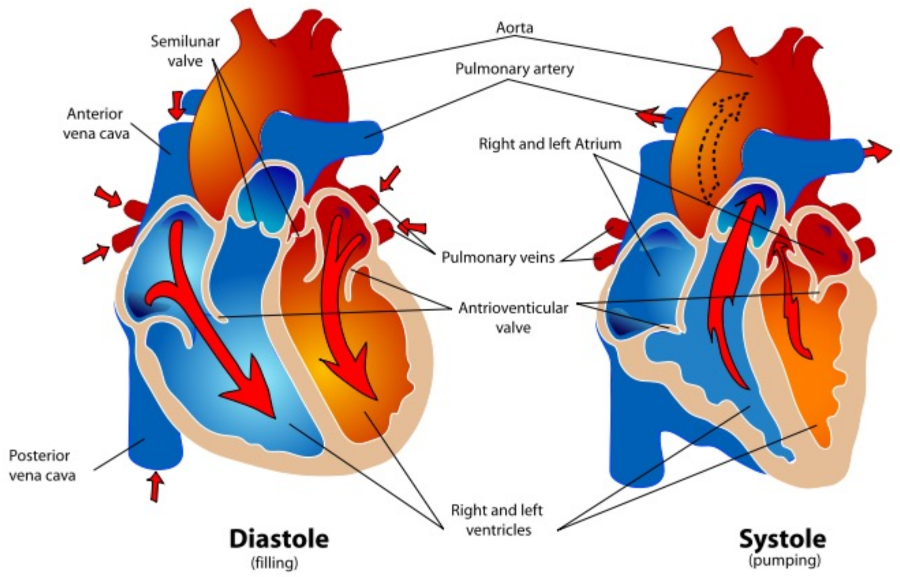


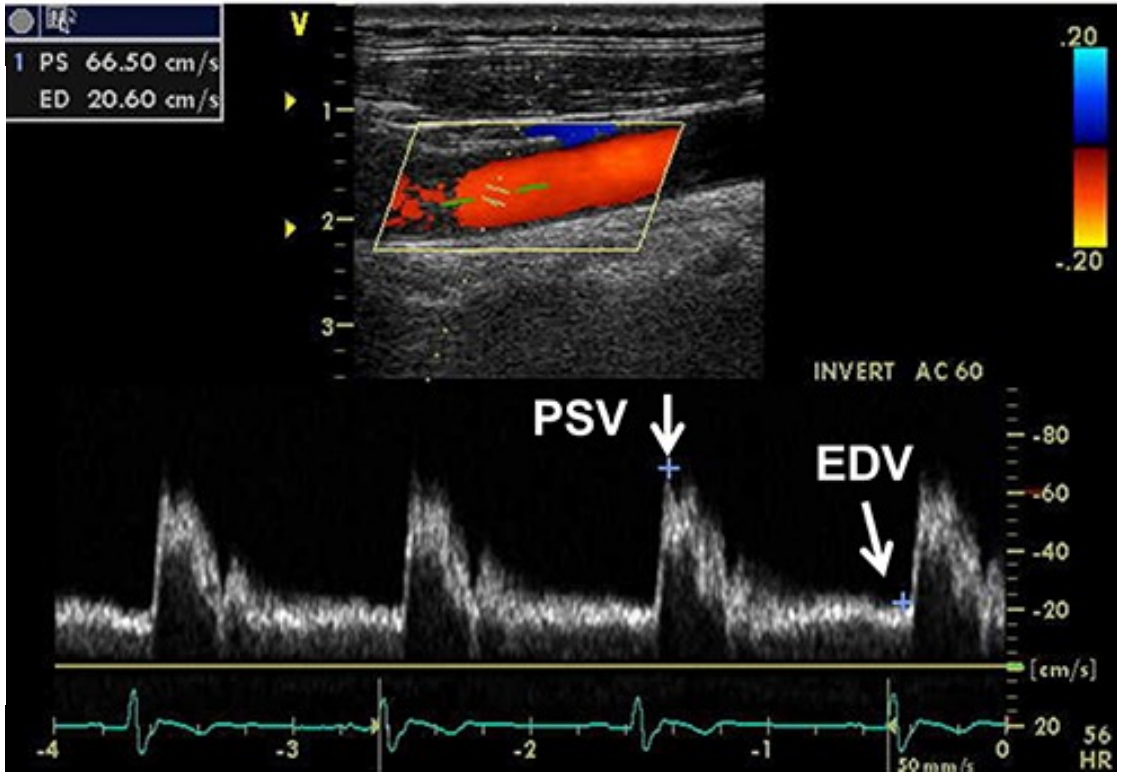
Doppler imaging

- Color Doppler
- Power Doppler
- Spectral Doppler

- Used to visualize and quantify blood flow or organ movement
  - Blood clots
  - Malfunctioning valves in leg veins
  - Heart valve defects and heart disease
  - Arterial occlusion
  - Decreased blood circulation in legs
  - Aneurysms
  - Narrowing of an artery, *e.g.* carotid artery stenosis
  - Umbilical cord

