MSc Advanced Neuroimaging Lectures

Ultrasound I

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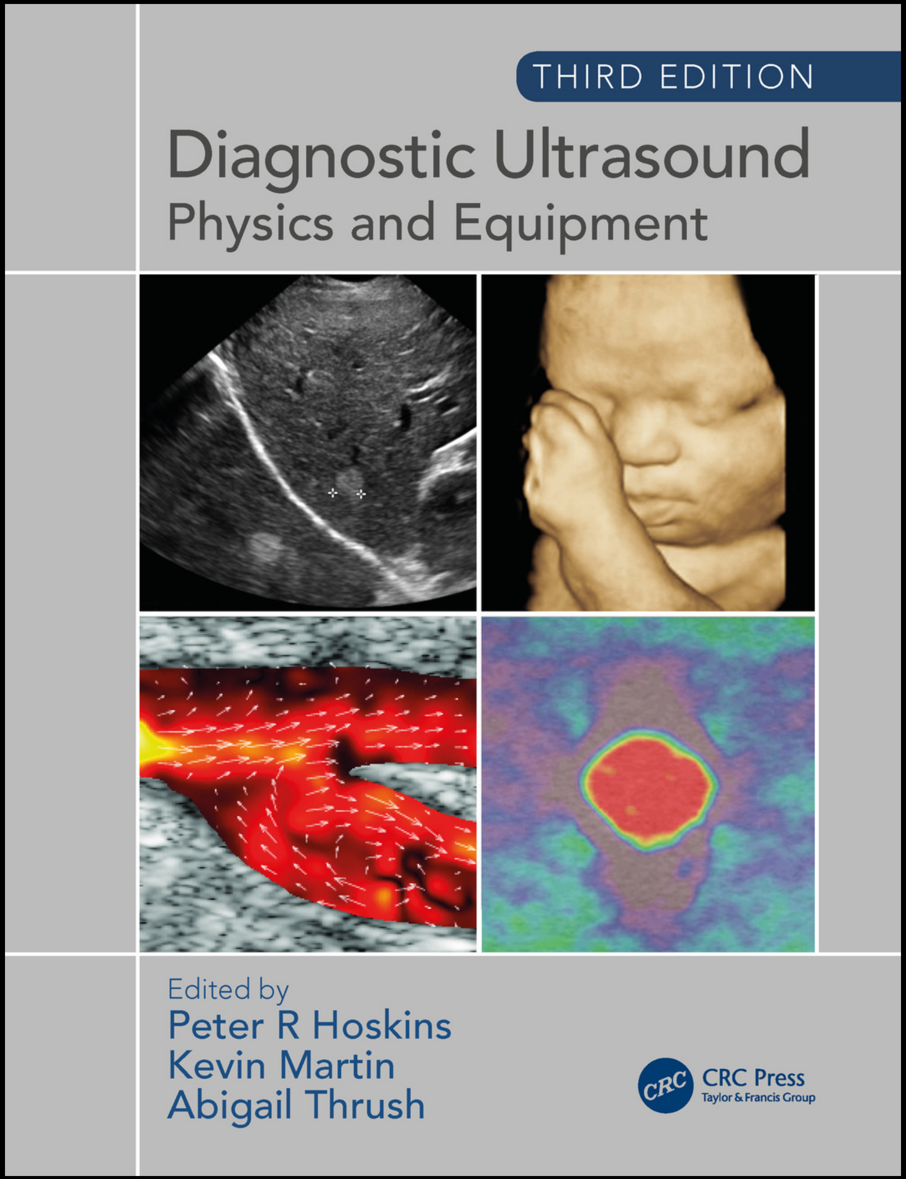
Learning outcomes

- Describe the **basic principles of ultrasound waves**, acoustic media and ultrasonic wave propagation
  - Interactions wioth tissue: *Reflection, Attenuation, Refraction and Scattering*
  - Acoustic properties: *Impedance, Reflection Coefficient, Attenuation Coefficient*
- Explain the concepts of **pulse-echo imaging** (echolocation) and how this is used to produce a medical ultrasound image (**A-mode** and **B-mode**)
  - Perform simple calculations to determine acoustic intensity (and pressure) following reflections at interfaces between different media and attenuation
- **Ultrasound transducers**: draw a diagram of the design of a simple disc transducer, label the components, and describe their function
- Describe two methods for **ultrasound beam focusing**
- Describe the basic design, underlying concepts, advantages, and common types of **array transducers**
- Explain how **electronic beam focusing and steering** are achieved
- Explain what **time-gain-compensation (TGC)** is and why it is needed
- List common B-mode ultrasound **image artefacts** and explain when and how they arise



THIRD EDITION

Diagnostic Ultrasound
Physics and Equipment

Edited by
Peter R Hoskins
Kevin Martin
Abigail Thrush

CRC Press
Taylor & Francis Group

Recommended books

- Hoskins, Peter R., Kevin Martin, and Abigail Thrush, eds. **Diagnostic ultrasound: physics and equipment.** *CRC Press, 2019.*
- Paul L. Allan, Grant M. Baxter and Michael J. Weston. **Clinical Ultrasound**, 2011

For a more "technical" / detailed description of diagnostic ultrasound and latest advancements:

- Szabo, Thomas L. **Diagnostic ultrasound imaging: inside out**. *Academic press, 2014.*

Basic principles

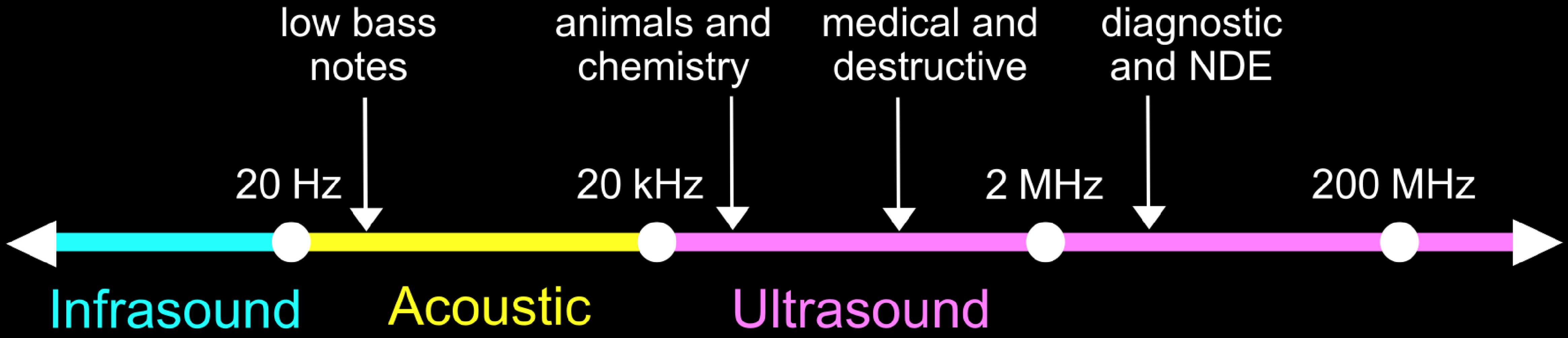
What is sound?

A mechanical vibration that propagates as a (longitudinal) **pressure wave**

Properties of ultrasound waves

Frequency range: $1 \sim 20$ **MHz**

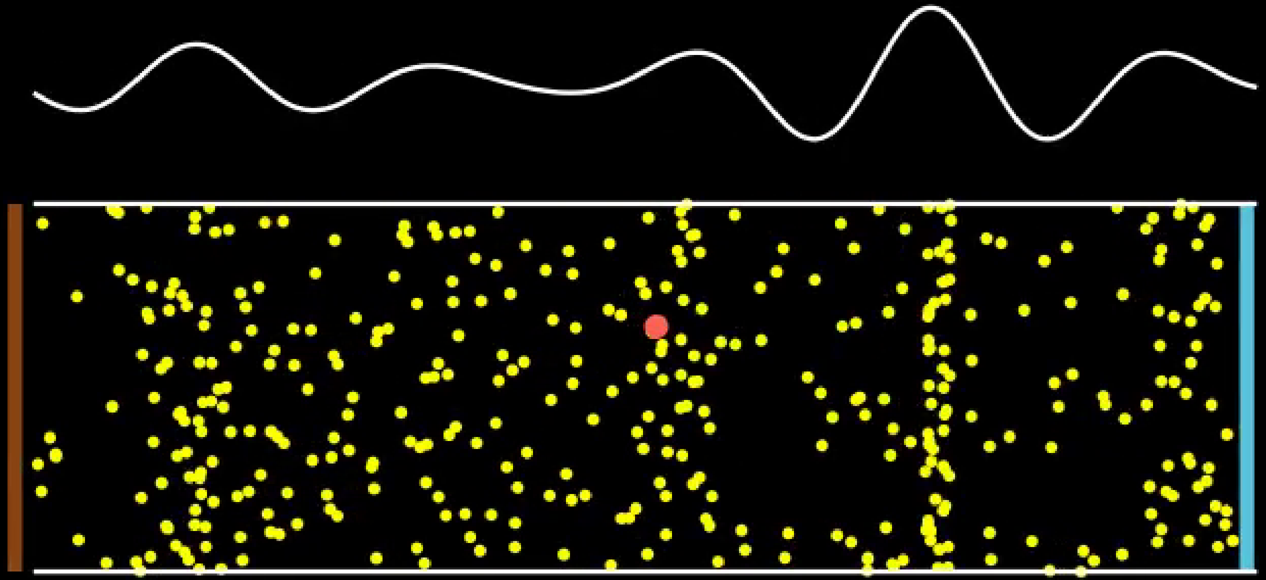
Wavelength: $80\mu\text{m} \sim 1.5\text{mm}$



[Wikimedia]

Ultrasound propagation in tissue

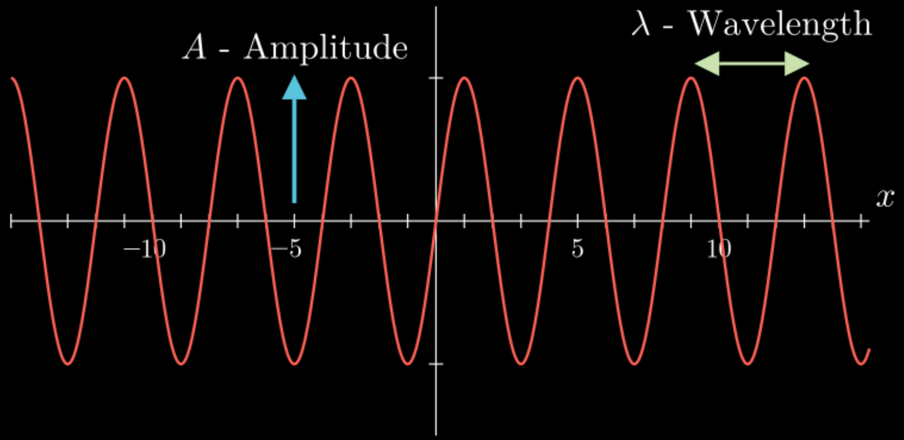
- **Compression** at the high values of instantaneous amplitude (⇈ pression)
- **Rarefaction** at the low values of instantaneous amplitude (⇊ pression)
- Energy is transfered in the direction of wave propagation

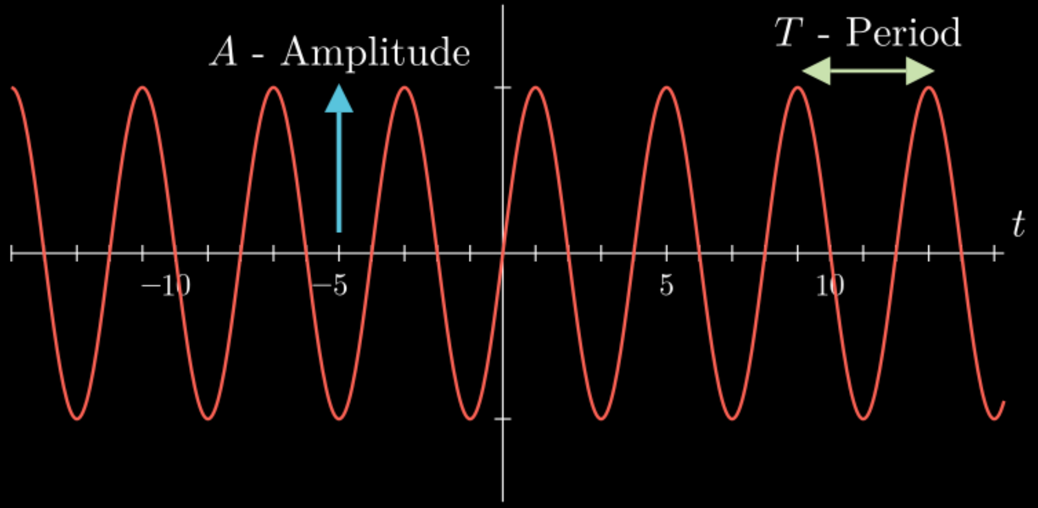


Pressure waves are always **longitudinal** and are the only possible waves in fluids (soft tissues)

Tissue is an **elastic medium** and can generate transverse (shear) waves

Ultrasound wave parameters





Amplitude: $A\ [\mathrm{Pa} = \mathrm{N}/m^2]$

Intensity: I, measures the energy $[W/m^2]$

Wavelength: $\lambda\ [m]$

Period: $T\ [s]$

Frequency: f, inverse of the period $[\mathrm{Hz} = 1/s]$

Speed of sound: $c = f \times \lambda\ [m/s]$

Ultrasound transducer

- Uses the piezoelectric effect of a PZT element to transform voltage into compression / expansion → acoustic waves
- PZT: Lead Zirconate Titanate
- Can be used to receive waves: oscillations of the PZT plate thickness are transduced into electrical signals

[Szabo, 2014]

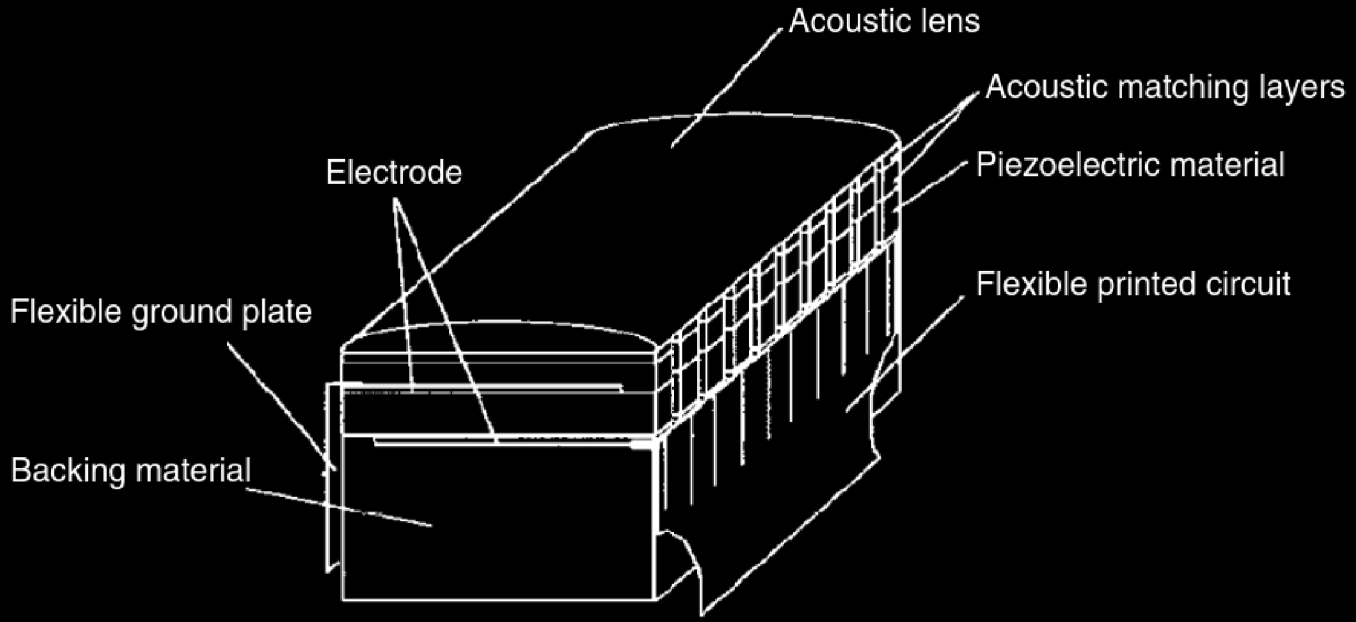


Figure 5.7 Construction of a one-dimensional array with an elevation plane lens (from Saitoh *et al.*, 1999, *IEEE*).

