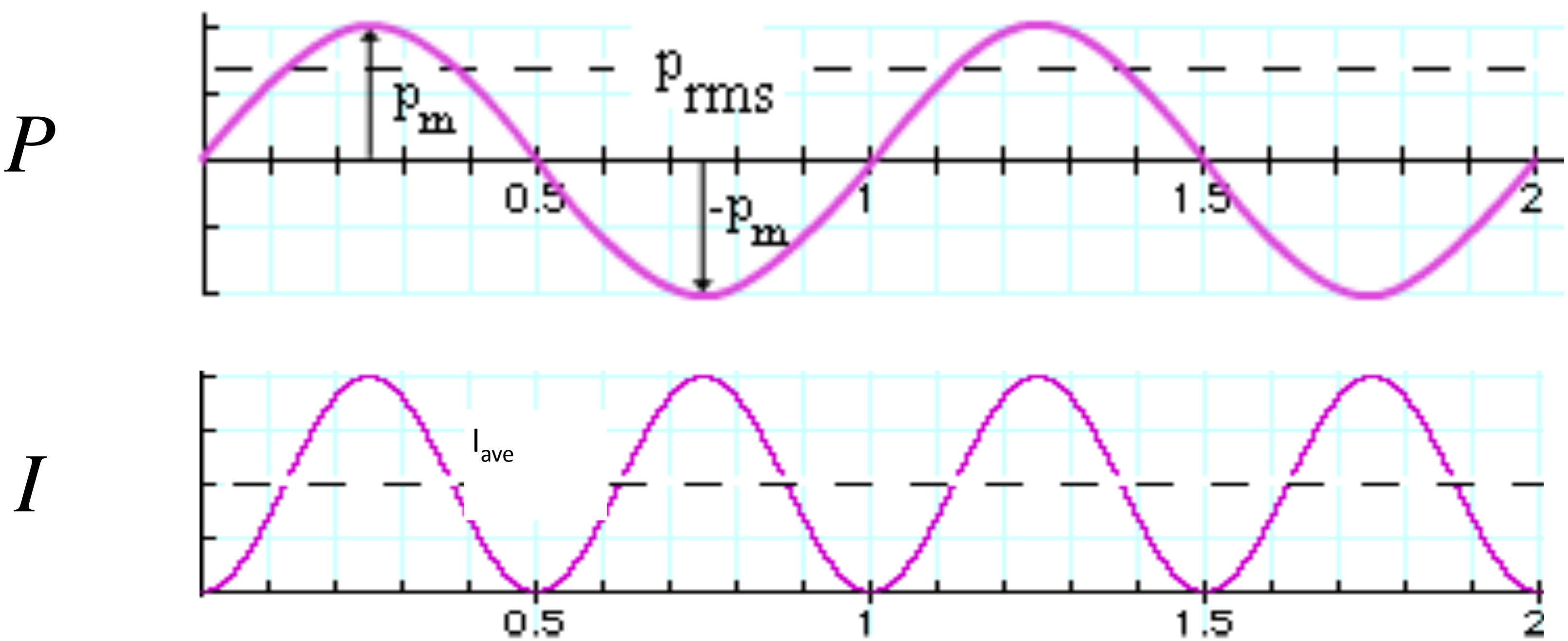
Acoustic Properties of Tissue

- Intensity
- Speed of Sound
- Acoustic Impedance
- Attenuation
- Intensity

Intensity

Intensity is the power transferred per unit area (W/m²)

$$I \propto P^2$$



will come back to this at end of lecture

Acoustic Properties of Tissue

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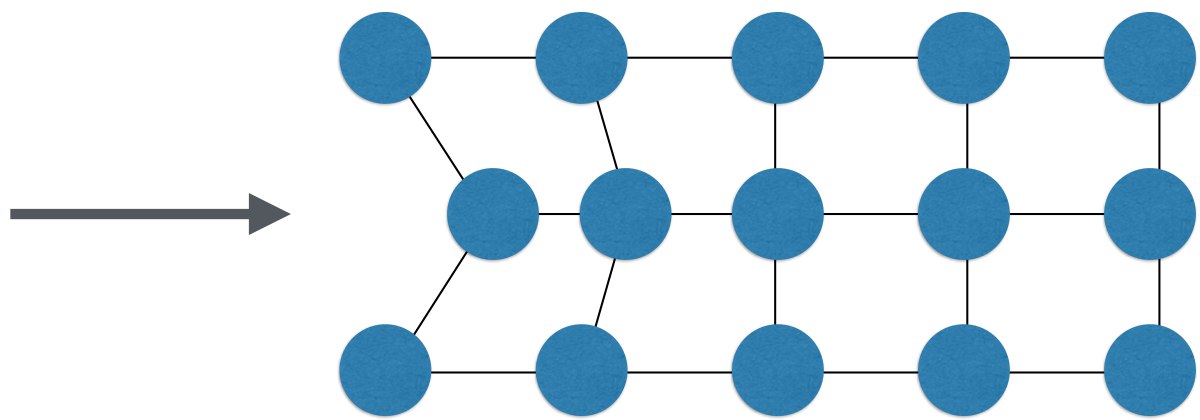
Particle Velocity vs Compression Wave Velocity

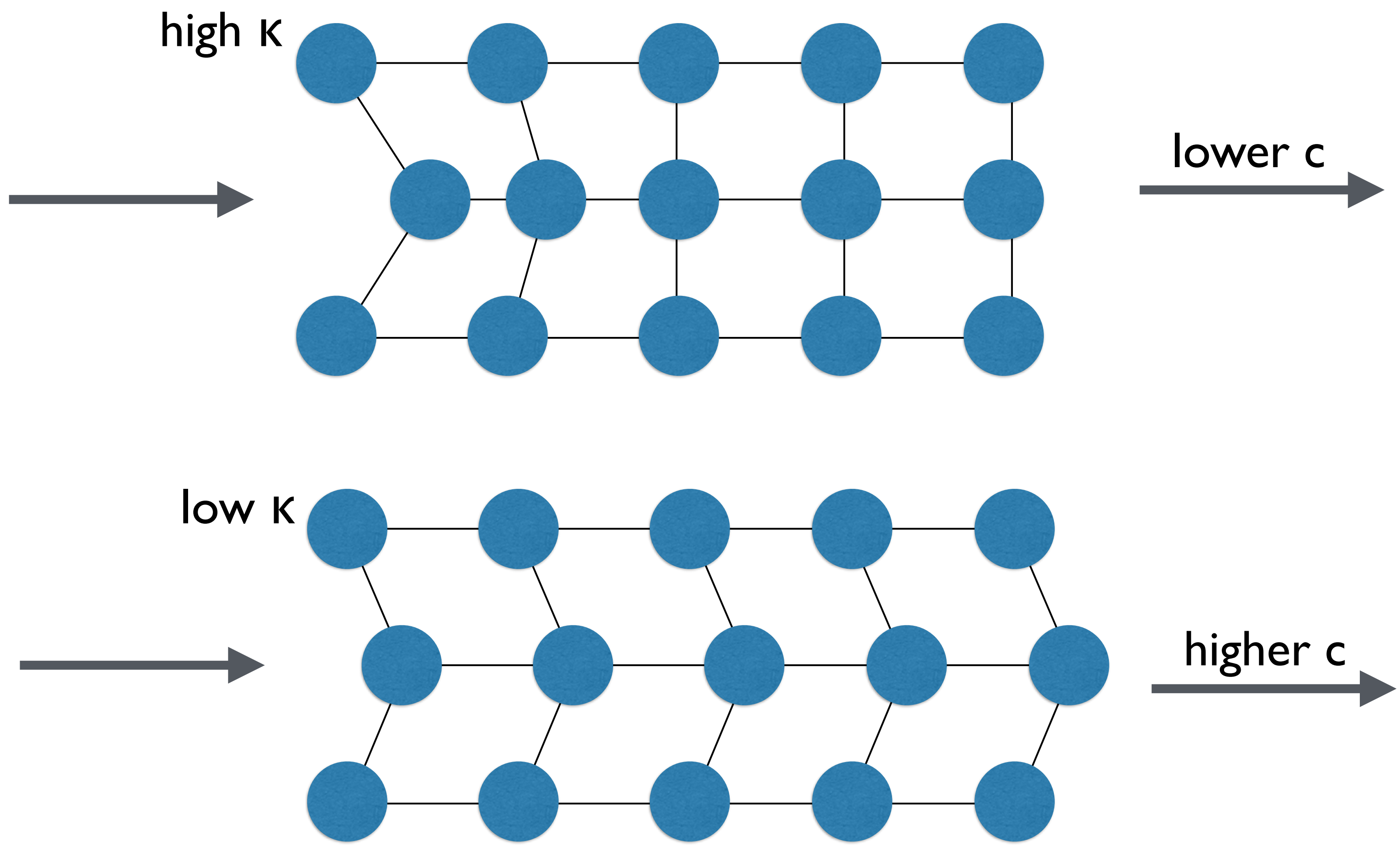
u = particle velocity



c = compression wave velocity (SoS)