Color Doppler and Spectral Doppler





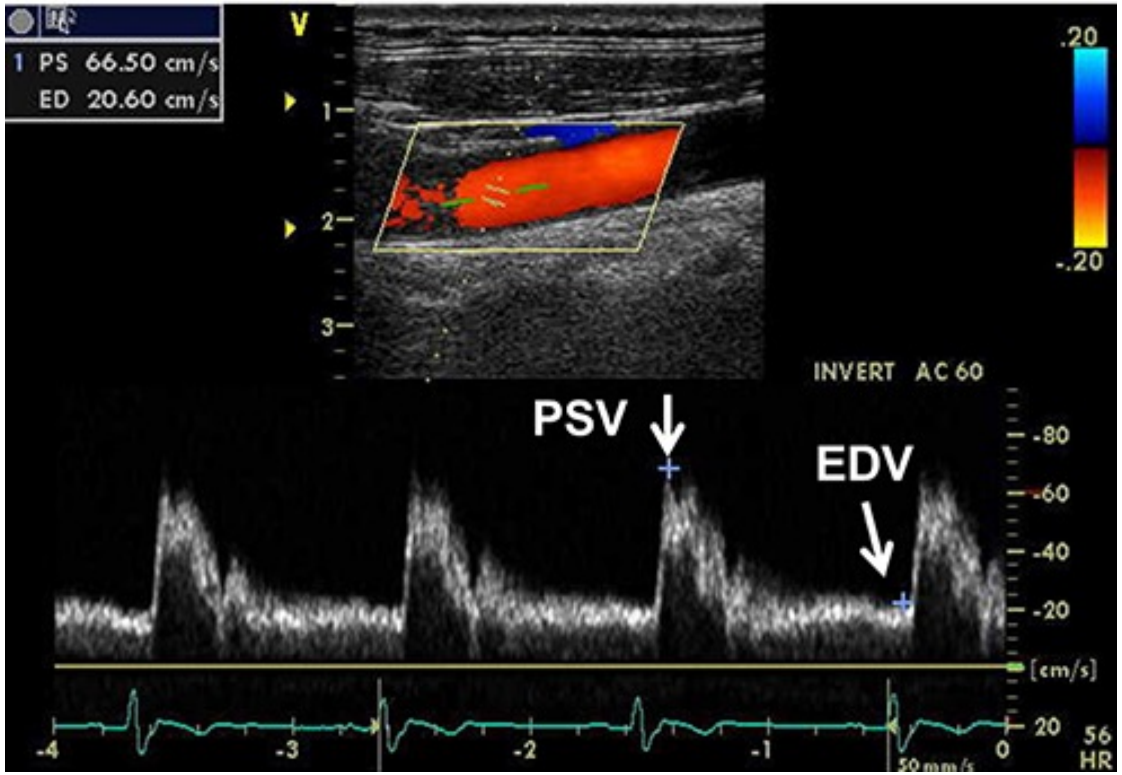
Color Doppler

Spectral Doppler

PSV = peak systolic velocity; EDV = end diastolic velocity

Color Doppler

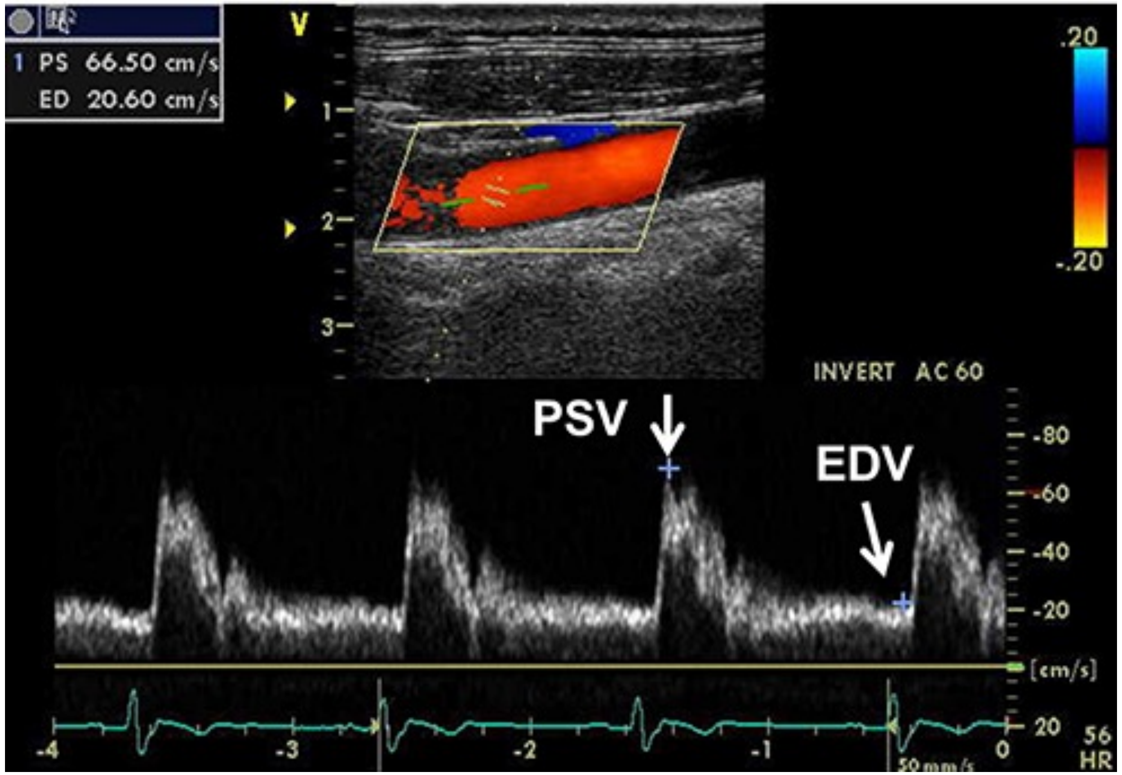
- **Provides velocity of the blood flow**
- **Angle-dependent**
- **Blue color = away from transducer**
- **Red color = towards transducer**



PSV = peak systolic velocity; EDV = end diastolic velocity

Spectral Doppler

- **Provides distribution of velocities of the blood flow within ROI**
- **Angle-dependent**



Spectral Doppler

PSV = peak systolic velocity; EDV = end diastolic velocity

Society of Radiologists in Ultrasound (SRU) consensus, internal carotid artery stenosis

This consensus developed recommendations for the diagnosis and stratification of ICA stenosis.

[PSV = peak systolic velocity; EDV = end diastolic velocity; ICA = internal carotid artery; CCA = common carotid artery]

normal

- ICA PSV is **<125 cm/sec** and no plaque or intimal thickening is visible sonographically
- additional criteria include ICA/CCA PSV ratio<2.0 and ICA EDV**<40 cm/sec**

<50% ICA stenosis

- ICA PSV is **<125 cm/sec** and plaque or intimal thickening is visible sonographically
- additional criteria include ICA/CCA PSV ratio<2.0 and ICA EDV**<40 cm/sec**

50-69% ICA stenosis

- ICA PSV is **125-230 cm/sec** and plaque is visible sonographically
- additional criteria include ICA/CCA PSV ratio of 2.0-4.0 and ICA EDV of **40-100 cm/sec**

≥70% ICA stenosis but less than near occlusion

- ICA PSV is **>230 cm/sec** and visible plaque and luminal narrowing are seen at gray-scale and colour Doppler ultrasound (the higher the Doppler parameters lie above the threshold of **230 cm/sec**, the greater the likelihood of severe disease)
- additional criteria include ICA/CCA PSV ratio>4 and ICA EDV **>100 cm/sec**

near occlusion of the ICA

- velocity parameters may not apply, since velocities may be high, low, or undetectable
- diagnosis is established primarily by demonstrating a markedly narrowed lumen at colour or power Doppler ultrasound