Physical interactions

Interactions happen at the **interface** between two regions with different material properties, e.g. different densities of the tissue.

Specular reflection and transmission

Echo location (sonar)

The wave needs to travel a distance d to reach the boundary. If the speed of sound is c, this is done in

$$T = d/c$$

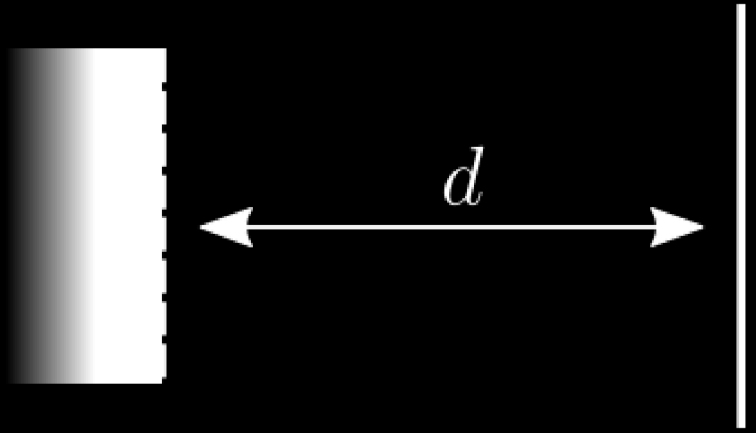
The reflection needs to travel back another d, therefore it is recorded at time

$$T_r = 2d/c$$

Therefore

$$d = cT_r/2$$

If c is known, distances can be estimated from the arrival time of the reflected wave



Reflection

Reflection coefficient

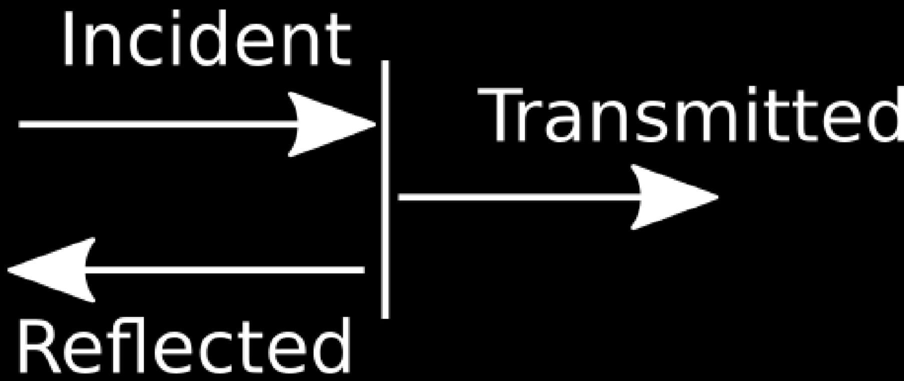
$$R_A = \frac{p_{reflect}}{p_{incident}} = \frac{Z_2 - Z_1}{Z_1 + Z_2}$$

Intensity of reflection

$$R_I = \frac{I_{reflect}}{I_{incident}} = R_A^2$$

Energy conservation

$$I_{incident} = I_{reflect} + I_{transmit}$$



Values for soft tissue

Material	Impedance ($10^6\, kg\, m^{-2} s^{-1}$)
Air	0.0004
Skin	1.68
Water	1.48
Blood	1.68
Skeletal muscle	1.65
Liver	1.64
Fat	1.33
Bone	5.69

[Szabo, 2014]

What happens if we try to transmit an ultrasound wave from the air to a muscle ❓

Physical interactions

Refraction

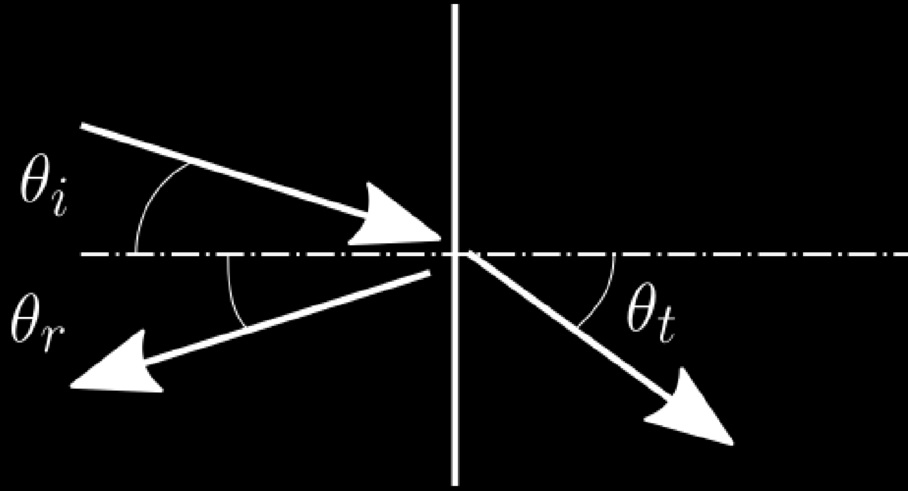
0:00 / 0:08

Physical interactions

In **specular reflection** $\theta_r = \theta_i$

In general, the **Snell's law** gives us the relationship between the incident and transmitted angles:

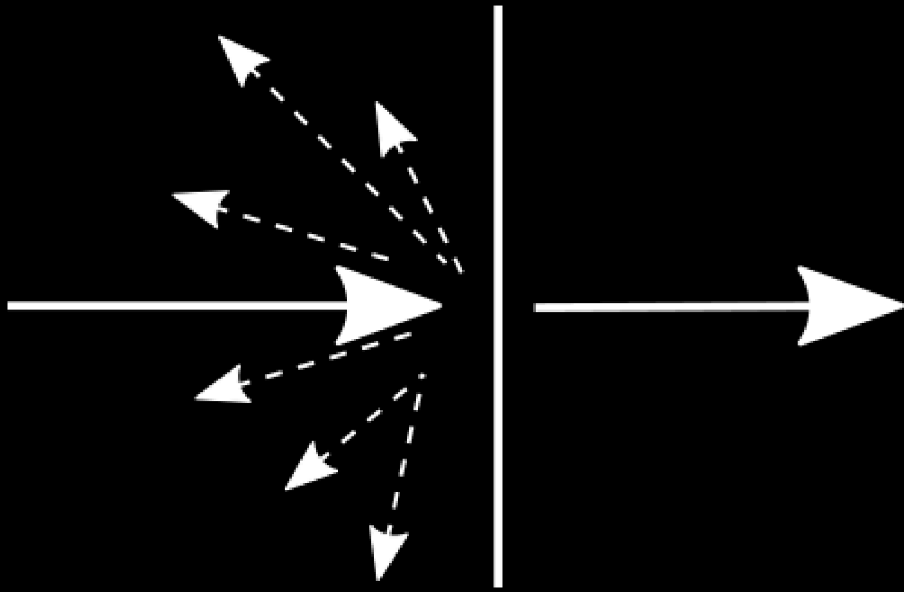
$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{c_1}{c_2}$$



All of this assume a perfectly **flat and smooth boundary** between the two media

Physical interactions

If the surface is not perfectly flat, the reflected wave is scattered over muiltiple paths, in what is called **diffuse reflection**



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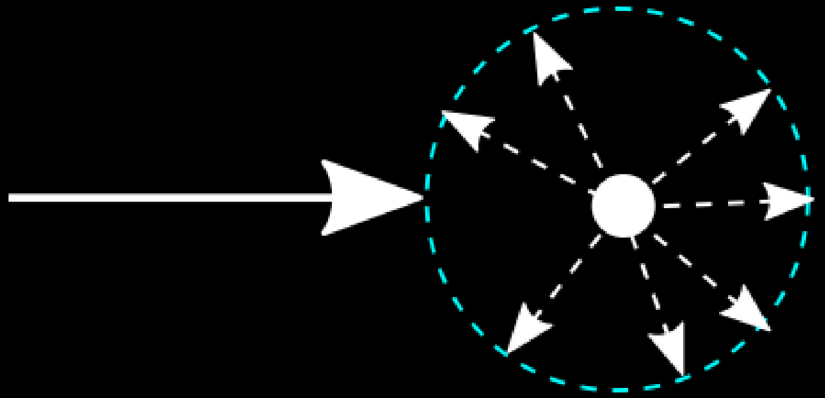
Physical interactions

Localized inhomogeneities produce **spherical waves**



Attenuation

Attenuation: Intensity reduction as the wave propagates in the medium.

Part of such loss is due to **beam divergence**

Absorption refers to the loss of acoustic energy into thermal energy

- It is given by the ration of intensities I_2/I_1
- Is measured in **decibels** (dB): $10 \times \log_{10}(I_2/I_1)$
    - **Example:** If the wave is attenuated by a factor of 100

$$10 \times \log_{10}(I_2/I_1) = 10 \times \log_{10}(1/100) = -20\, dB$$

Attenuation coefficient

- In soft tissue, attenuation depends approximately linearly from the frequency: $A = \alpha_0 f_0$
- Units of dB/(MHz cm)
- High frequencies are more attenuated than lower ones

Material	α_0 [Culjat et al, 2010]
Bone	6.9
Brain	0.6
Fat	0.48
Muscle	1.09
Water	0.0022

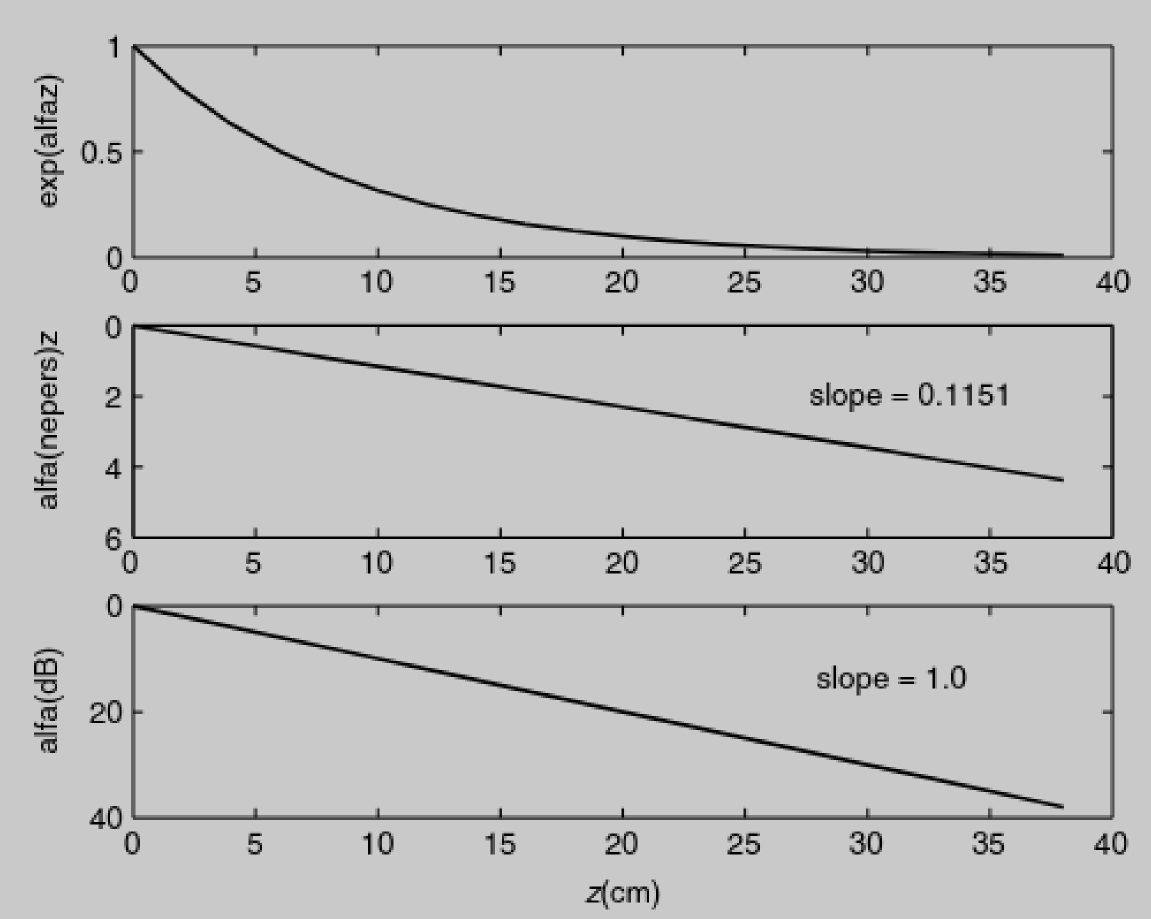


Figure 4.1 Constant absorption as a function of depth on a (top) linear scale, (middle) dB scale, and (bottom) neper scale.