κ determines speed of sound

κ=compressibility

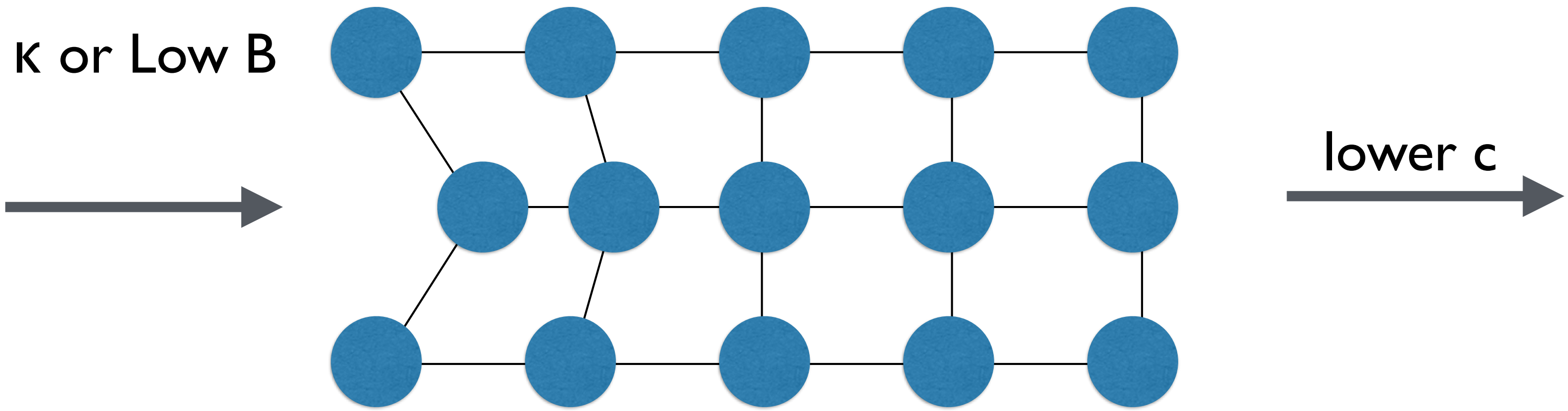


Bulk Modulus

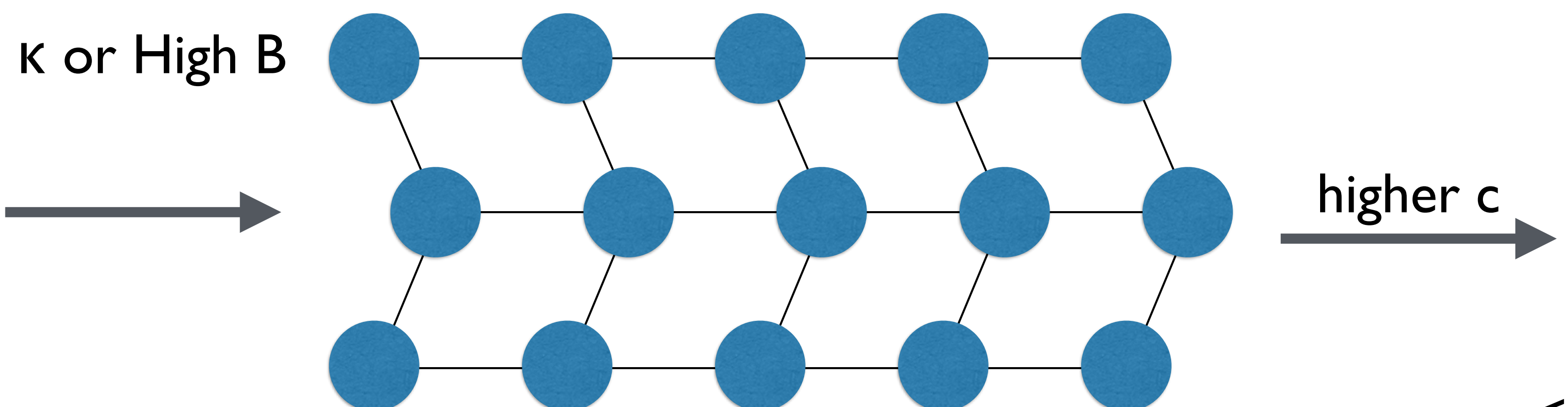
$$B = \frac{dP}{\left(\frac{dV}{-V}\right)}$$

B = Bulk Modulus = measure of the stiffness (Pa)
 - resistance to being compressed
B = 1/κ where κ=compressibility
ratio of infinitesimal pressure increase to the resulting relative decrease in the volume

high κ or Low B



low κ or High B



u<c

Acoustic Velocity/Speed of Sound

$$c^2 = \frac{1}{\kappa\rho}$$

B = Bulk Modulus = measure of the stiffness (Pa)
B = 1/κ where κ=compressibility
ρ = density (kg/m³)

$$c^2 = \frac{B}{\rho}$$

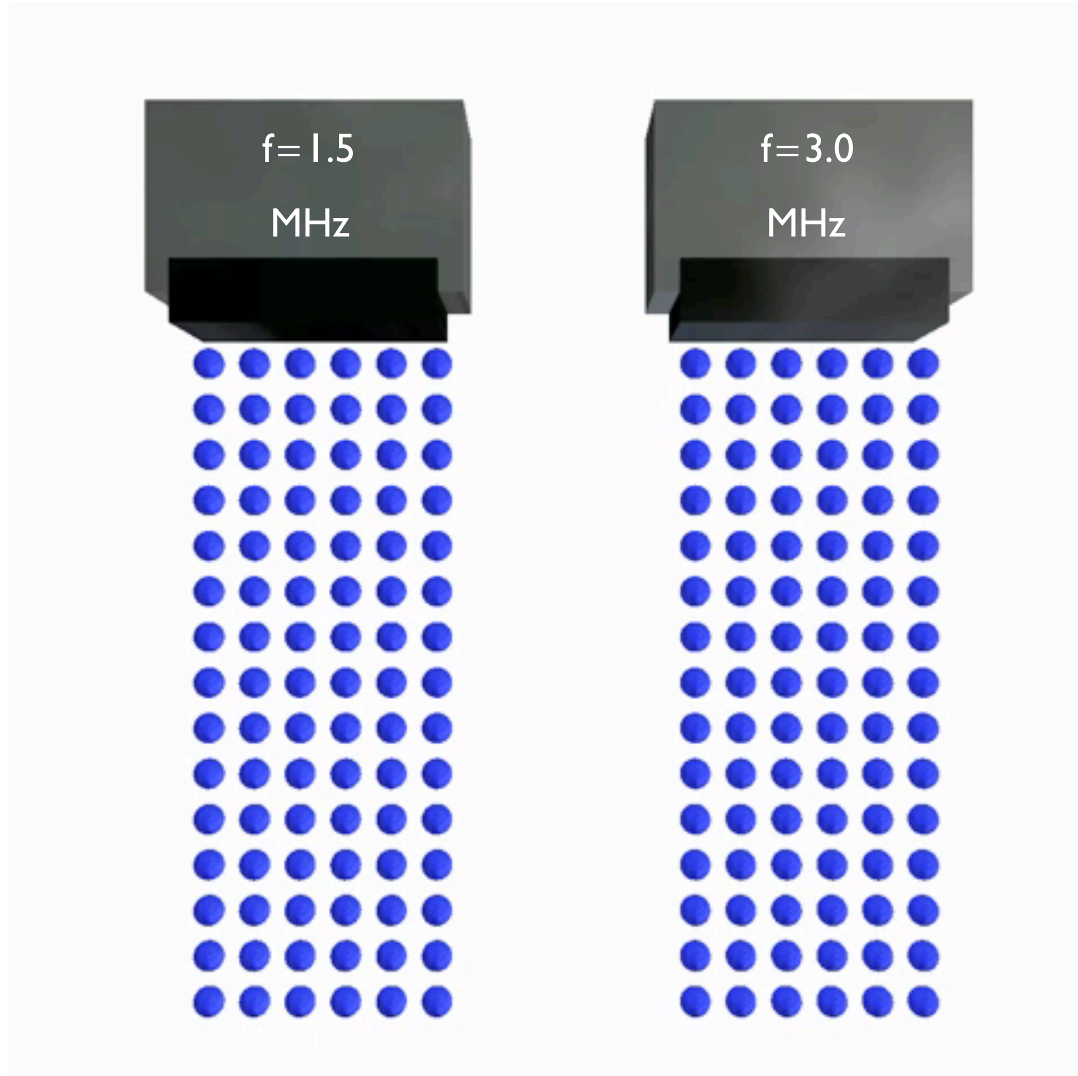
$$c = \sqrt{\frac{B}{\rho}}$$

	Density ρ (kg/m³)	Bulk Modulus B (MPa)	Speed of Sound c (m/s)
Air (25°C)	1.16	0.137	344
Fat	928	1900	1430
Water (22°C)	998	2190	1482
Blood	1060	2660	1584
Skeletal muscle	1041	2600	1580
Liver	1050	2610	1578
Kidney	1050	2560	1560
Bone	1600	18100	3360