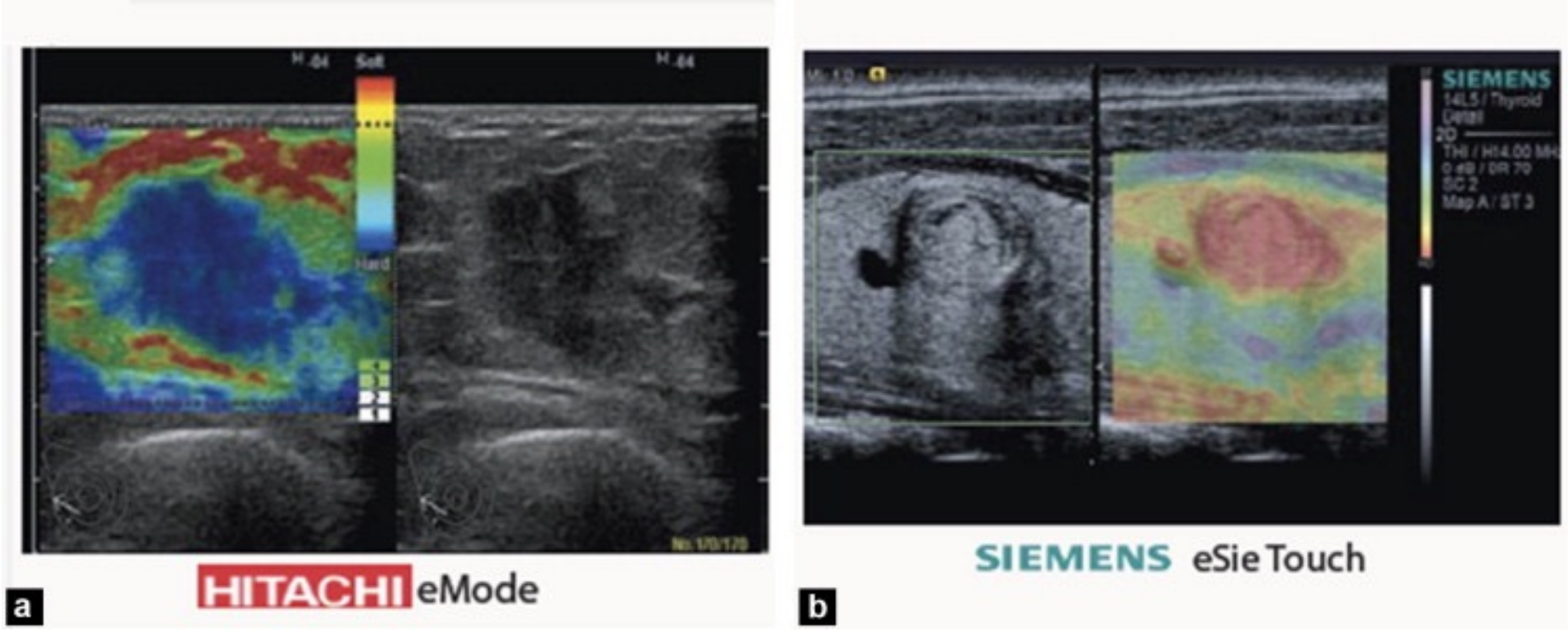
total occlusion of the ICA:

- no detectable patent lumen at gray-scale US and no flow with spectral, power, and colour Doppler ultrasound
- there may be compensatory increased velocity in the contralateral carotid