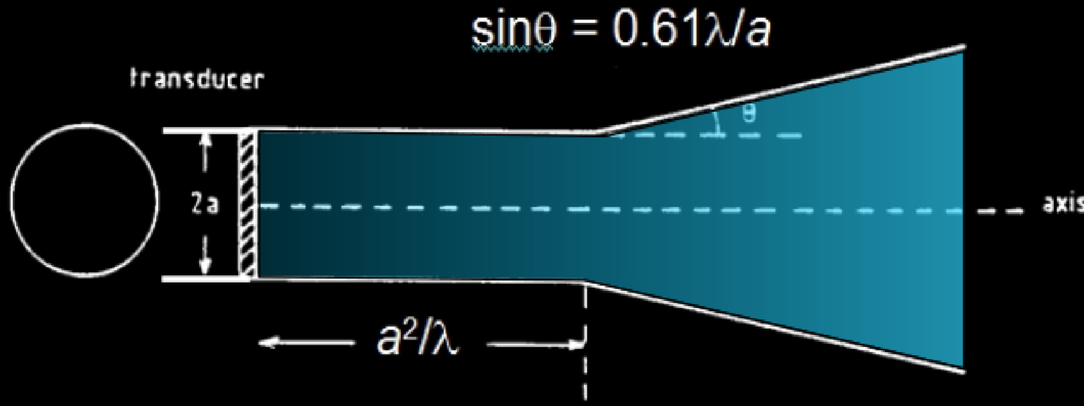
Ultrasound beam-pattern

Transmission beam region where most of the pulse travel. The *beam width* is equivalent to the lateral pulse width

Reception beam dual of the transmission beam: if a point source is in the reception beam, it is *visible* to the transducer

- Reception and transmission beams are the same for ideal **disk transducers**
- Both beams depend on the frequency content of the signal
- Transducer beams can be divided in **near field** (Frensel zone) and **far field** (Fraunhofer zone)

The frequency of the transmit signal affects the axial resolution

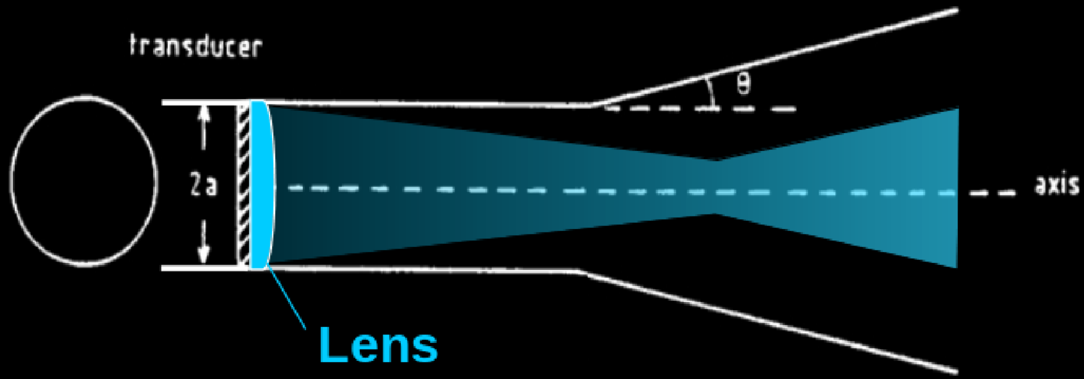


[image from Prof. Dean Barrett]

Ultrasound beam-pattern

The ideal beam-pattern is long and narrow

- Small aperture $a \rightarrow$ Divergent beam
- Large aperture $a \rightarrow$ Low lateral resolution
- Large wavelength (small frequency) $\rightarrow$ High attenuation
- Large wavelegnth (high frequency) $\rightarrow$ High attenuation $\rightarrow$ low penetration depth

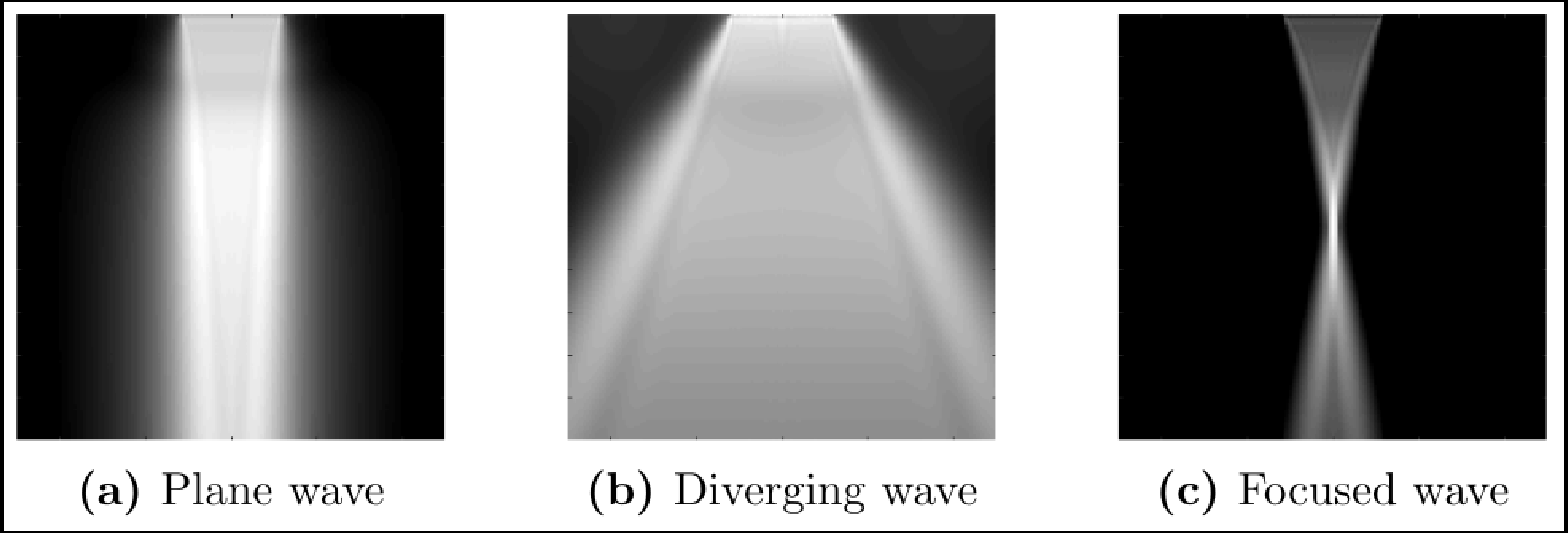


Convex lenses or concave transducers can be used to narrow the beam

- Modern scanners use multi-element transducers and electronic focusing

[image from Prof. Dean Barratt]

Common beams


(a) Plane wave (b) Diverging wave (c) Focused wave

[Stanziola, 2018]

Multi-element transducer

[Szabo, 2014]

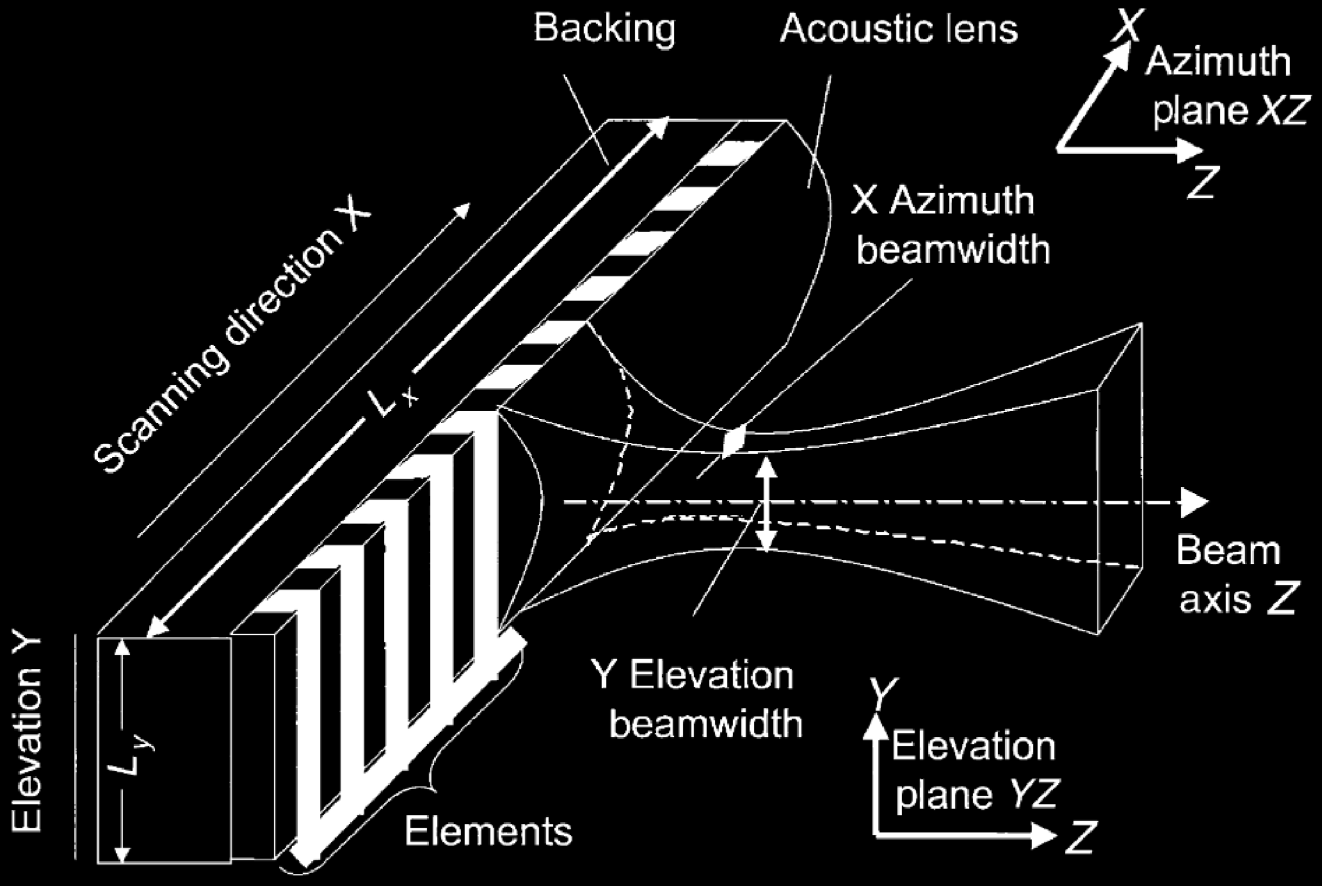


Figure 7.4 Relation of phased array to azimuth (imaging) and elevation planes (adapted from Panda, 1998).

Time reversal

Most of the time, we can use properties of an ultrasound array in transmission mode to understand reception and vice-versa.

Time reversal

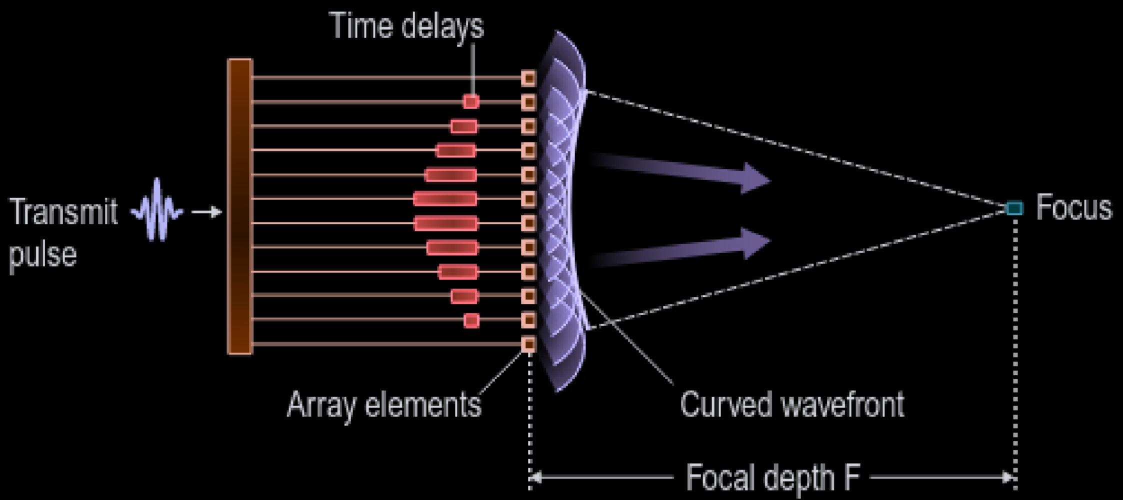
That's how focusing and imaging algorithms are designed

Electronic focusing

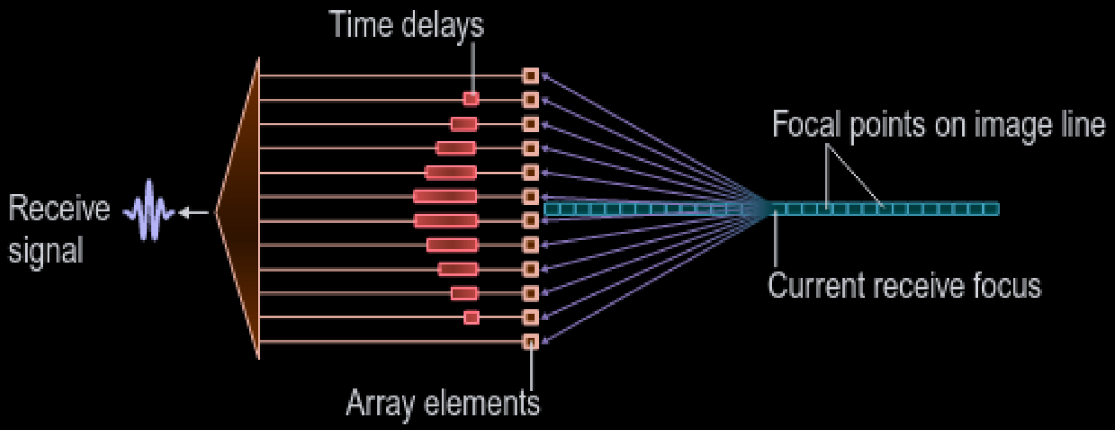
Rather than using a lens, we use **the same delays** for focusing in transmit to **focus** in reception

Ⓐ The ratio of aperture *a* to focal depth *F* is restricted for sector transducers leading to weak focusing

Ⓑ A higher ratio of aperture *a* to focal depth *F* can be maintained in linear arrays by increasing the active aperture at larger depths



Ⓐ Transmit focus: if the outer elements are fired first with increasing delays towards the central elements, a converging wavefront is formed which produces a focused transmit beam



Ⓑ Receive focus: in reception, delays are applied to the signals received at each element before they are added together. The delays are calculated for each target depth so that the receive focus tracks the current receive depth, producing a much narrower receive beam

[Allan et al., 2011]

Electronic focusing

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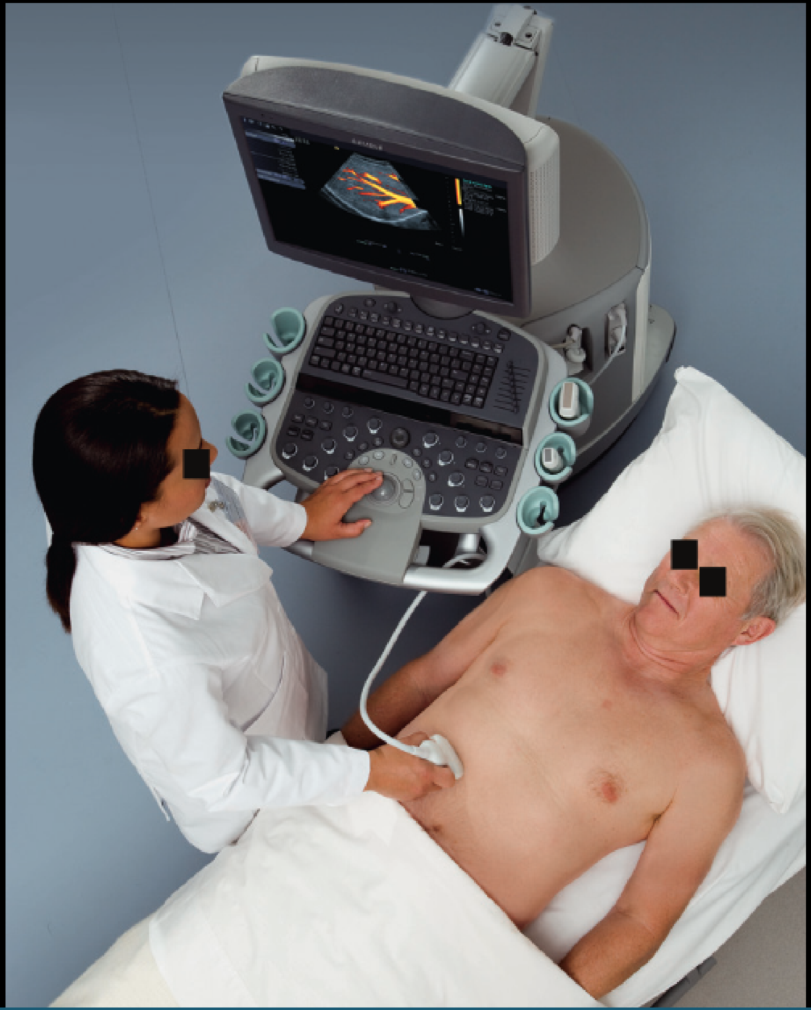
Clinical ultrasound