Szabo

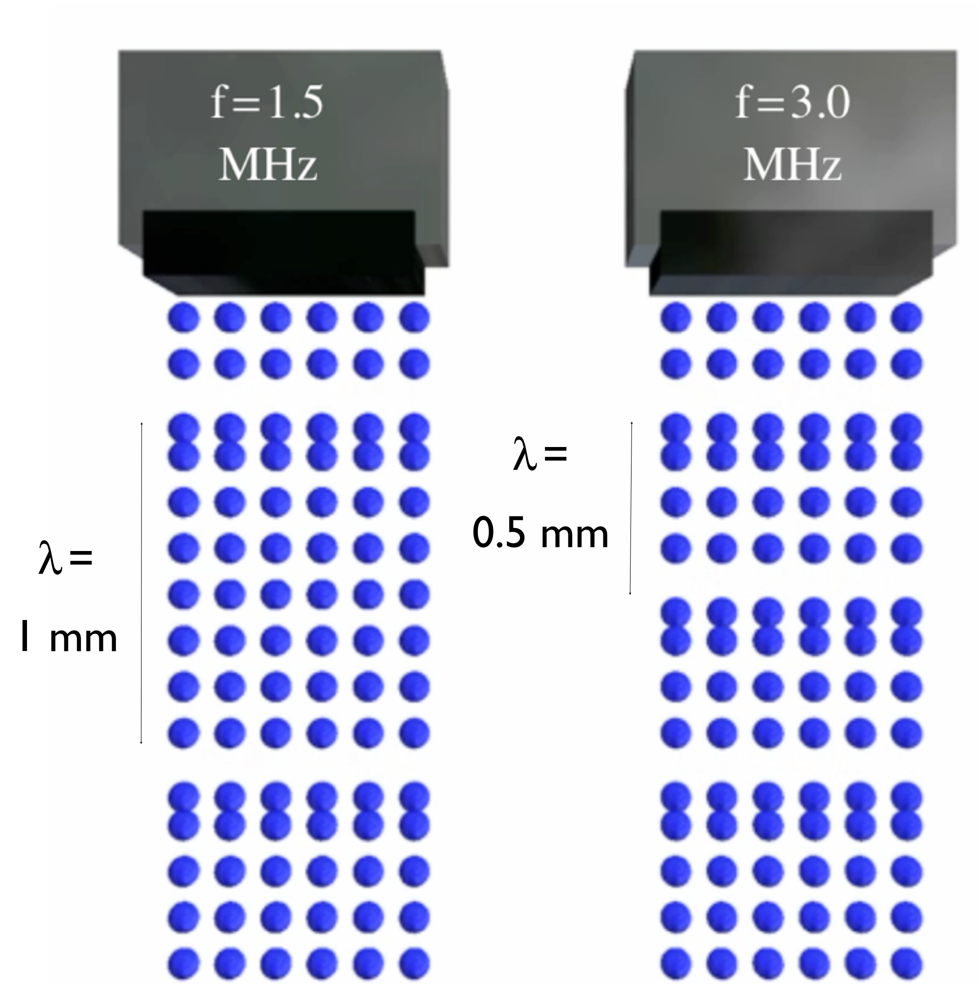
Speed of Sound

The pulse moves through tissue at a velocity specific to the tissue and *independent of the applied frequency.*



Speed of Sound

The pulse moves through tissue at a velocity specific to the tissue and *independent of the applied frequency.*



- Velocity (c), frequency (f), and wavelength (λ) are related:
- $c = \lambda f$

c in soft tissue

$$c = f\lambda$$

1540 m/s = 1 MHz * 1.54 mm

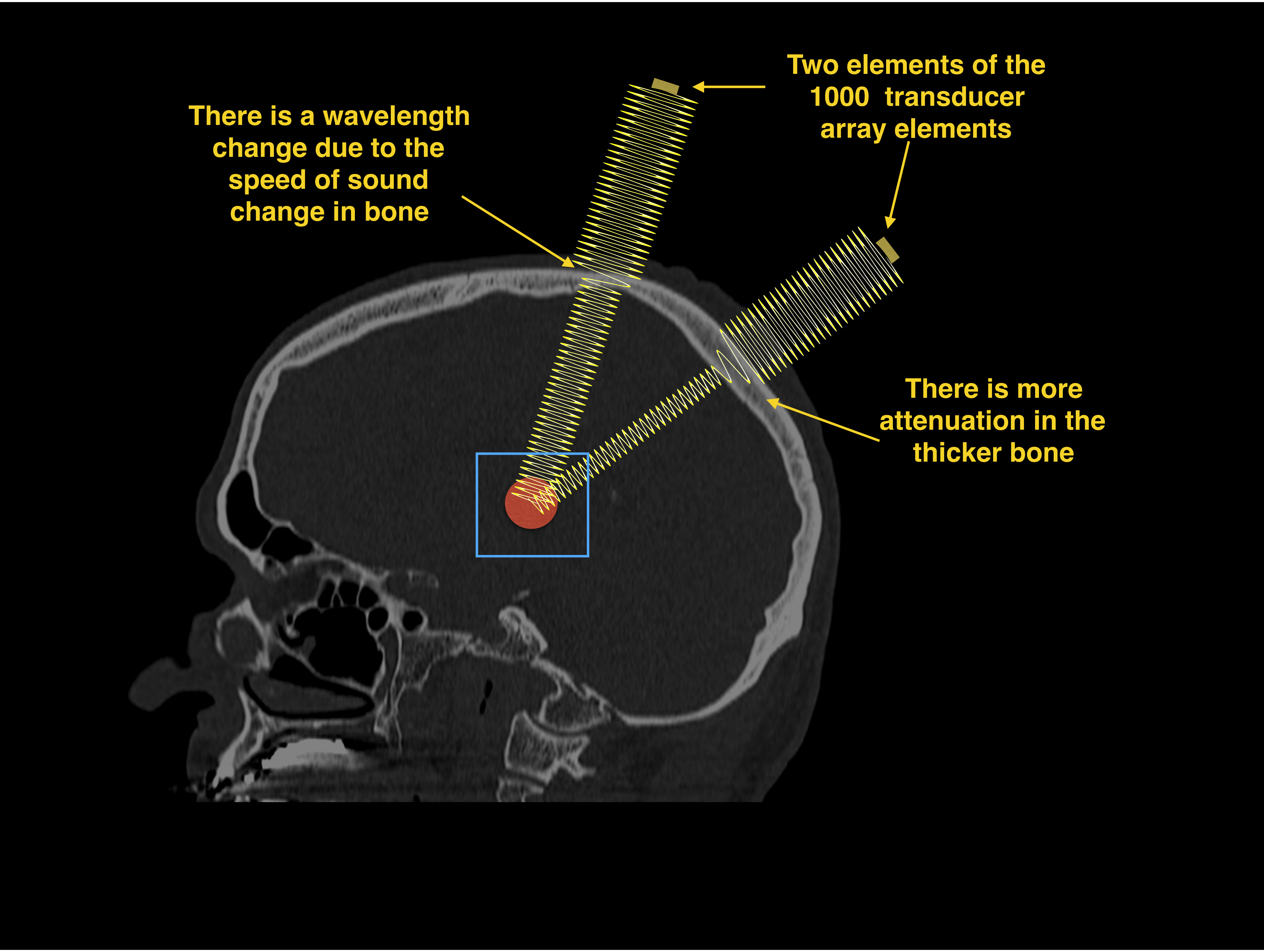
What is the wavelength for 500 kHz ultrasound in soft tissue?
~ 3 mm