Elastography

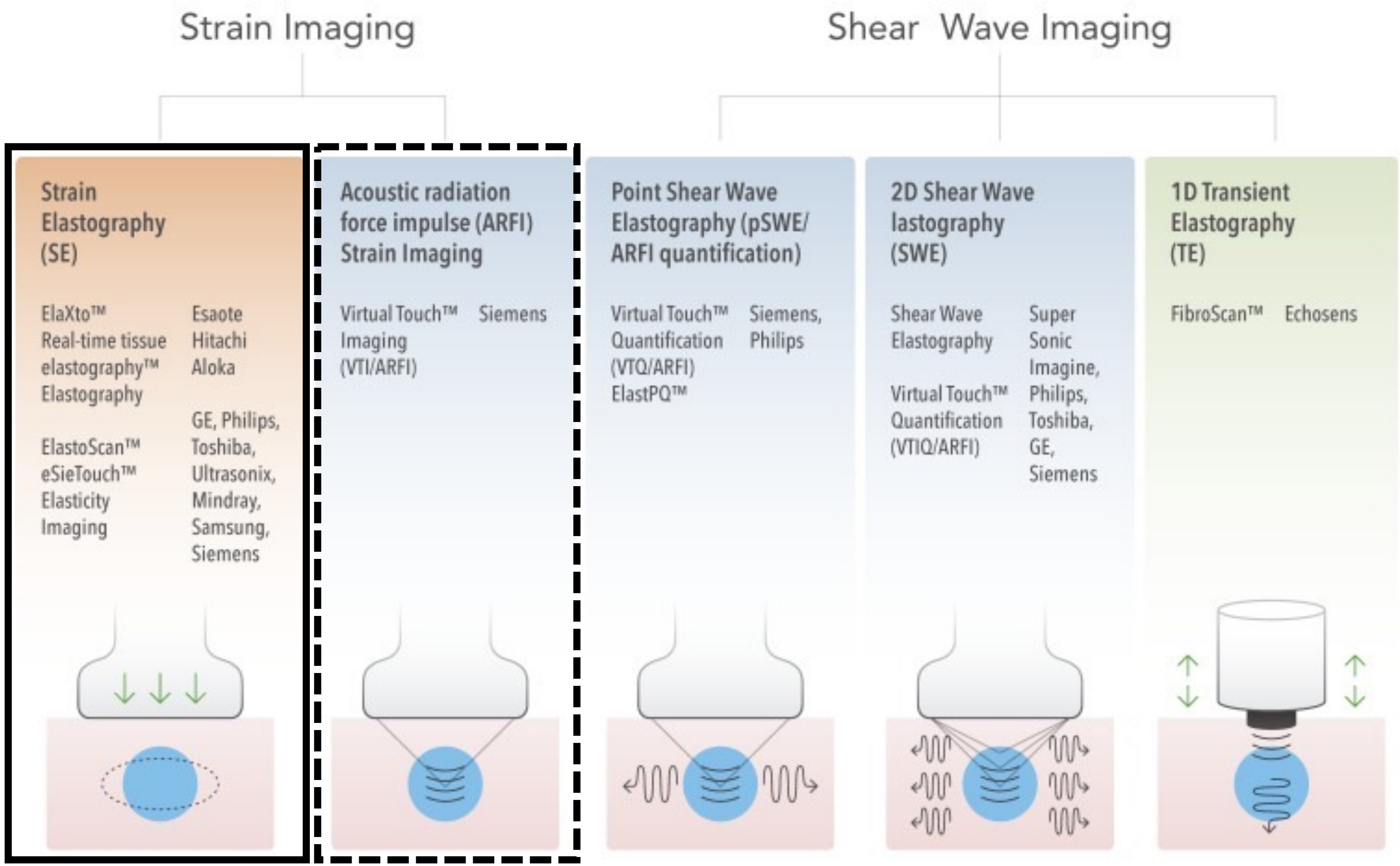
Imaging of tissue elasticity

- Different pathologies can change the stiffness of the tissue as compared to the surrounding tissue