[Allan et al., 2011]

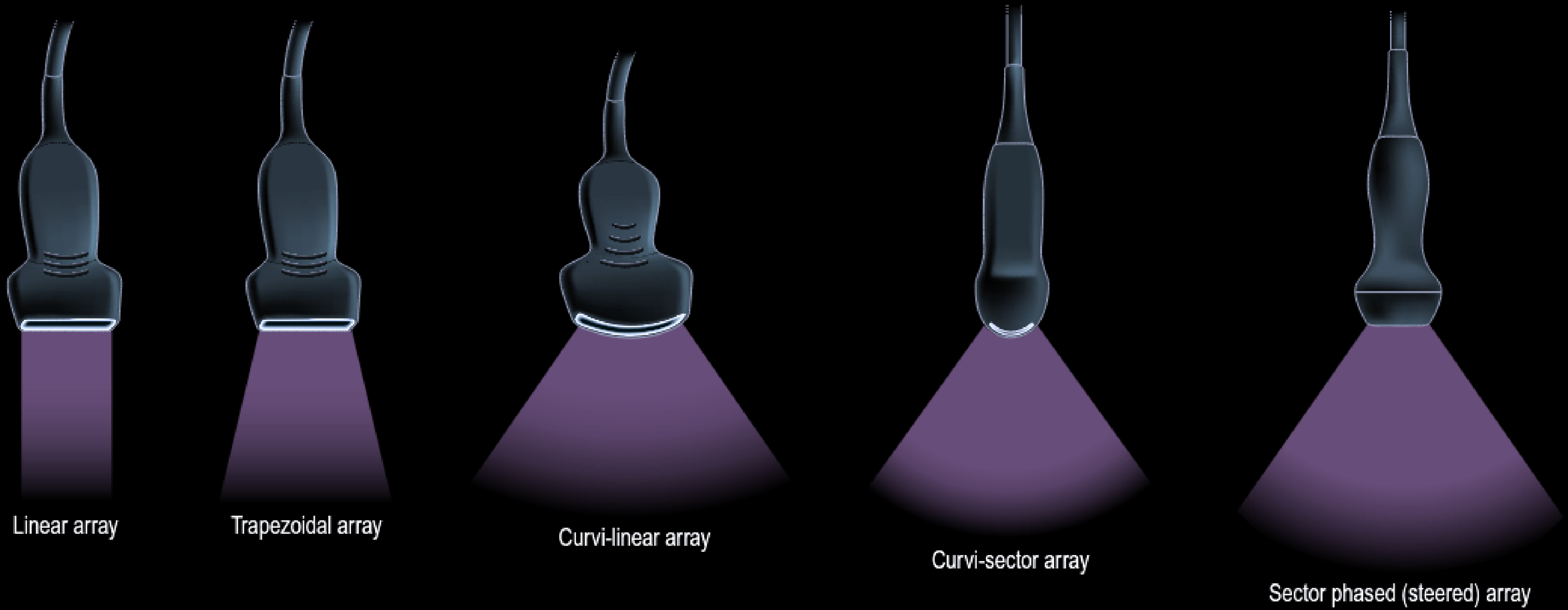


Types of Array Transducers

Fig. 1 Photograph of ultrasonic transducers [5]

Types of Array Transducers

Linear, convex and phased array transducers [Lee1 and Roh, 2017]



[Allan et al., 2011]

Single transducer pulse-echo imaging

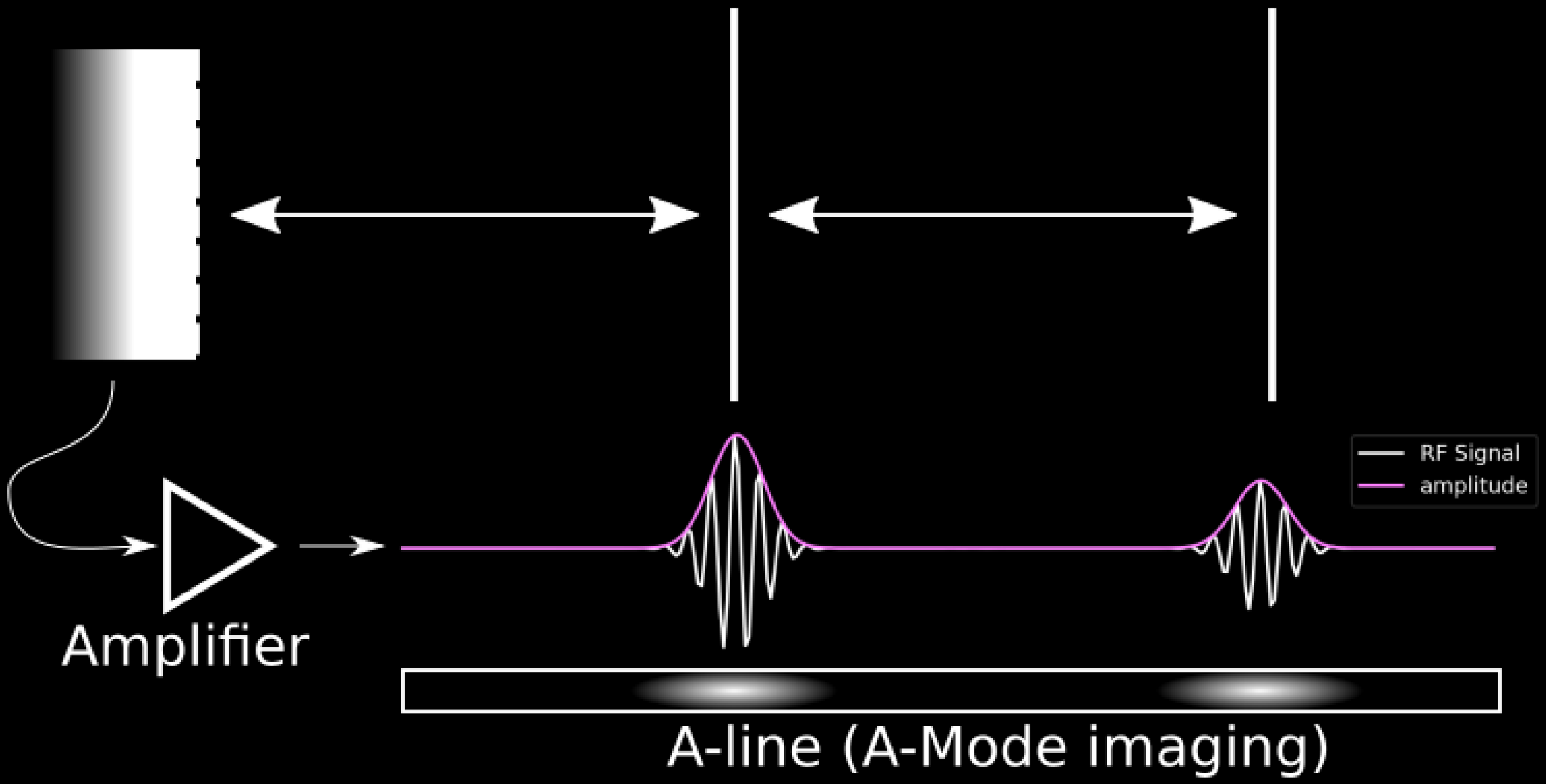
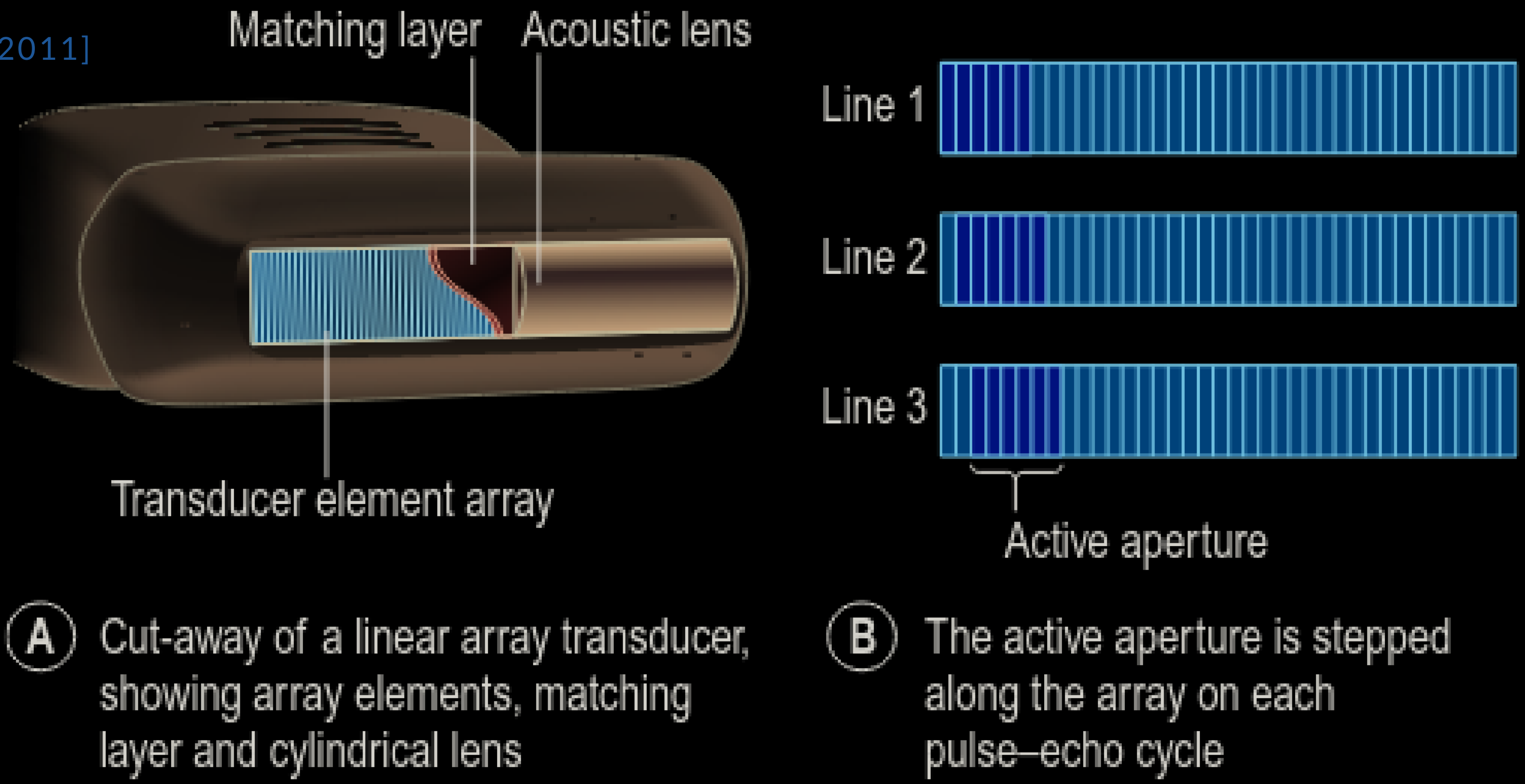


Image formation (B-Mode)

[Allan et al., 2011]

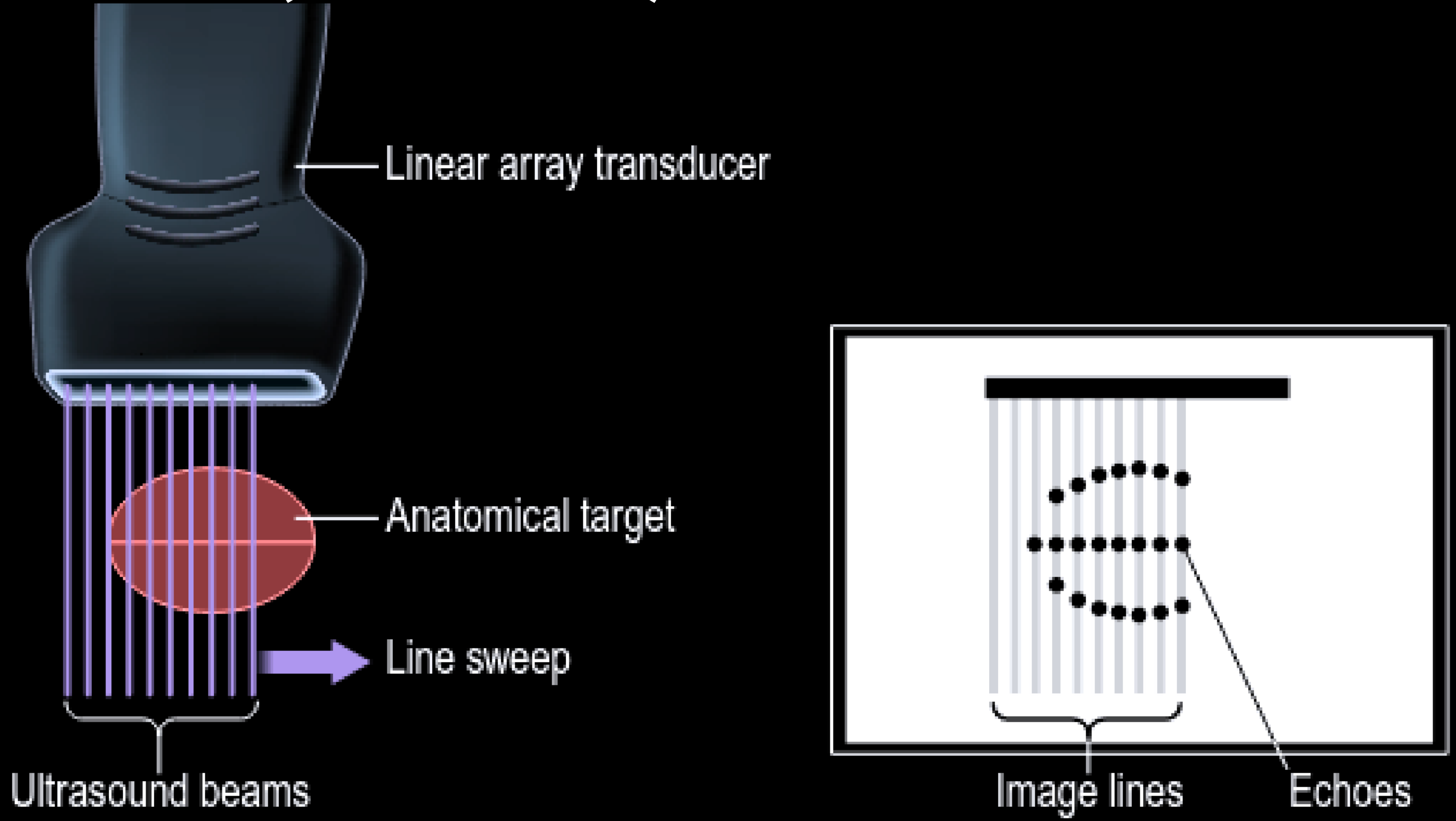


Ⓐ Cut-away of a linear array transducer, showing array elements, matching layer and cylindrical lens

Ⓑ The active aperture is stepped along the array on each pulse–echo cycle

Image formation (B-Mode)

[Allan et al., 2011]



Ⓐ Pulse-echo cycles are initiated at a series of adjacent beam positions along the transducer face