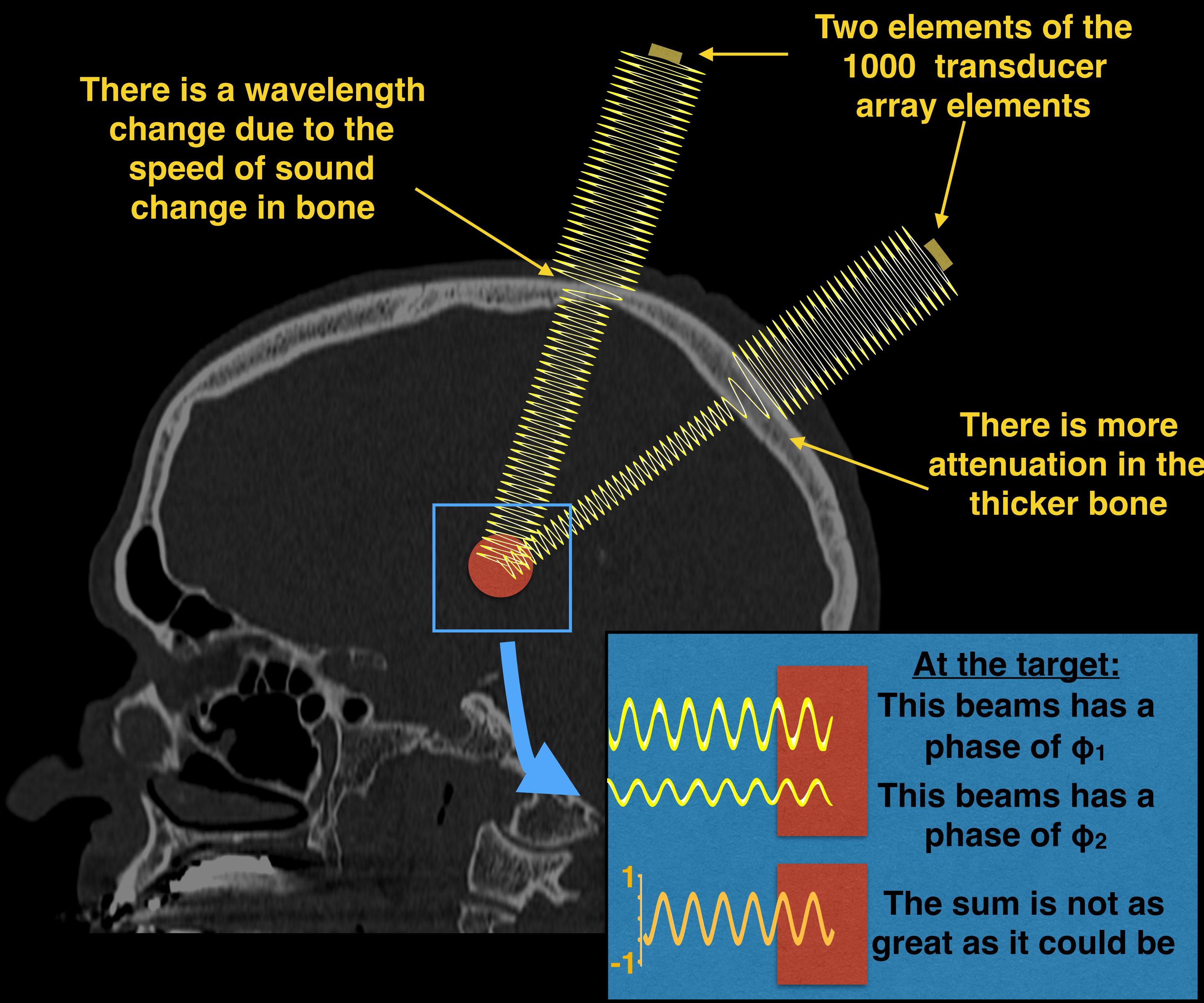
Why does this matter?

1) resolution ~ wavelength
⇒ higher frequency gives better resolution

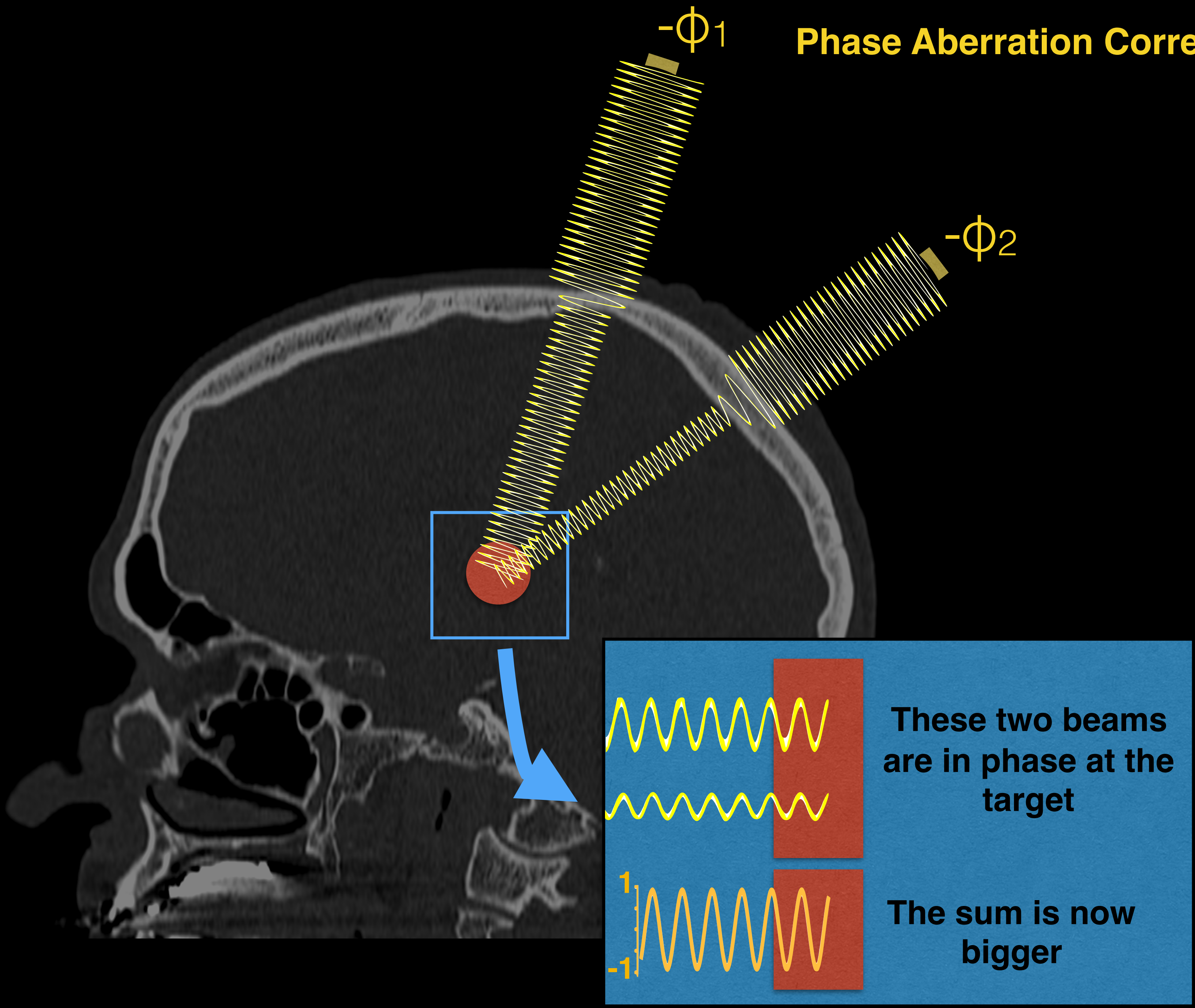
we'll talk about this more later

2) phase aberrations


There is a wavelength change due to the speed of sound change in bone
Two elements of the 1000 transducer array elements
There is more attenuation in the thicker bone


There is a wavelength change due to the speed of sound change in bone
Two elements of the 1000 transducer array elements
There is more attenuation in the thicker bone
At the target:
This beams has a phase of ϕ1
This beams has a phase of ϕ2
1
-1
The sum is not as great as it could be