  - E.g. cancer tissue can be calcified and ”hard”, whereas the surrounding tissue is non-calcified and ”soft”



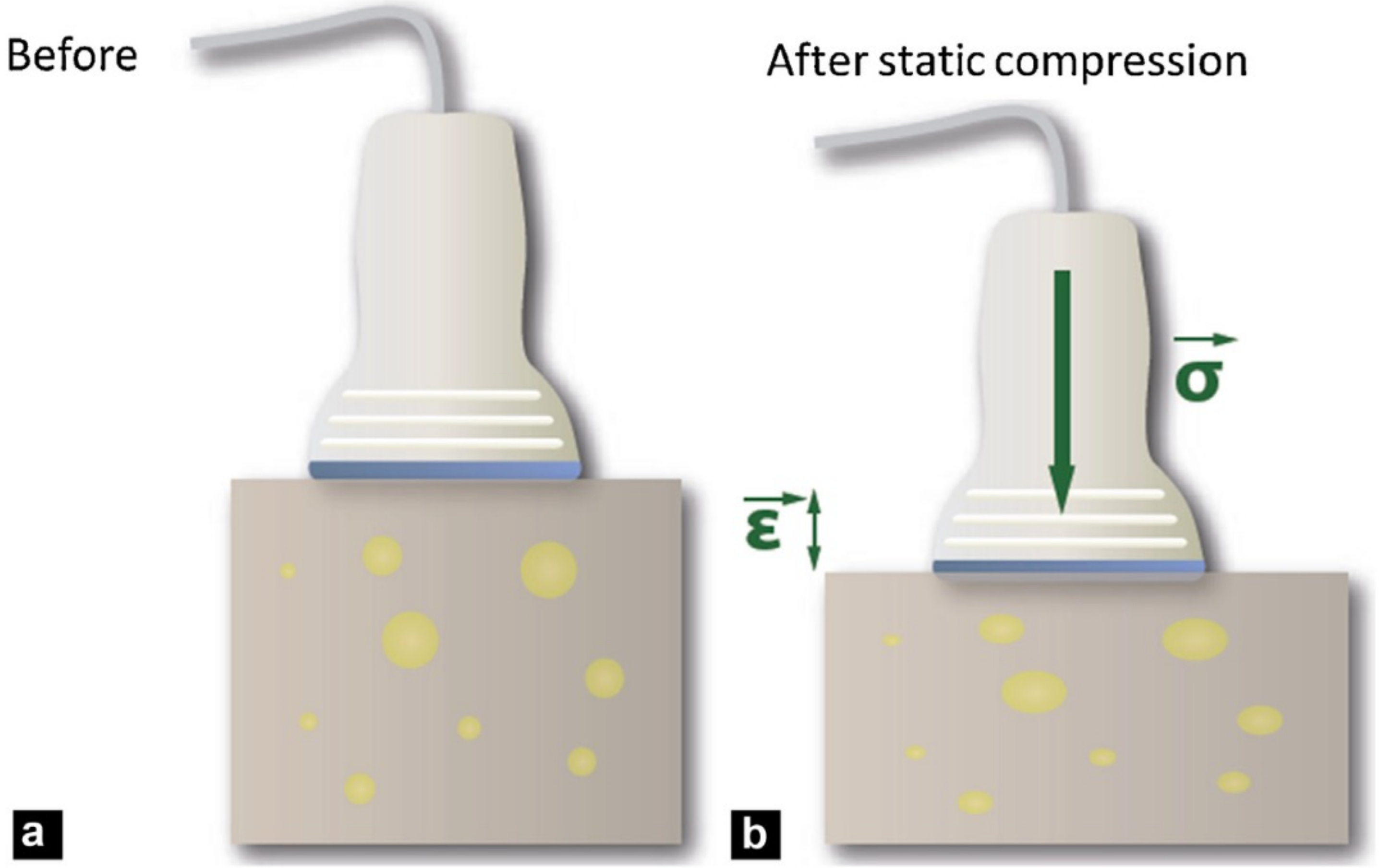
Gennisson et al. 2013: https://doi.org/10.1016/j.diii.2013.01.022