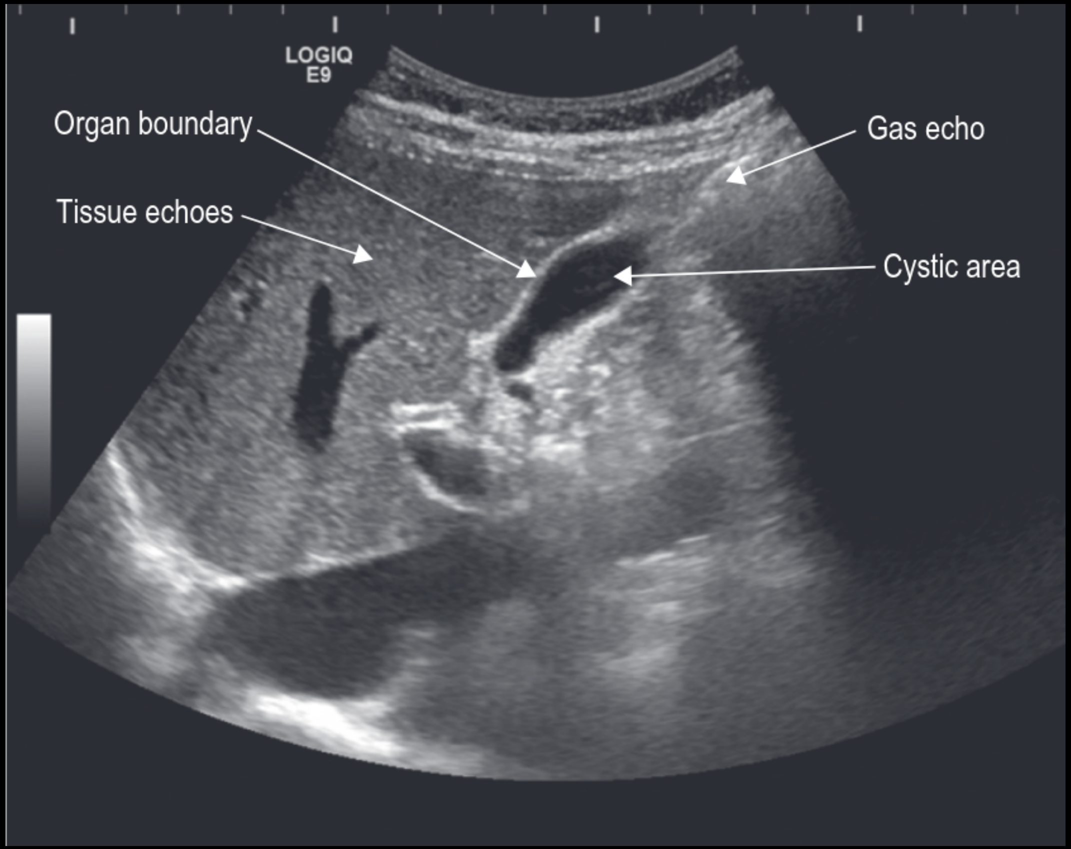
Ⓑ The line of echoes produced by each cycle is used to form a B-mode line in the image

Example B-mode images

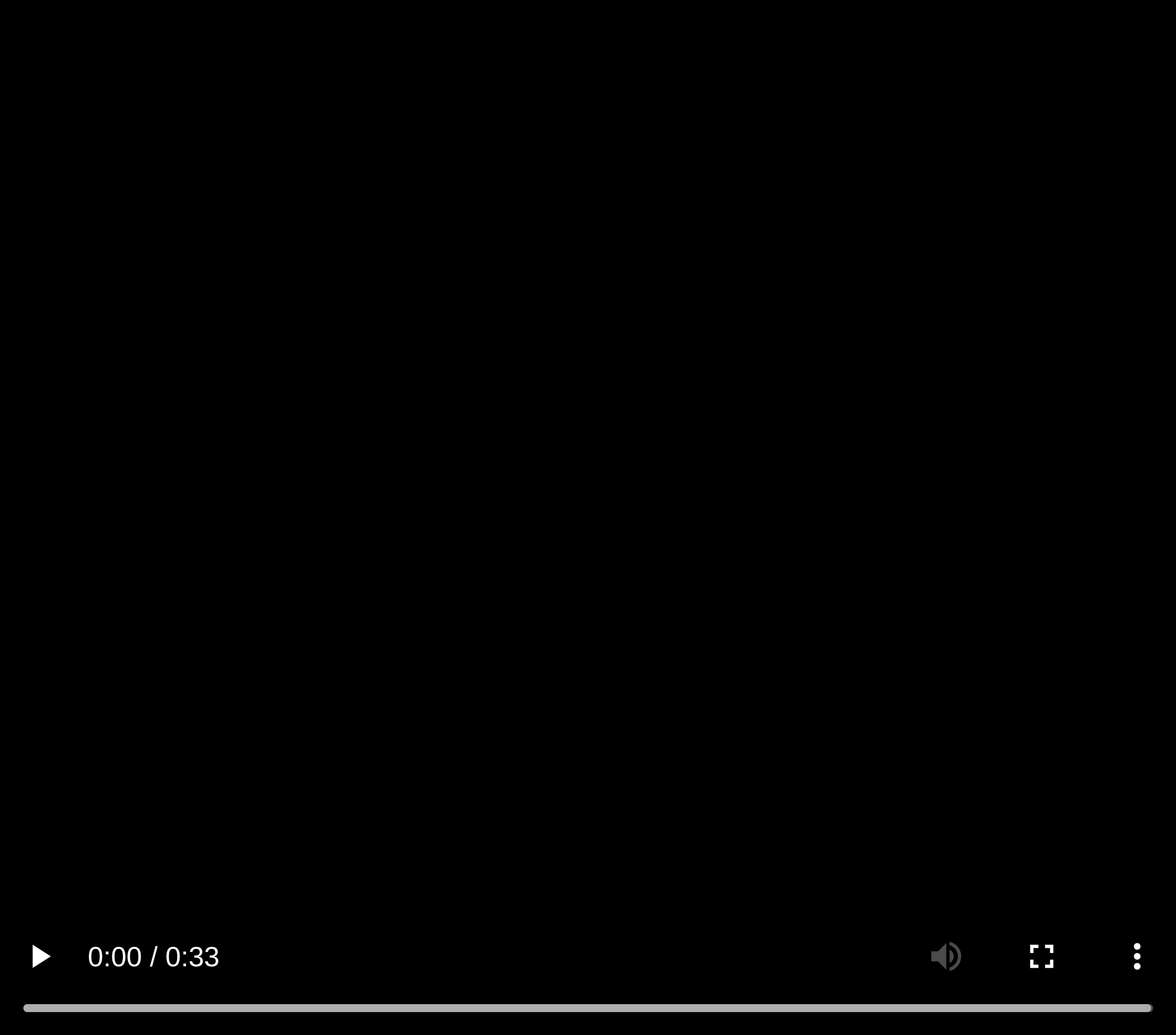
Ultrasound image of a kidney

- TIssue echoes (speckle) are due to small scale variations of the acoustic properties
- Received echoes (backscattered signals) are **very weak!**
- Speckle apperance can have clinical significance

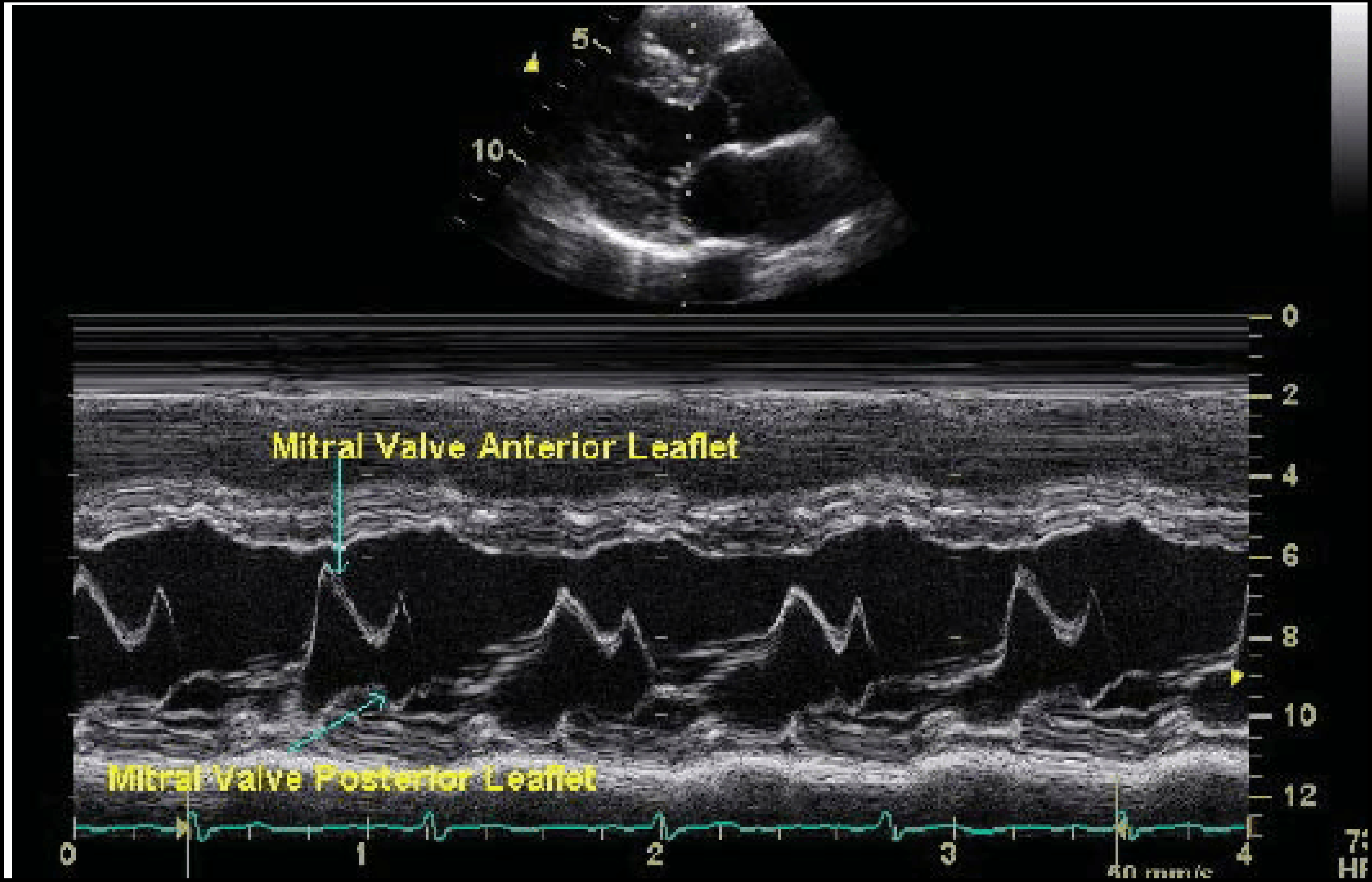
[Allan et al., 2011]