Phase Aberration Correction



Acoustic Properties of Tissue

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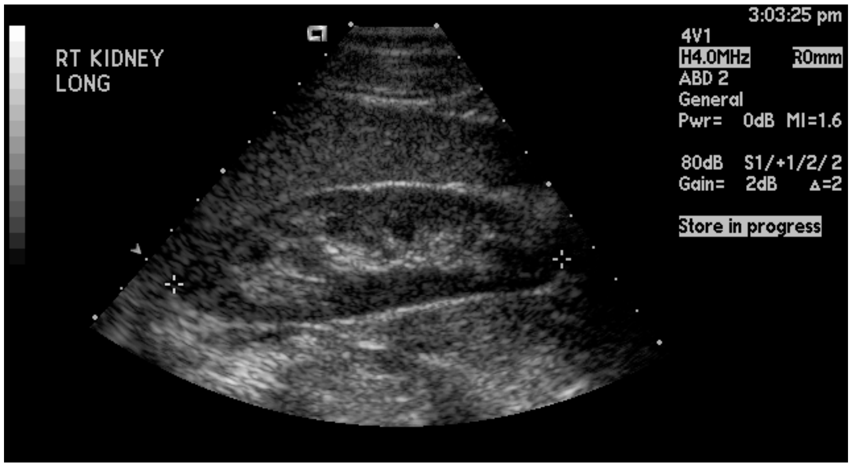
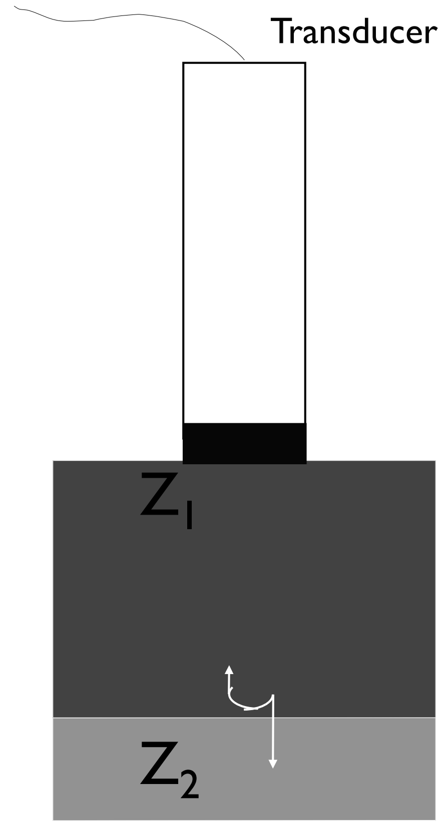
- Intensity

Example

Sound echo off a wall
The wall has a different property from the air

Acoustic Impedance





- At each interface, some sound is reflected and some is transmitted.
- The relative amounts depend on the acoustic impedances Z_1 and Z_2.

Acoustic Impedance

$$Z = \frac{P}{u}$$

P is the pressure
u is the particle velocity
think of it like resistance

Acoustic Impedance

$$Z = \sqrt{B\rho}$$

$$B = -V\frac{dP}{dV}$$

B = Bulk Modulus = measure of the stiffness (Pa)
B = $1/\kappa$ where κ=compressibility

ratio of infinitesimal pressure increase to the resulting relative decrease in the volume

and using $c = \sqrt{\frac{B}{\rho}}$

$$Z = \rho c$$

Acoustic Impedance

$$Z = \rho c$$

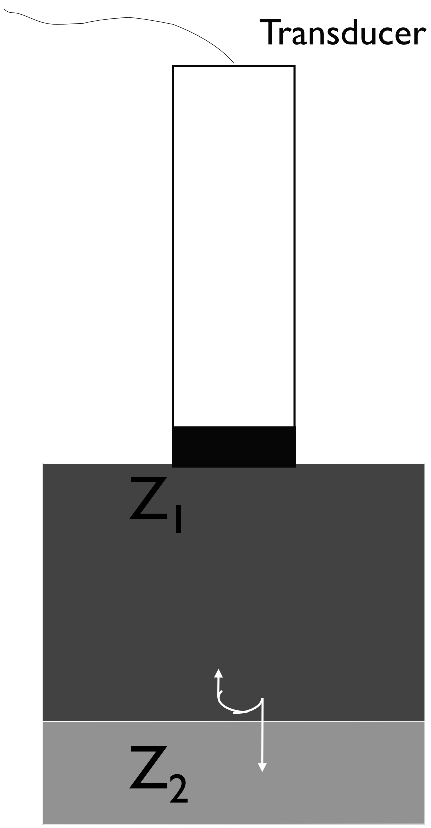
	Density	Speed of Sound	Impedance (MRayl)
	ρ (kg/m^3)	c (m/s)	Z (10^6 kg/m^2/s)
Air (25°C)	1.16	344	0.0004
Water (22°C)	998	1482	1.48
Blood	1060	1584	1.68
Skeletal muscle	1041	1580	1.65
Liver	1050	1578	1.64
Kidney	1050	1560	1.64
Fat	928	1430	1.33
Bone	1600	3360	5.69

Szabo

Acoustic Impedance Z

$$\%reflection = 100 * \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

$$\%transmitted = 100 * 4 * \frac{Z_1 Z_2}{(Z_2 + Z_1)^2}$$



Reflection Examples

- What is the reflection at a fat-muscle interface?
  reflection = $100*(1.7-1.38)^2/(1.7+1.38)^2 = 1.1\%$

- What is the reflection at a muscle-bone interface?
  reflection = $100*(7.8-1.7)^2/(7.8+1.7)^2= 41\%$

Acoustic Properties of Tissue

- Intensity
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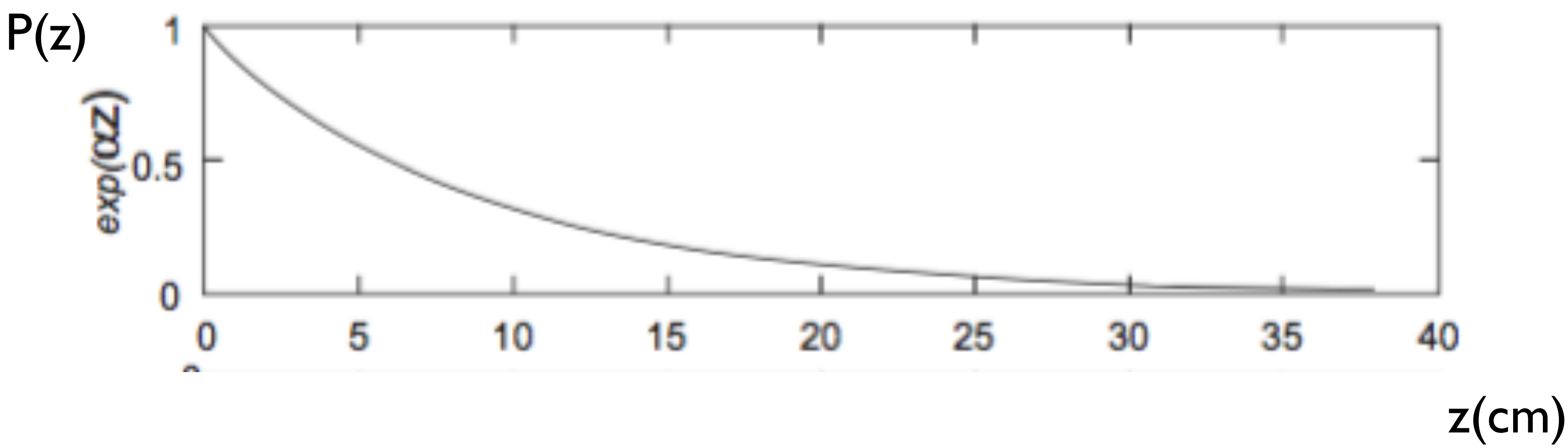
- Attenuation
- Intensity