Different approaches



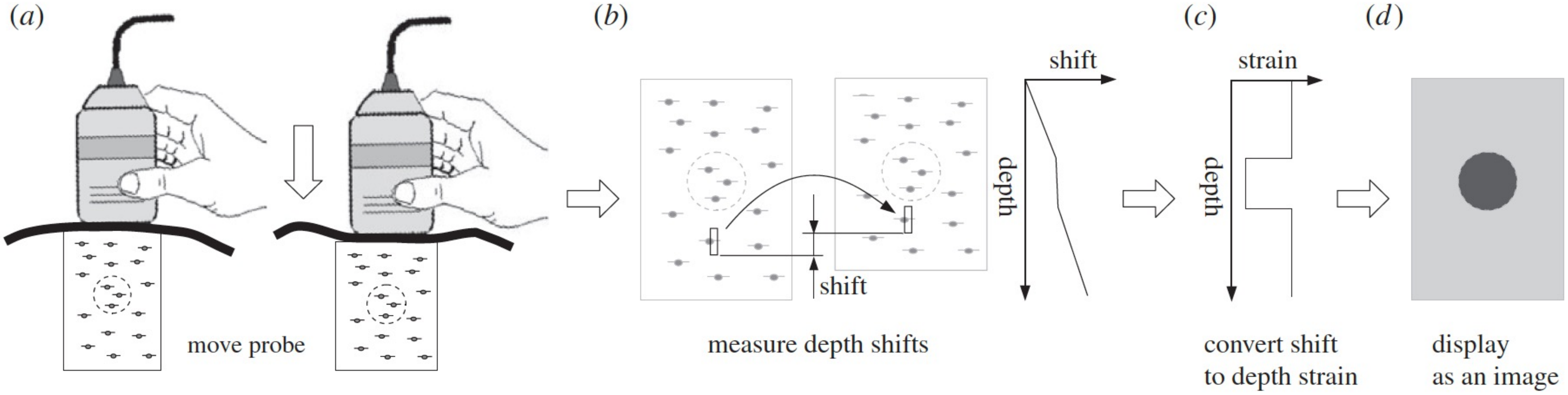
Sigrist et al. 2017: doi: 10.7150/thno.18650