M-mode imaging

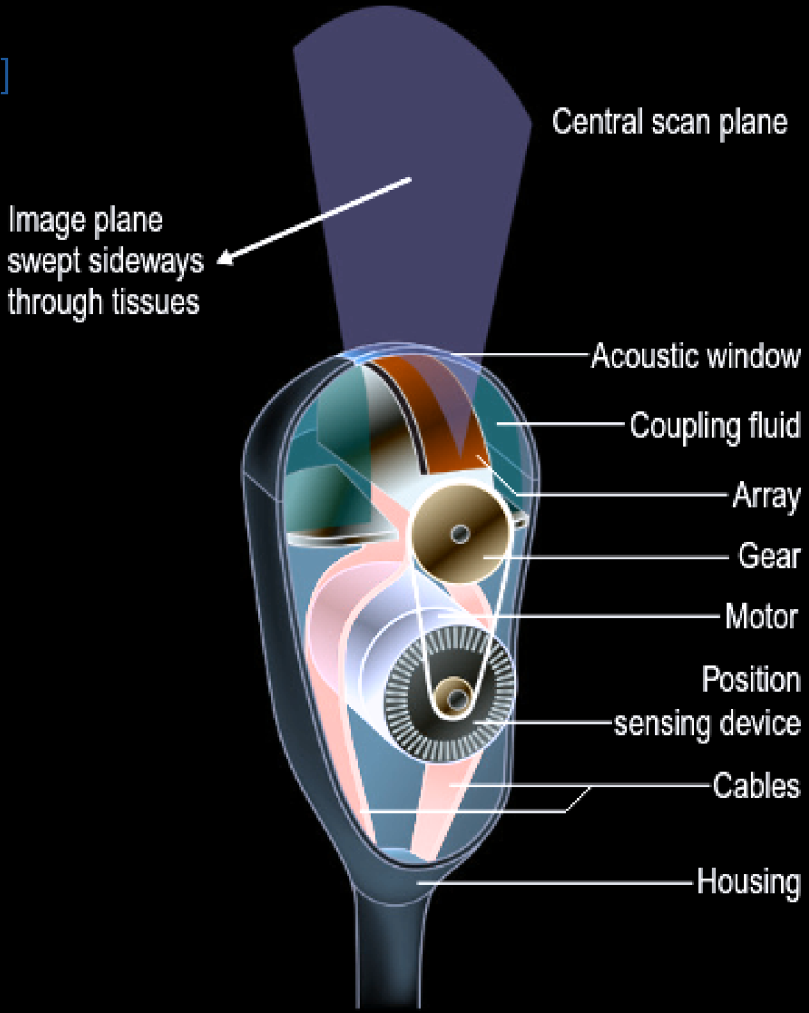


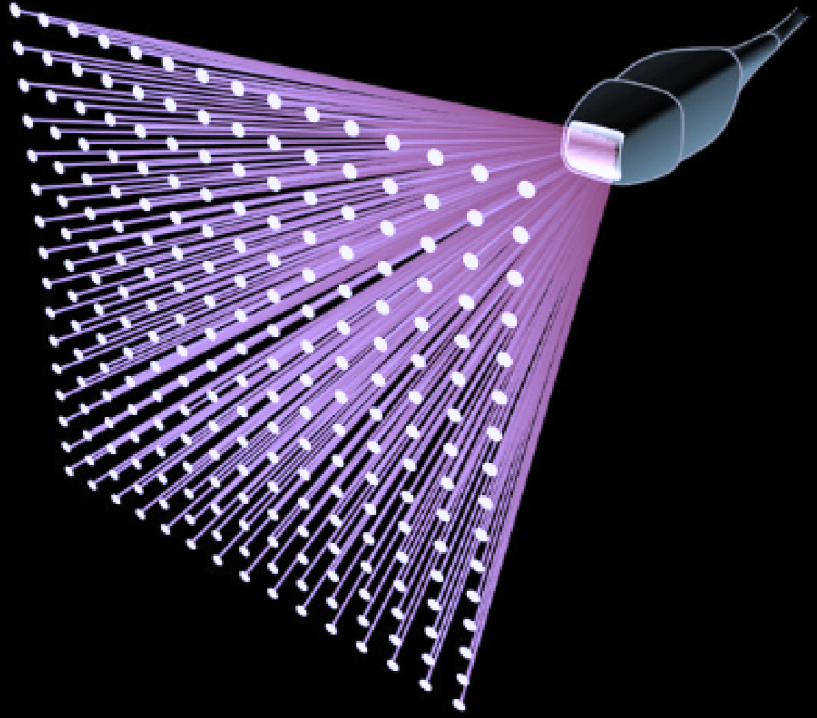
M-mode imaging



3D Ultrasound

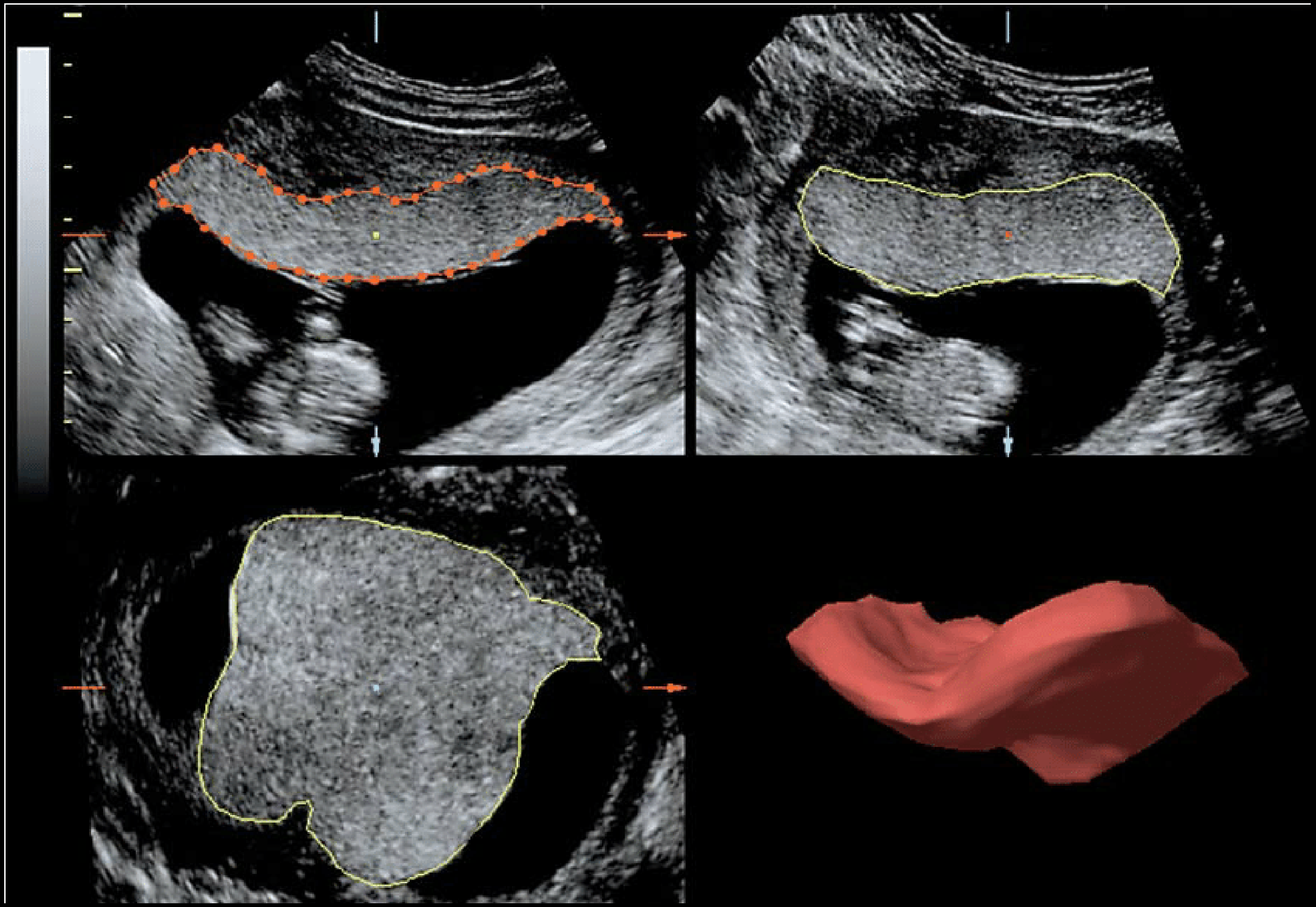
[Allan et al., 2011]





3D Ultrasound

[Plasencia et al., 2011]



Why artifacts arise?

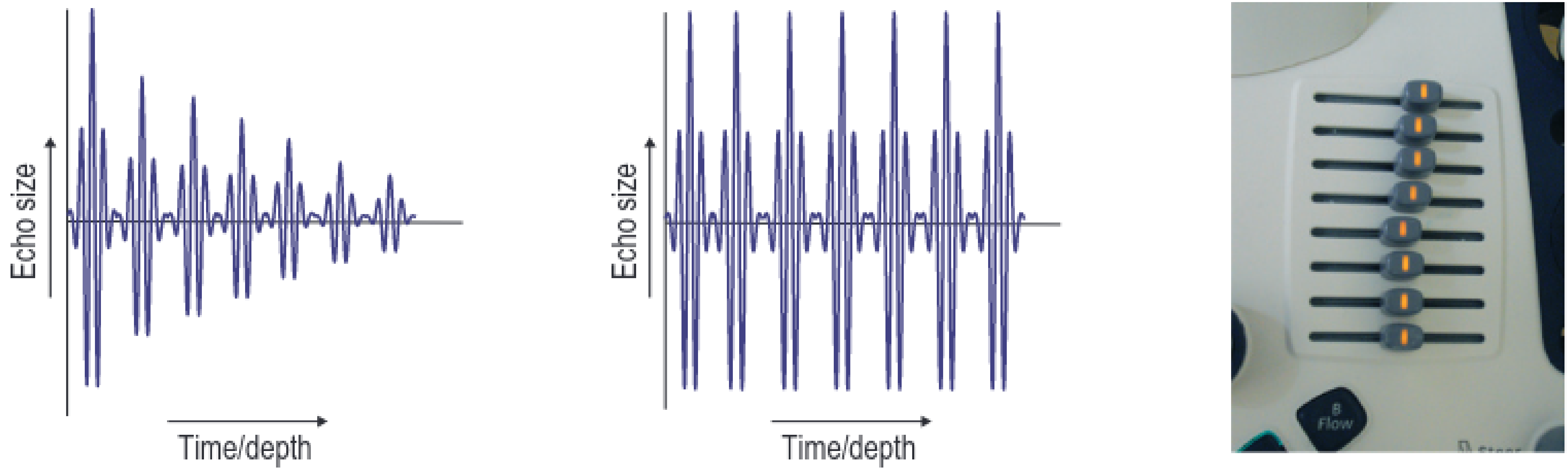
Most ultrasound imaging systems make the following assumptions

- Linear propagation
- Speed of sound is constant ($\sim 1540\, m/s$)
- Only primary reflections generate echoes
- Diffraction and refraction are negligible
- The beam loses energy at a known rate with depth (tunable wioth TGC)
- There beam is ideal: narrow in both elevation and lateral direction
- THe ultrasound machine is in good working conditions
- THe target doesn't move (too much) between pulses

Whenever one of them is not well satisfied, artifacts became visible

Ultrasound artefacts can be subtle!

TGC (Time Gain Compensation)



Ⓐ Echo signals received at the transducer become weaker with increasing depth/time of arrival due to attenuation

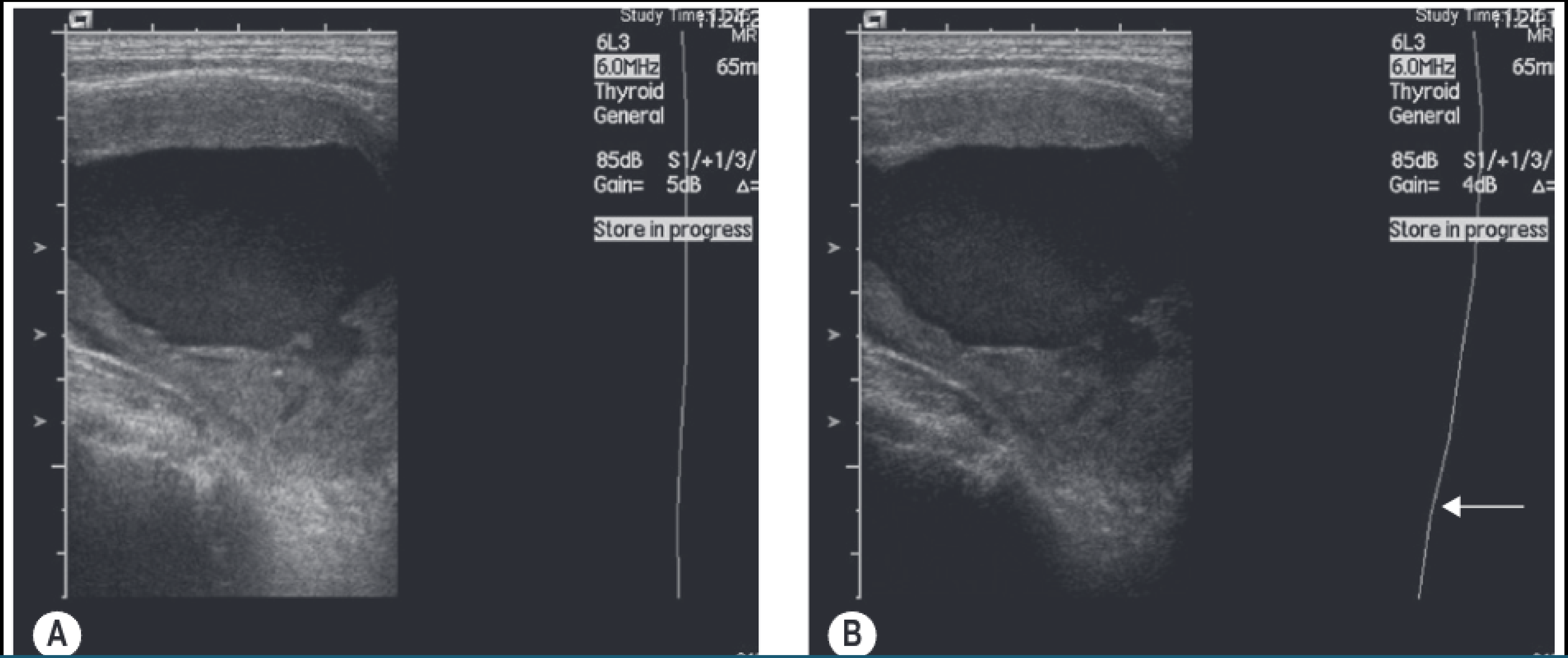
Ⓑ TGC is used to compensate for attenuation so that echoes from similar targets are the same size regardless of target depth

Ⓒ The user can adjust the TGC via slide controls on the console

[Allan et al., 2011]

Enhancement artifact and TGC

[Allan et al., 2011]

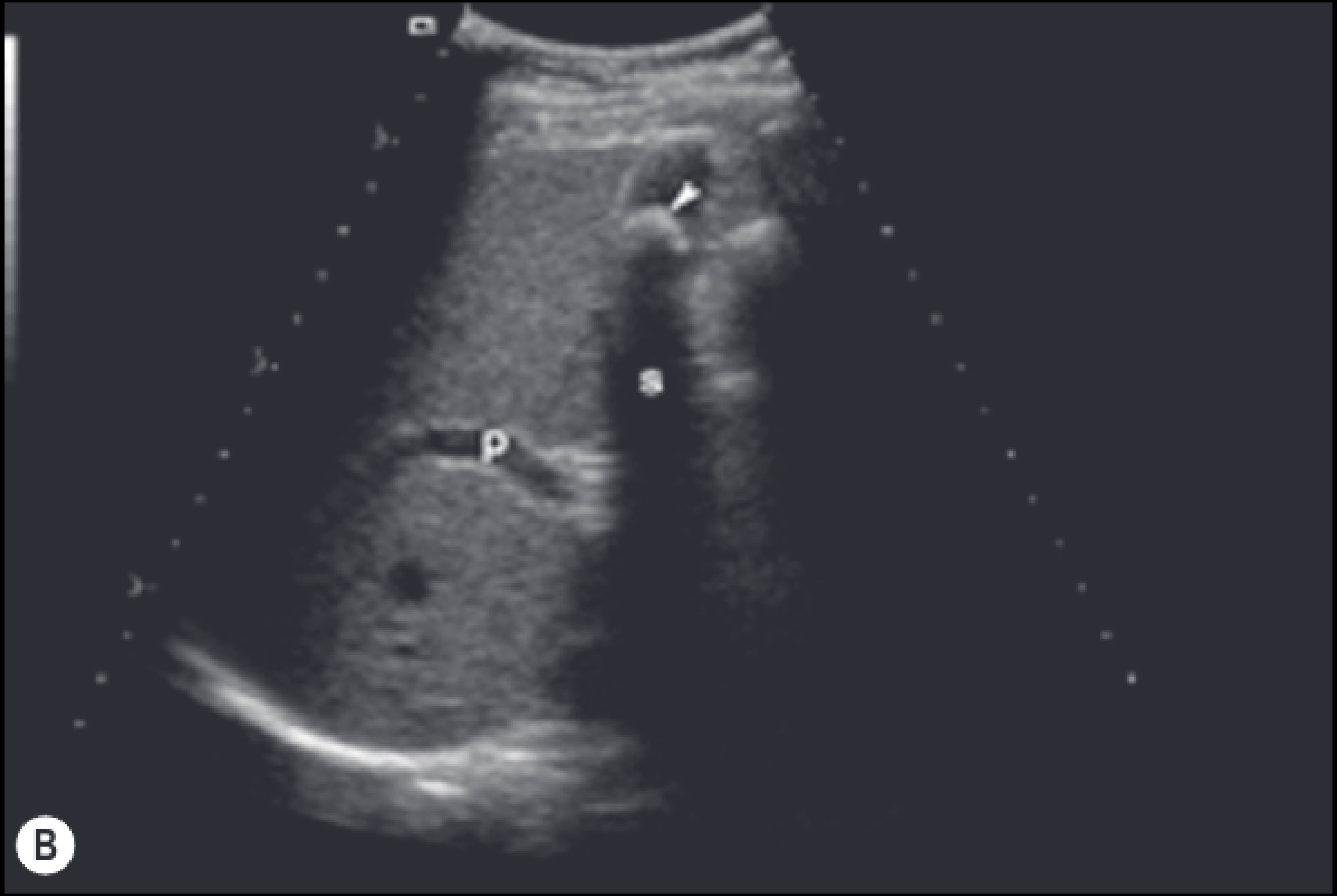


Shadowing

A strong reflector reduces the acoustic energy transmitted below its surface, hence reducing the echo amplitude.