Attenuation

For a single frequency plane wave,

$$P(z,t) = P_0 e^{i(w_c t - kz)} e^{-\alpha z}$$

α is given in nepers/cm



$$\alpha = \alpha_a + \alpha_s$$

α_a = attenuation due to absorption

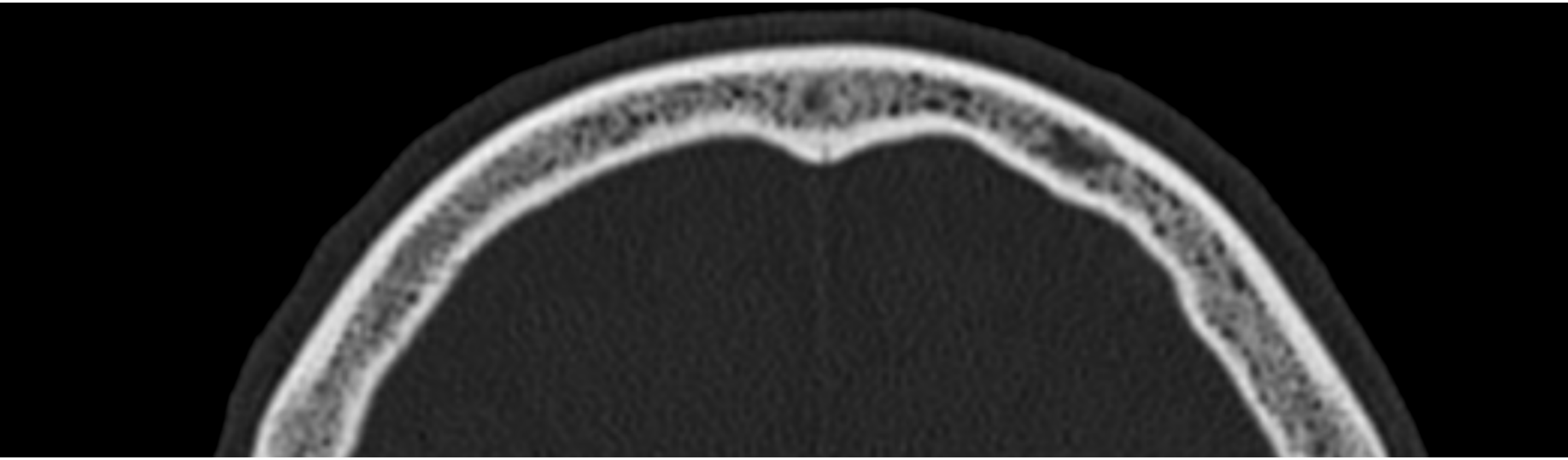
α_s = attenuation due to scattering

Attenuation

$$\alpha = \alpha_a + \alpha_s$$

α_a = attenuation due to absorption - dominates in soft tissue

α_s = attenuation due to scattering - dominates in medullary bone



Attenuation

loss of signal as the sound wave travels through the tissue

Loss of signal
Worse at high frequency

Two sources: 1) reflection and scatter and 2) absorption (heat)

dB

$$\text{Relative } SignalLevel(dB) = 20\log\left(\frac{P}{P_0}\right)$$

$$\text{Relative } SignalLevel(dB) = 10\log\left(\frac{P}{P_0}\right)^2$$

$$\text{Relative } SignalLevel(dB) = 10\log\frac{I_2}{I_1}$$

Relative Sound Intensity

when $I = 0.5\ I_o$, relative sound intensity is -3 dB
when $I = 0.1\ I_o$, relative sound intensity is -10 dB

↑ multiply ↑ add

when $I = 0.25\ I_o$, relative sound intensity is -6 dB
when $I = 0.001\ I_o$, relative sound intensity is -30 dB

Attenuation in dB

$$loss_{dB} = 20\log_{10}(loss)$$

$$\alpha_{dB} z = 20\log_{10}\left(\frac{P}{P_0}\right)$$

$$\alpha_{dB} = \frac{1}{z} 20\log_{10}\left(e^{-\alpha_{nepers} z}\right)$$

$$\log_b(x) = \frac{\log_a(x)}{\log_a(b)}$$

$$\alpha_{dB} = 8.6886\alpha_{nepers}$$

You can use either

$$P(z,t) = P_0 e^{-\alpha z}$$

$$loss_{db} = \alpha_{db} z$$

Attenuation

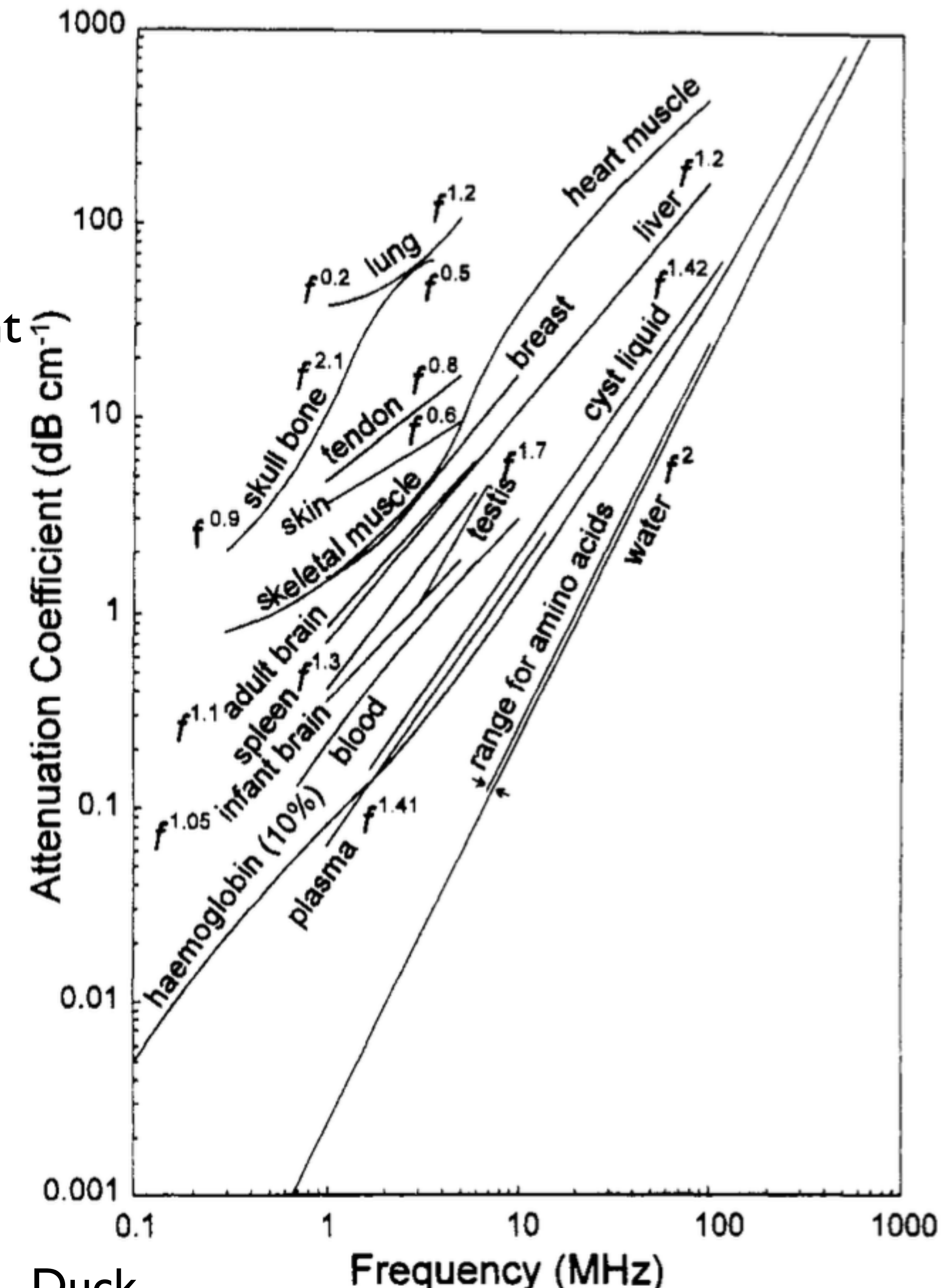
attenuation (dB) = $\alpha f z$

α = attenuation coefficient

f = frequency in MHz

z = distance in cm

Material	*α(dB/cm/MHz)*
Water	0.0022
Blood	0.14
Liver	0.45
Muscle	1
Soft Tissue	0.5
Air	12
Bone	10



Duck

Attenuation Examples

attenuation (dB) = α f z

- A 5 MHz beam passes thru 6 cm of tissue. The intensity is attenuated by how much?

attenuation = -1 dB/cm/MHz * 5MHz * 6cm

= -30dB

The received signal is 1/1,000 the transmitted signal.

Usually receive 1/1,000,000 the transmitted signal.

Attenuation Examples

Stanford's Ultrasound units are typically set to filter out signals <-60dB. What effect does this have?

It reduces some artifacts, but also limits depth reception.