Basic principles: strain elastography



Gennisson et al. 2013: https://doi.org/10.1016/j.diii.2013.01.022

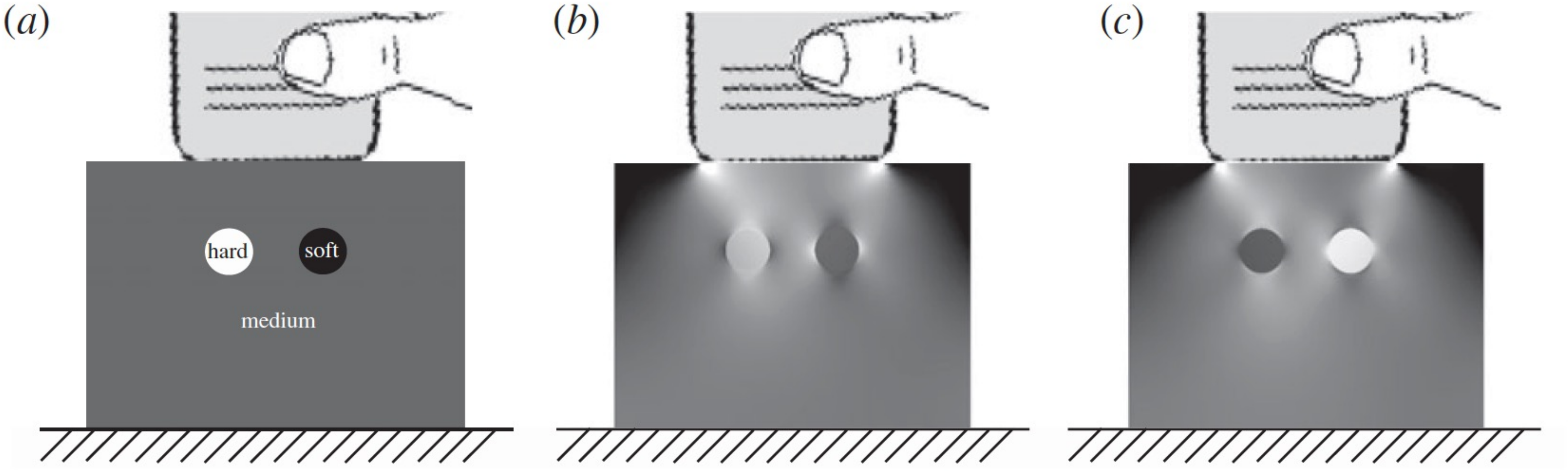
Basic principles: strain elastography



Treece et al. 2011, doi:10.1098/rsfs.2011.0011

Basic principles: strain elastography

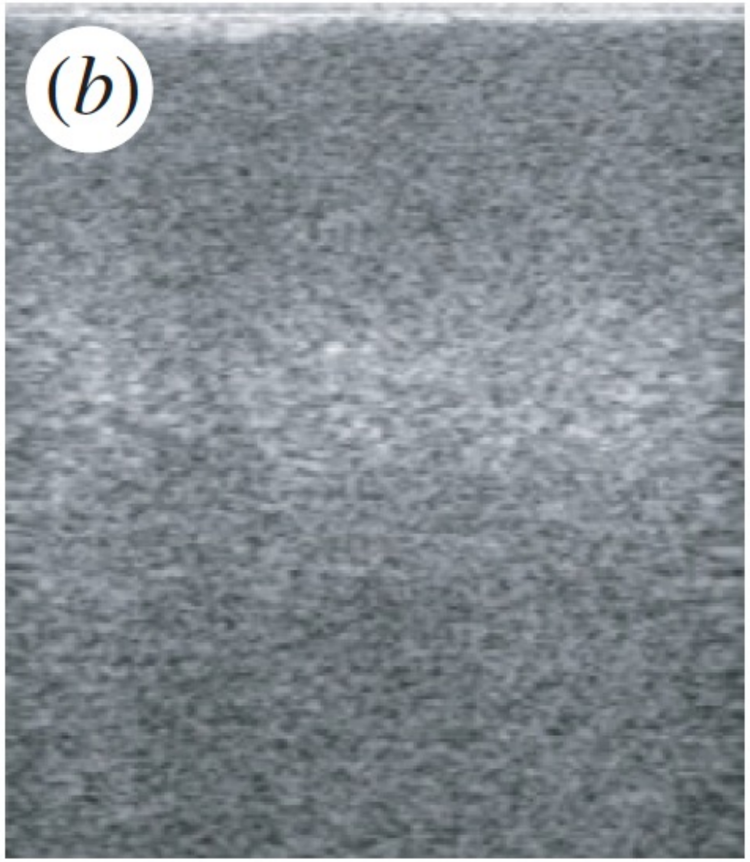
Material stiffness | Stress field | Strain map



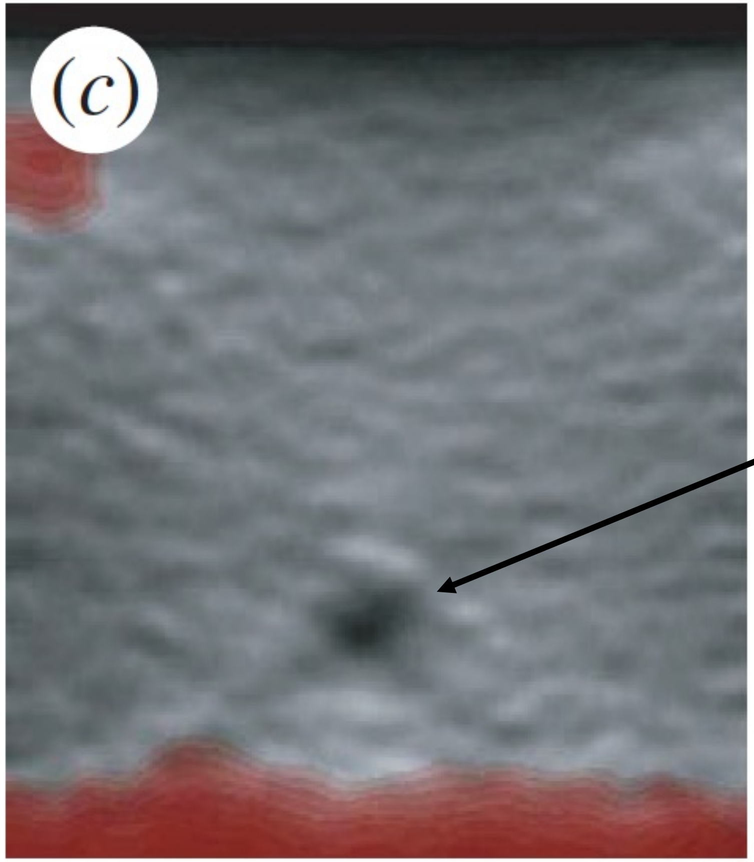
Treece et al. 2011, doi:10.1098/rsfs.2011.0011