This is a localized phenomenon that can't be compensated with TGC

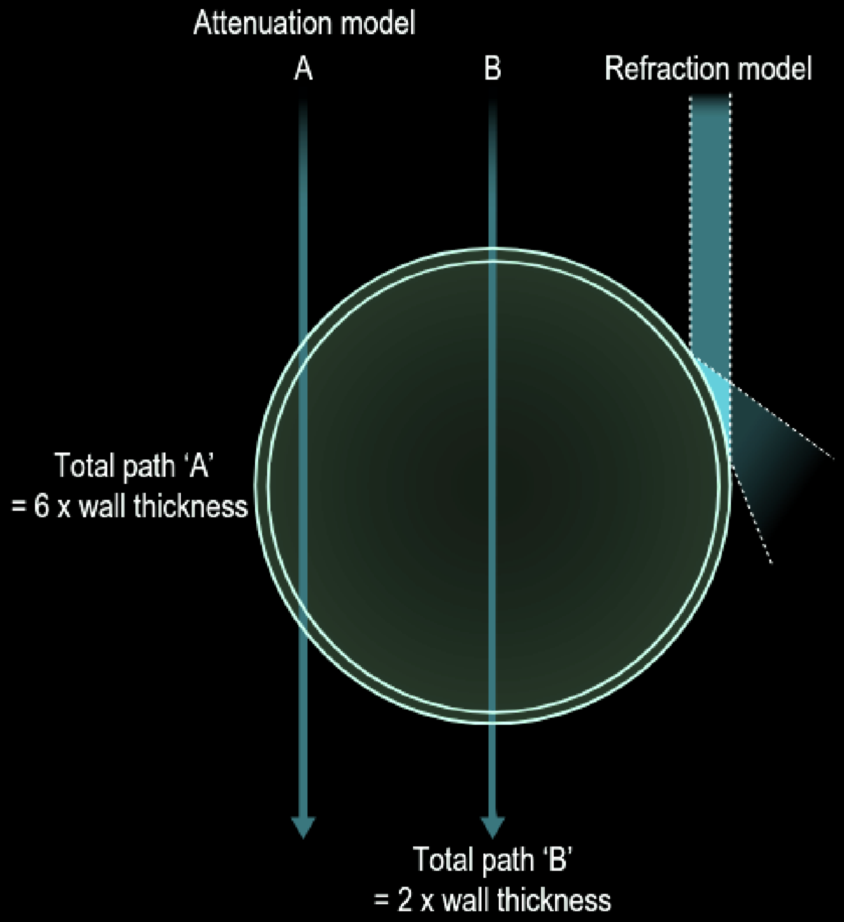
[Cosgrove, 2011]

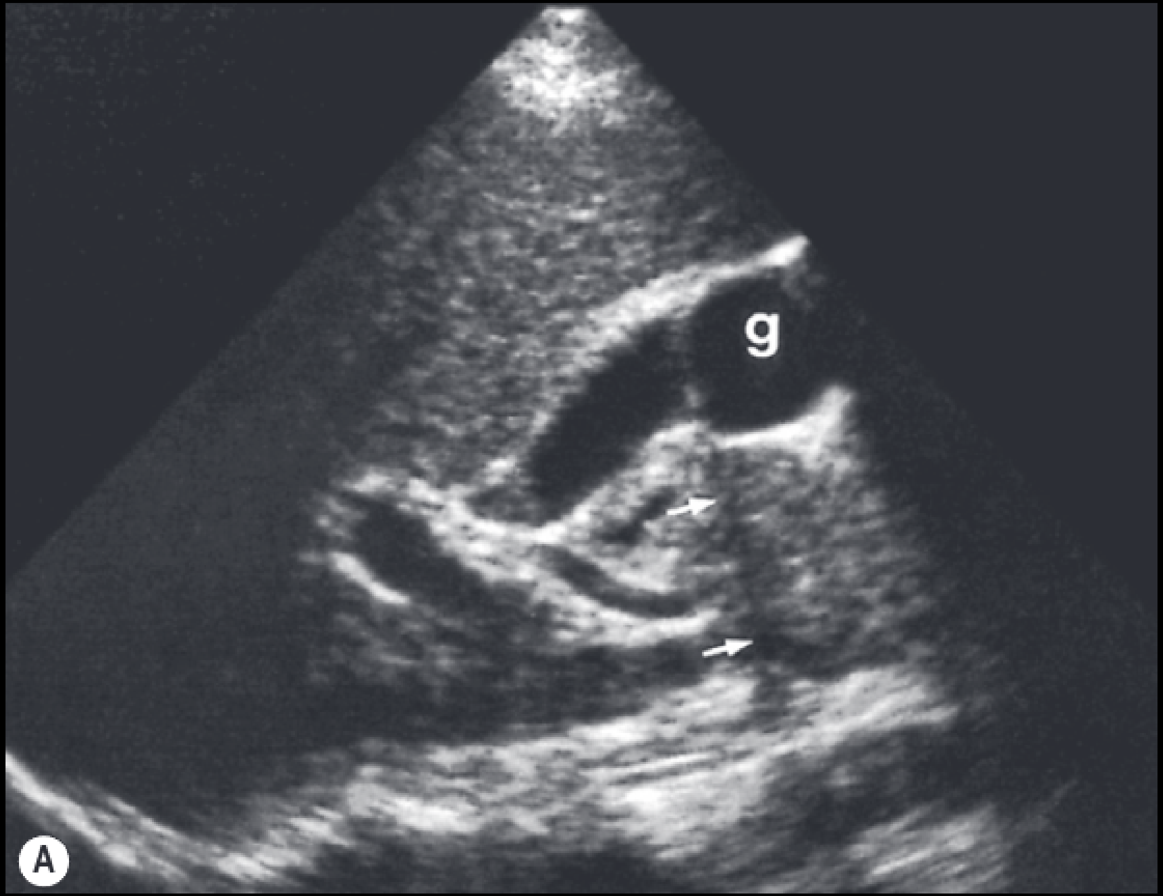


Edge shadow

Happens when refraction is significant

[Cosgrove, 2011]

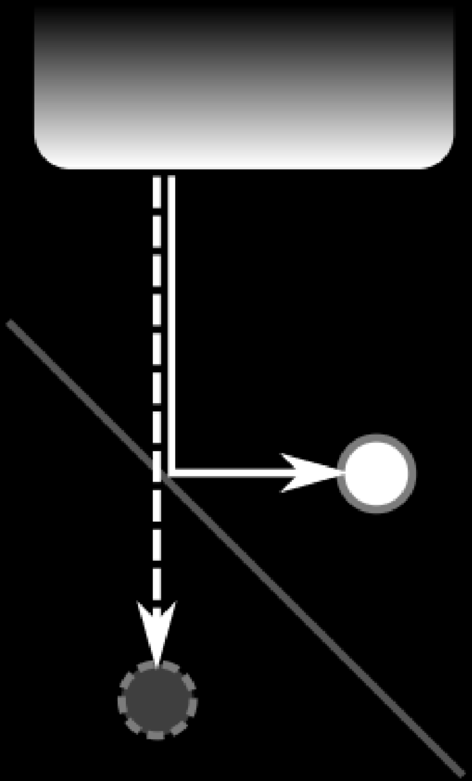


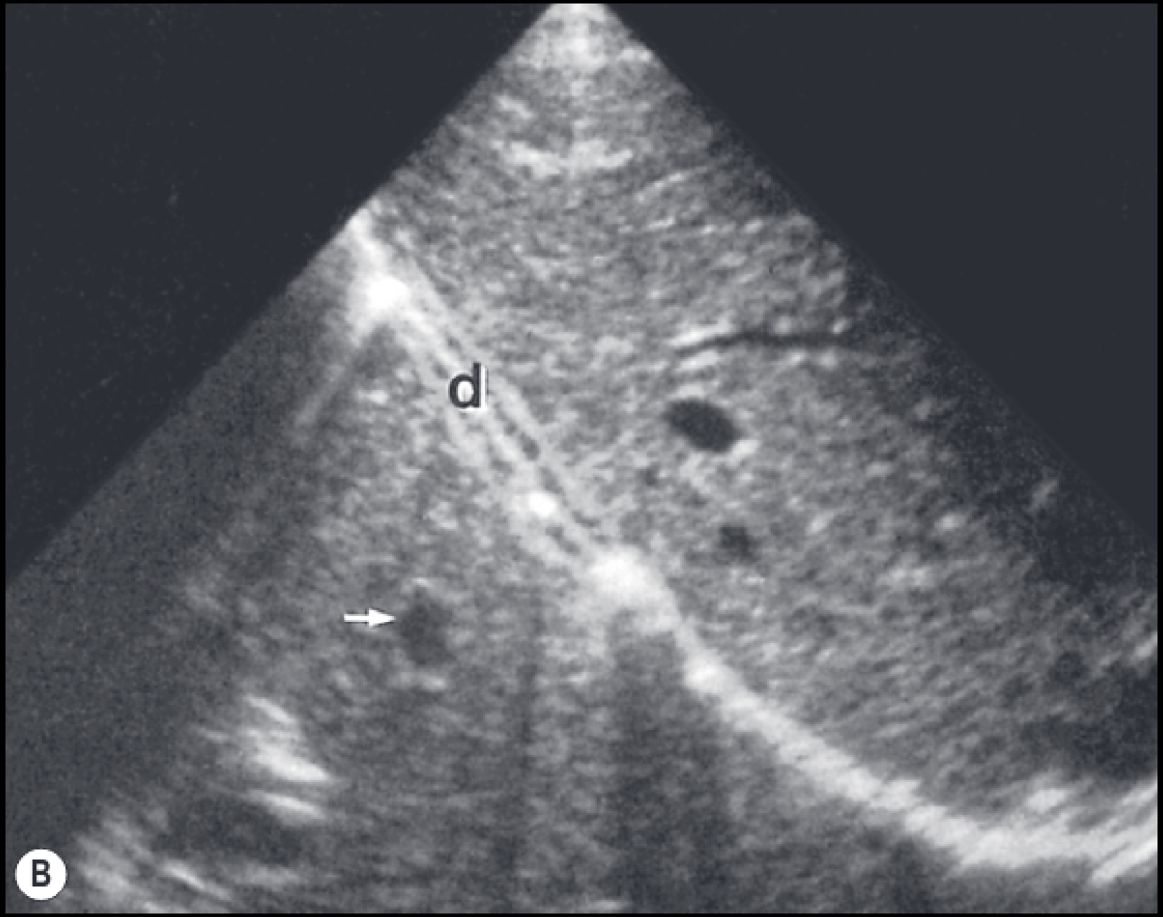


Mirror image artefact

Generated by strong reflecting interfaces

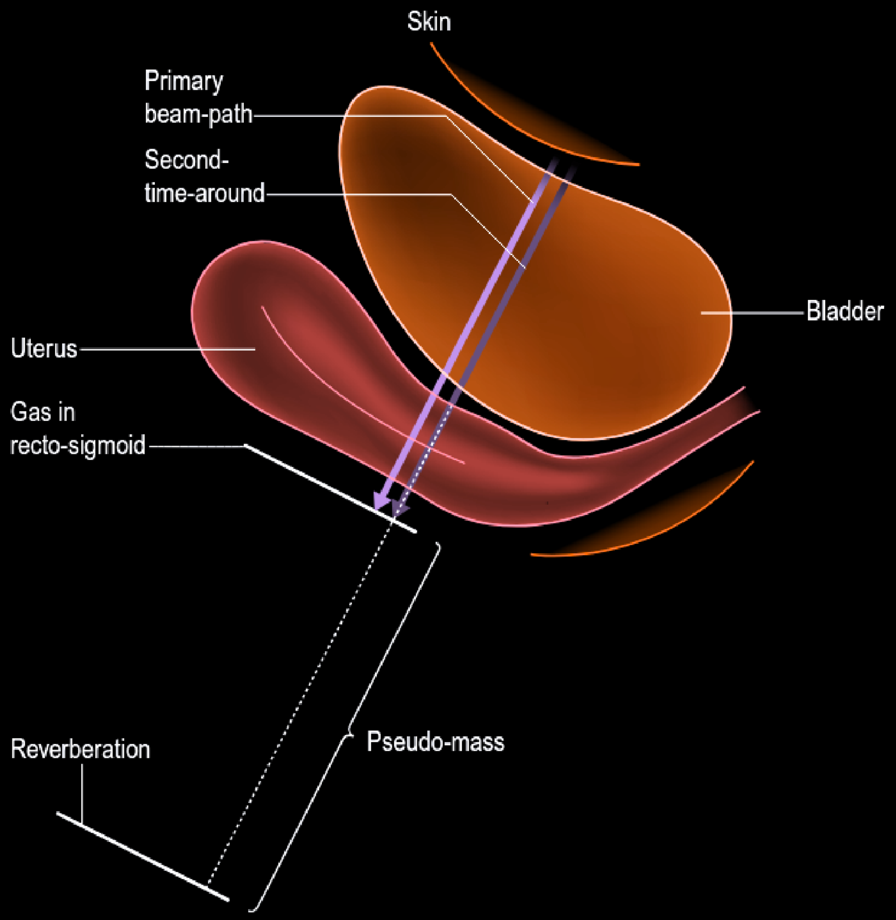
[Cosgrove, 2011]

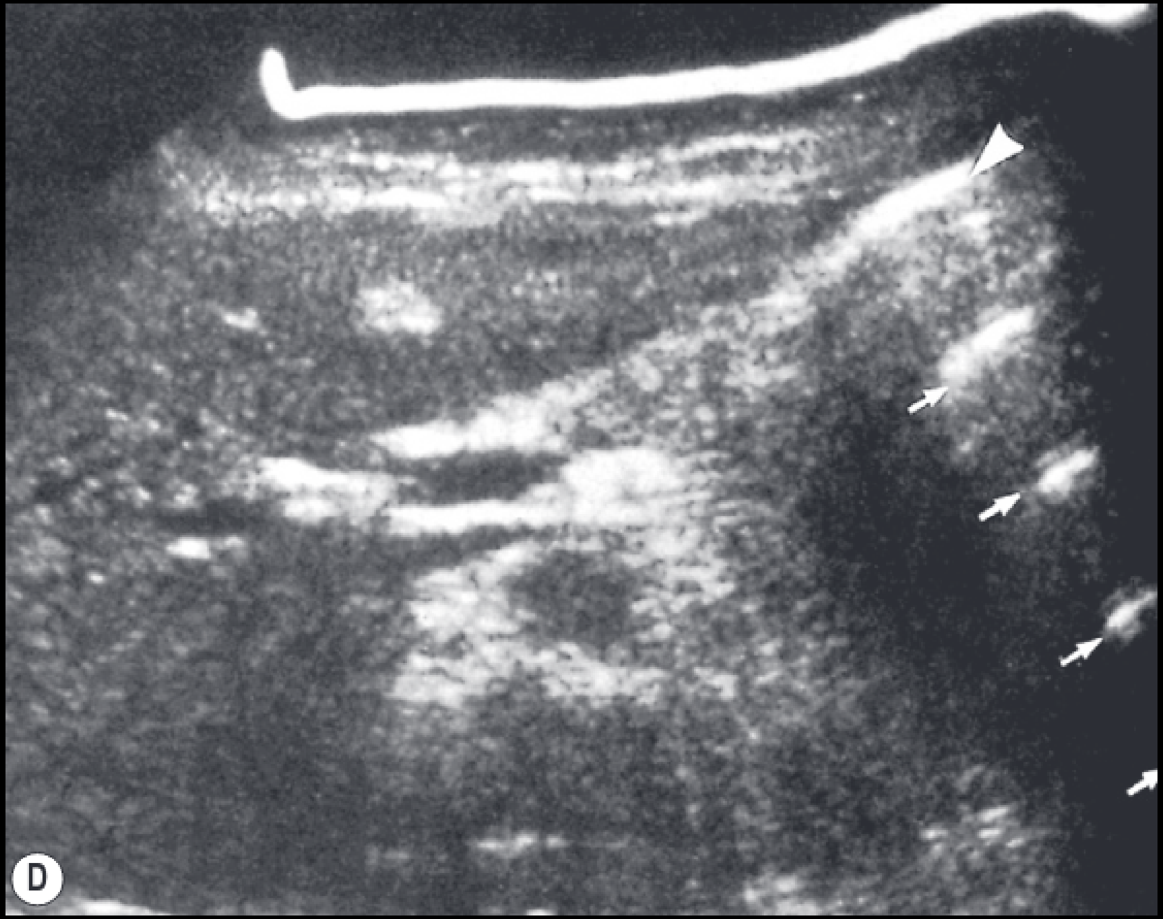




Reverberation artefact

[Cosgrove, 2011]