How does this limit depth reception? If we have a -60 dB dynamic range and operate @5MHz, then depth is set:

-60dB = -1 dB/cm/MHz * x cm * 2 * 5 MHz

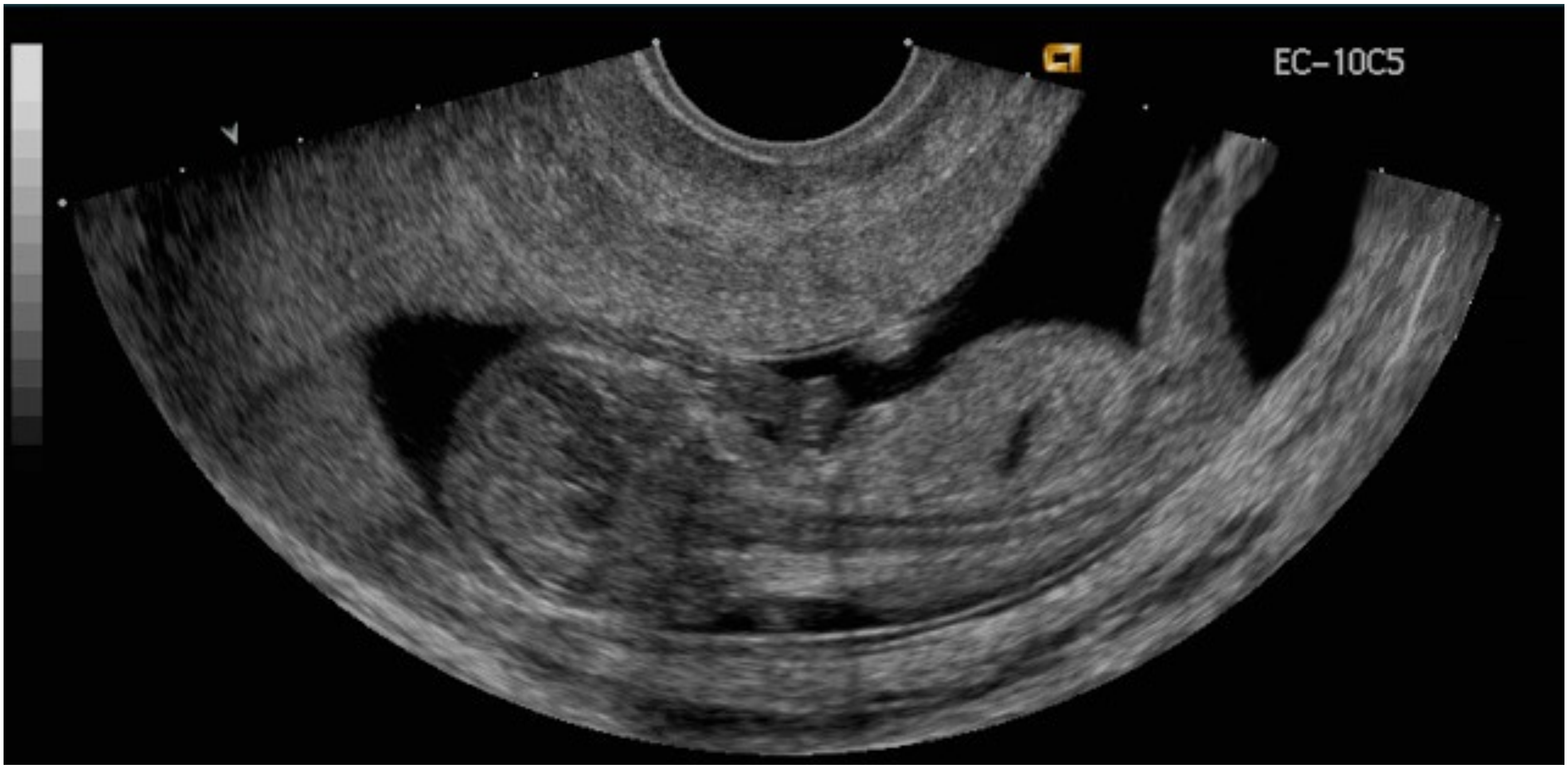
depth = 6 cm

attenuation (dB) = $\alpha f z$

- *For imaging deeper, need lower frequency*
- *More superficial structures, can use a higher frequency*

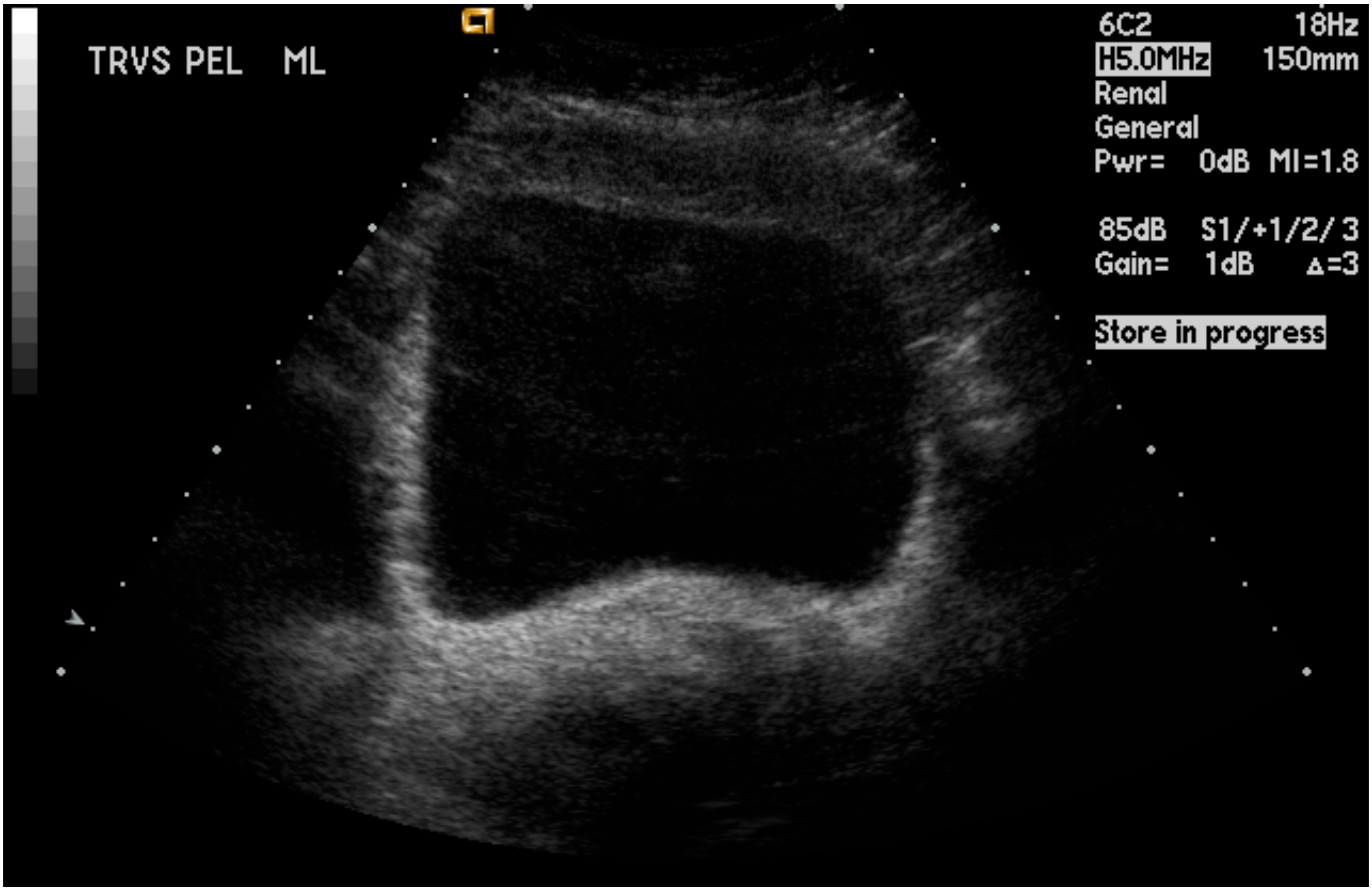
Time Gain Control

TGC - Amplifies the signal based on its depth - equalizes the signal across the image.