Basic principles: strain elastography (phantom)

B-mode imaging



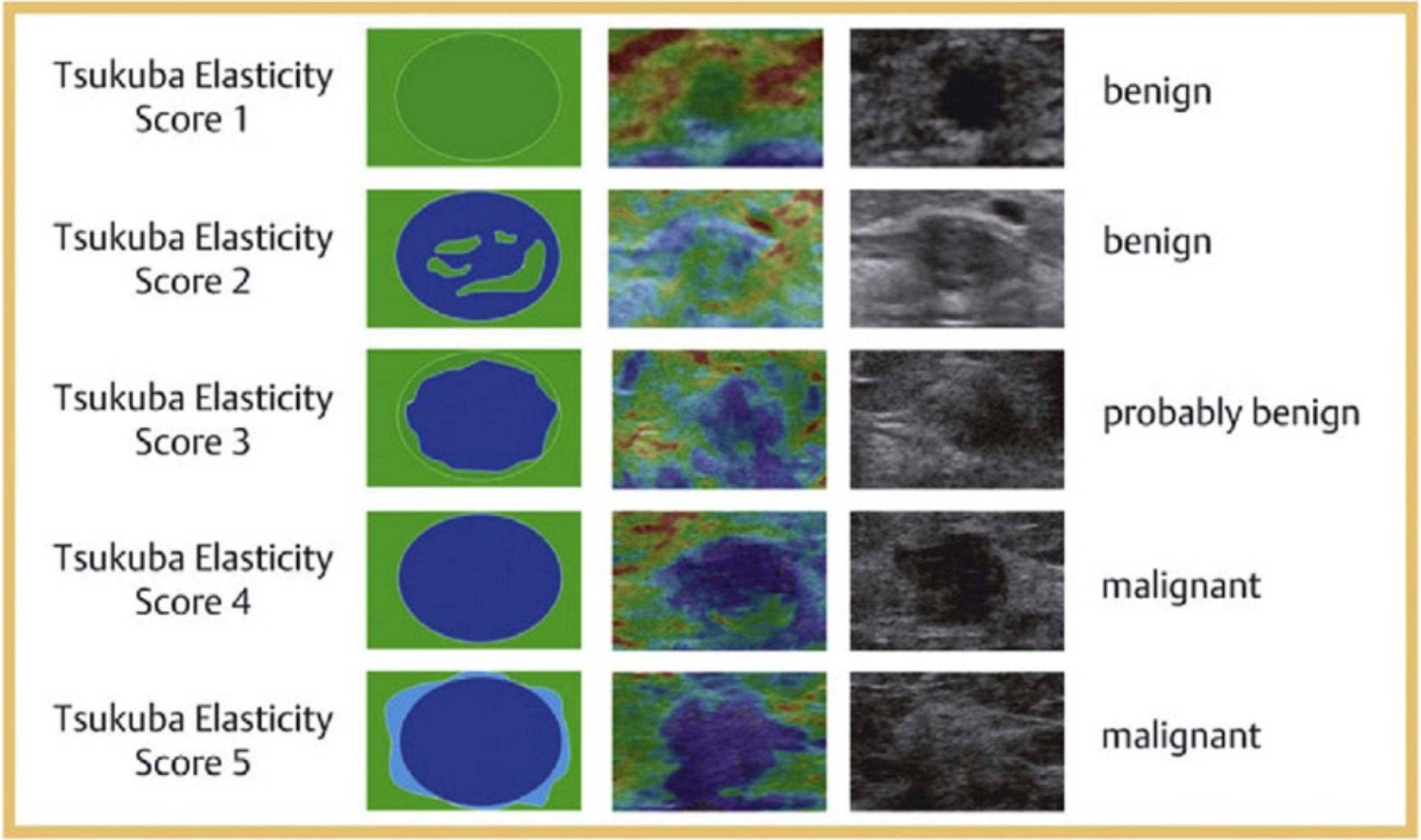
Strain image



Hard inclusion

Treece et al. 2011, doi:10.1098/rsfs.2011.0011

Basic principles: strain elastography (breast)



Schwab et al. DOI: 10.1016/j.ultrasmedbio.2016.06.017