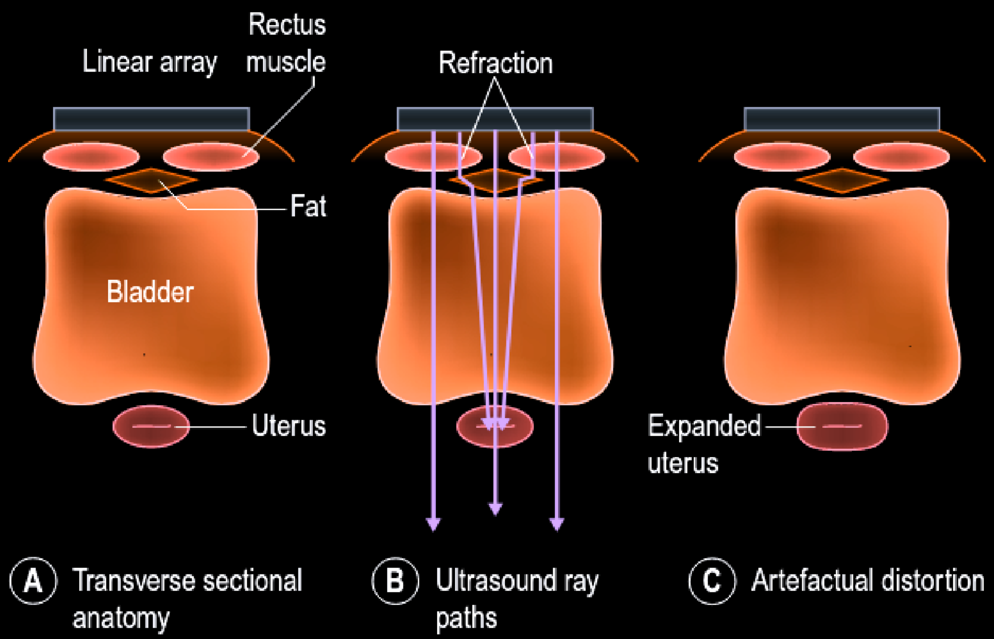


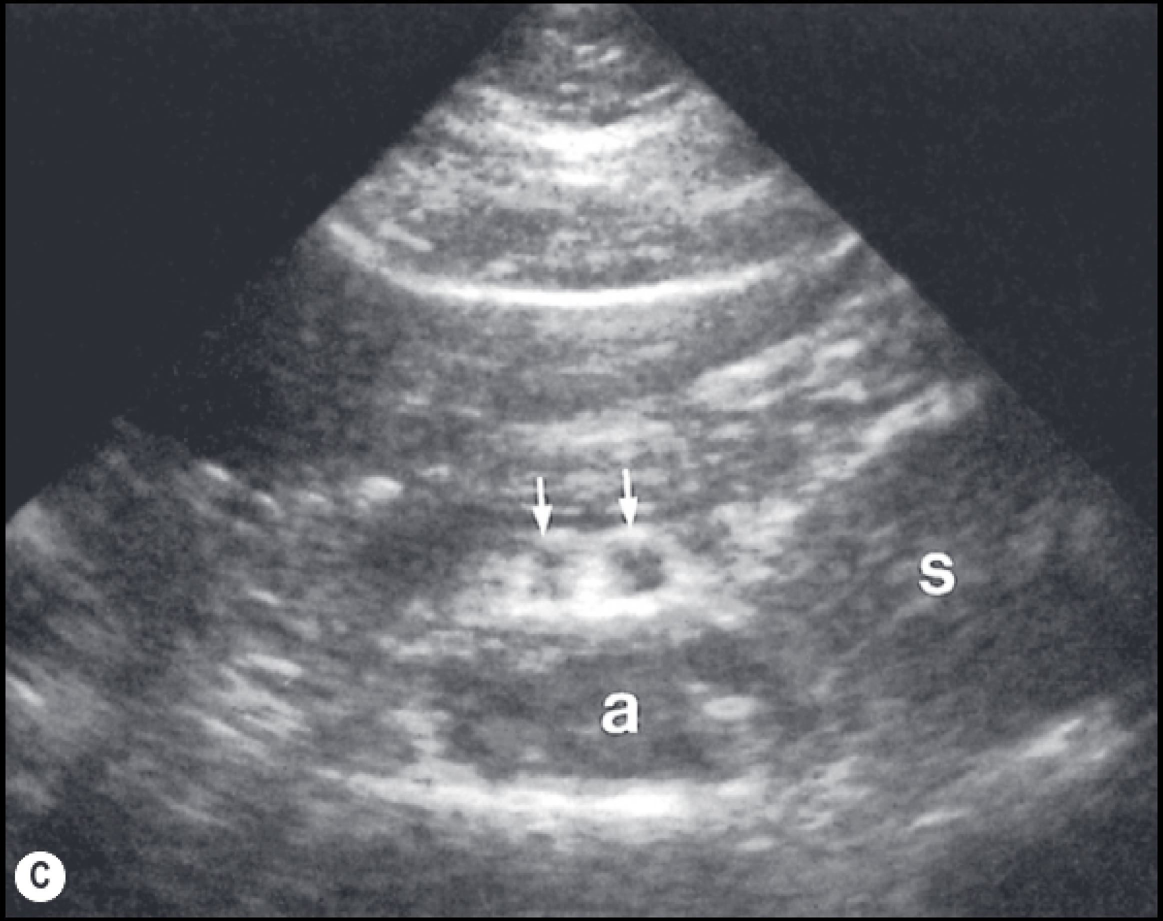


Refraction artefact

Happens whenever the assumption of straight-lines propagation breaks down

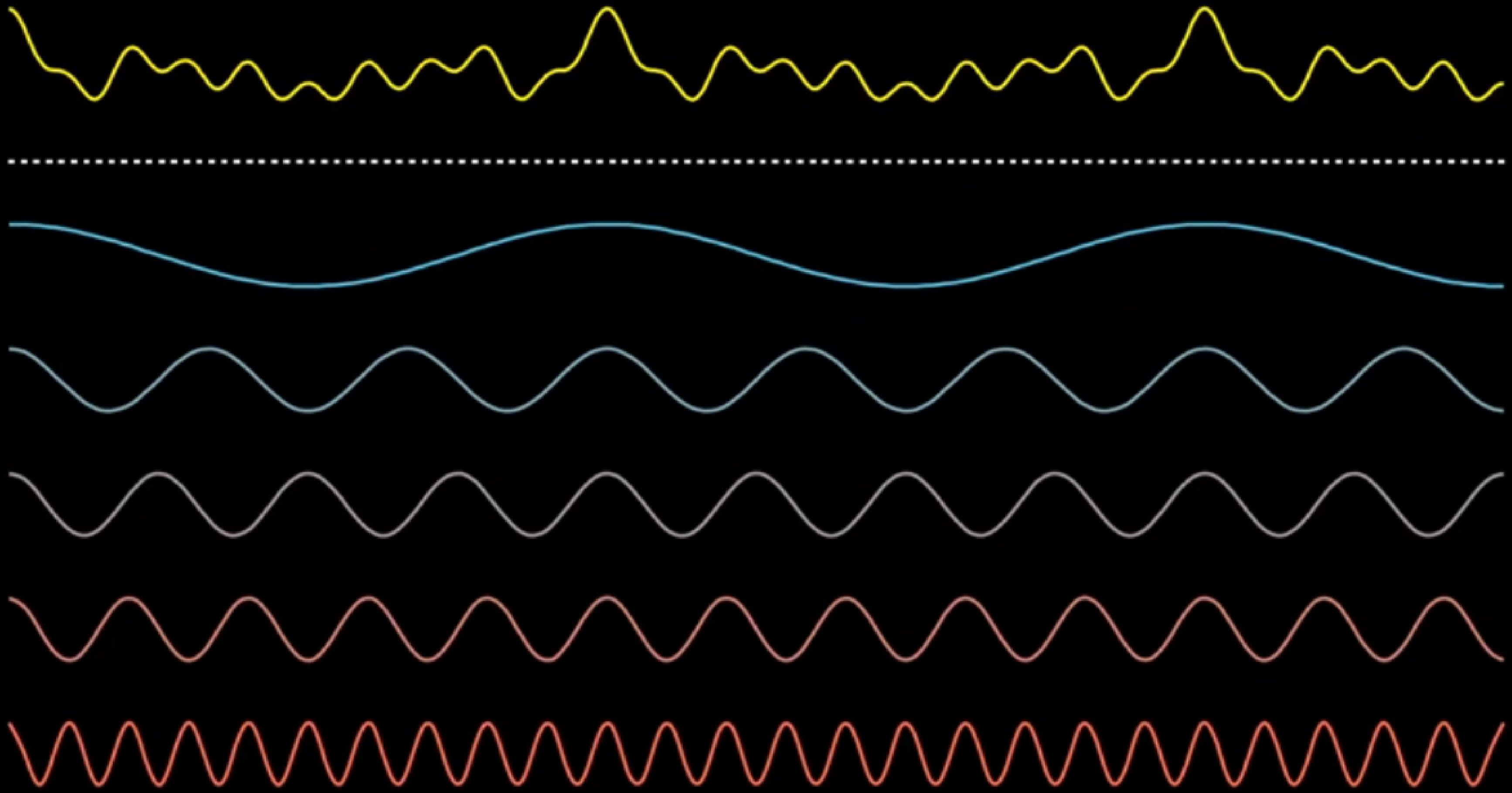
[Cosgrove, 2011]





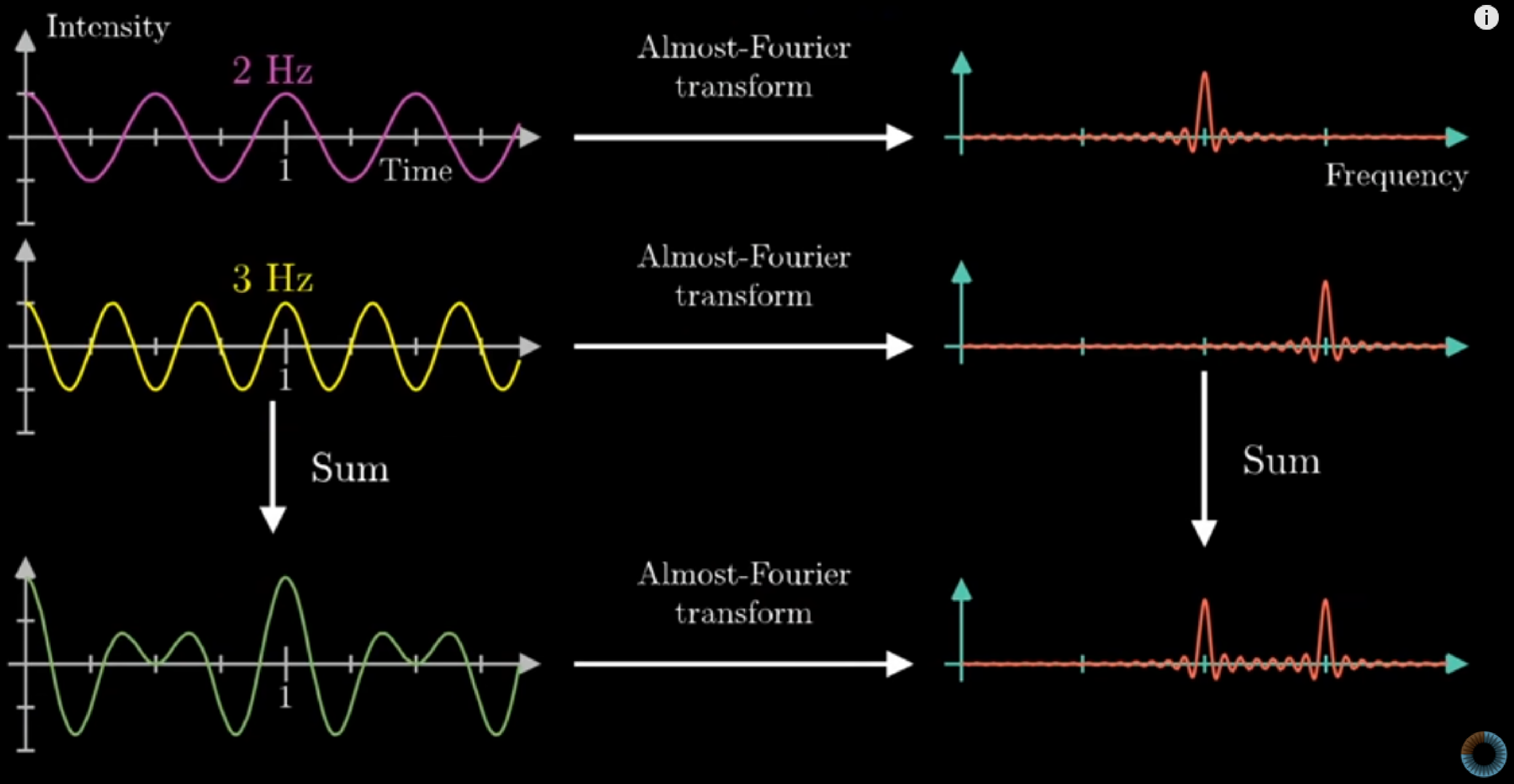
More on Time/Frequency duality

Signals (and waves) can be decomposed into a sum of sinusoids at different frequencies



[3b1b channel, Youtube]

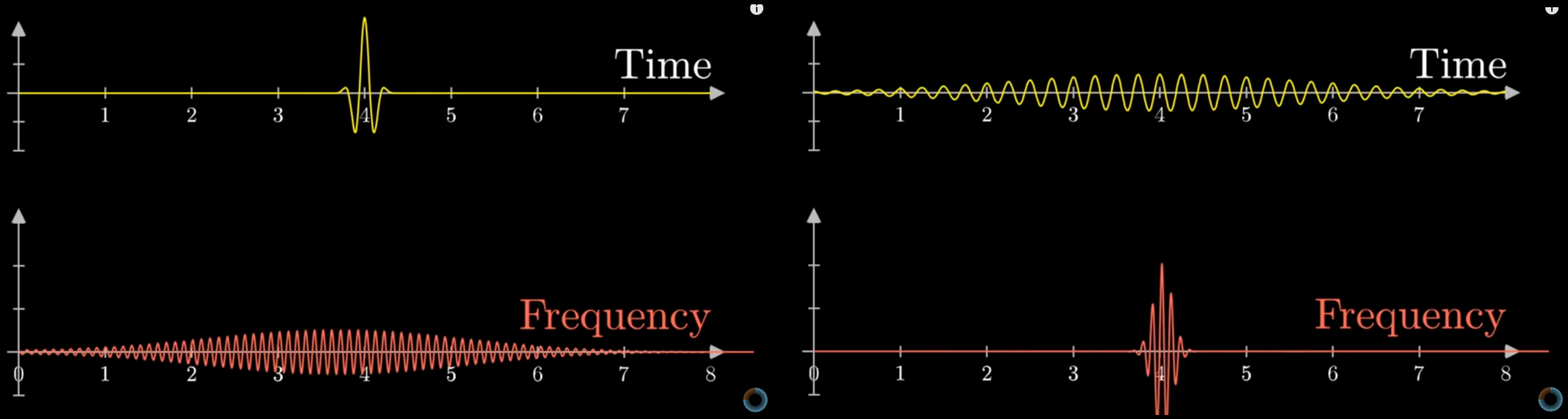
Fourier transform



[3b1b channel, Youtube]

TIme/Frequency uncertainty

Duality of between time and frequency properties



[3b1b channel, Youtube]

Some acoustic properties, like *attenuation*, depend on the frequency.

Notably, **speed of sound does not depend on frequency**, hence we can create imaging algorithms