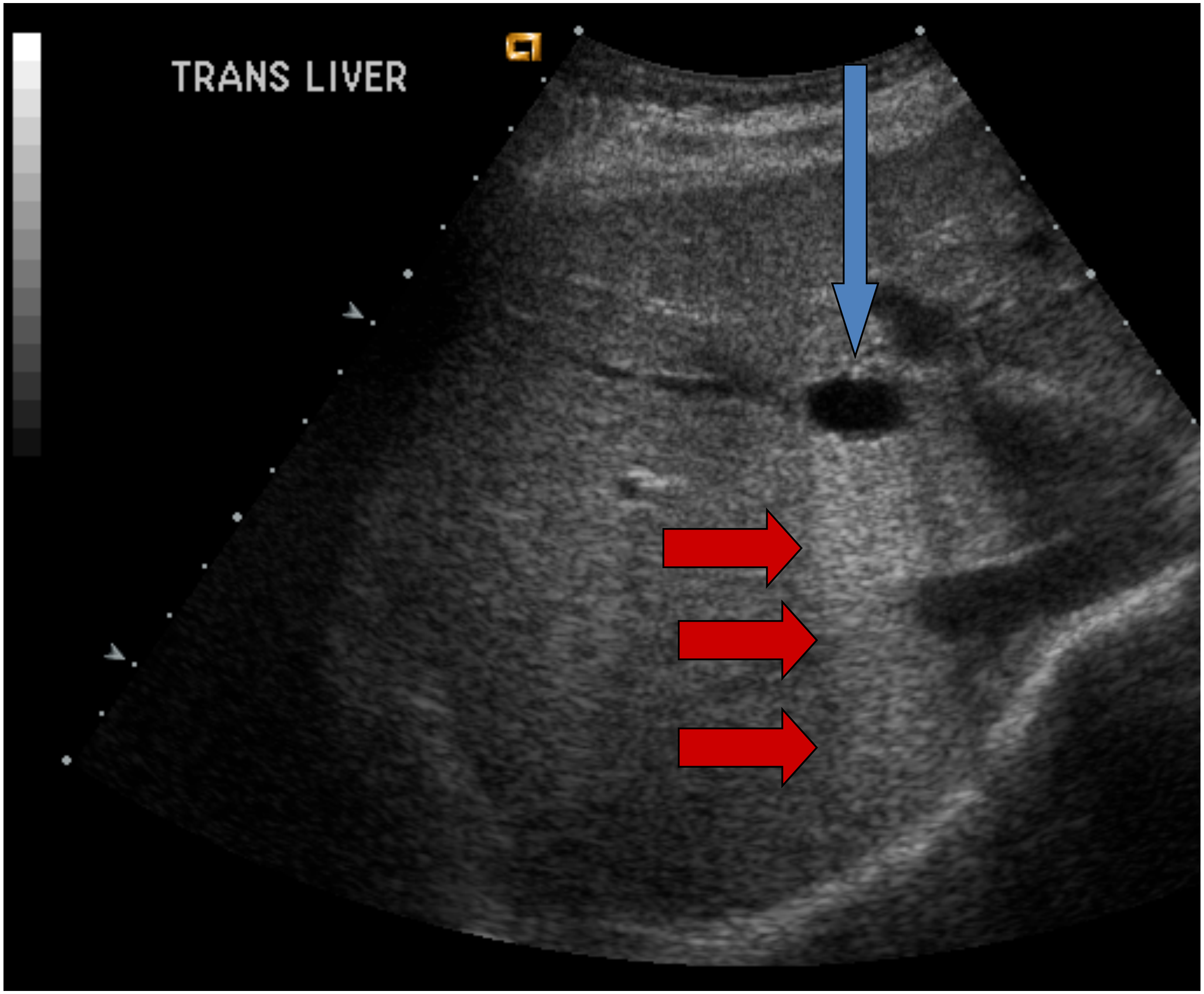


Artifactual Enhancement

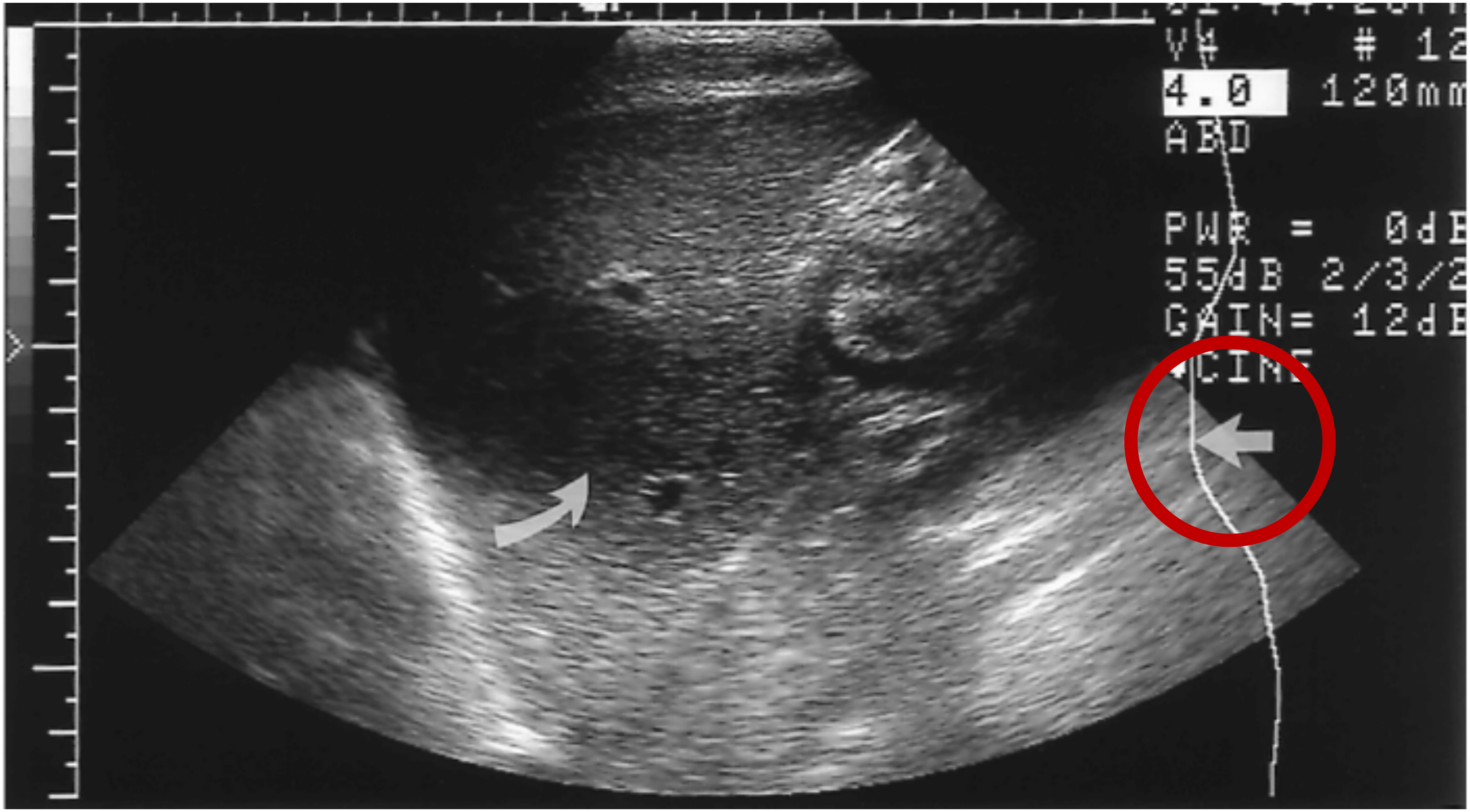
- Some structures do not have much attenuation - cysts, bladder.
- Can have high signal beyond these structures. "Acoustic Window"



Acoustic enhancement



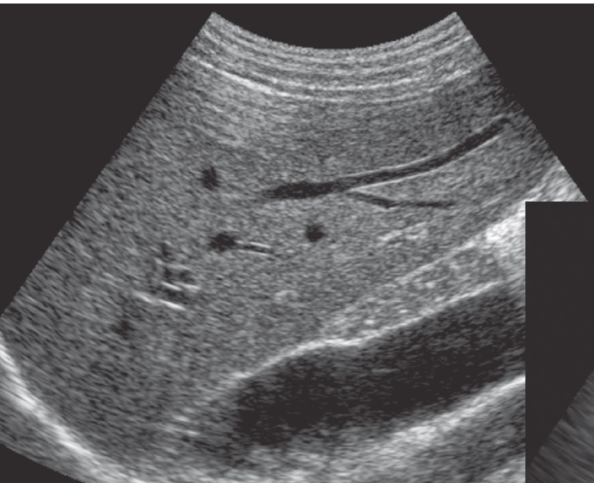
Artifact 1:
What is causing this Liver Lesion?

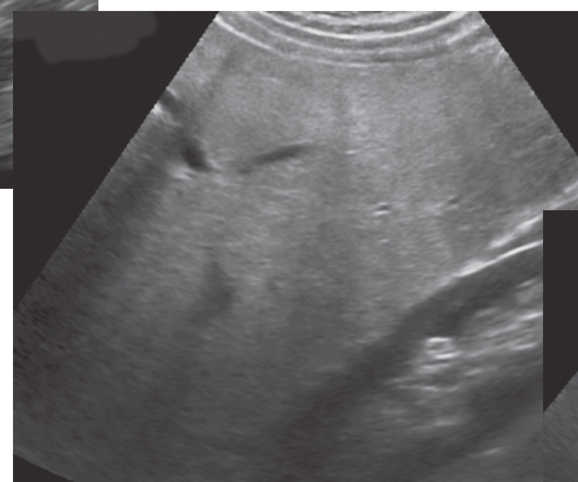


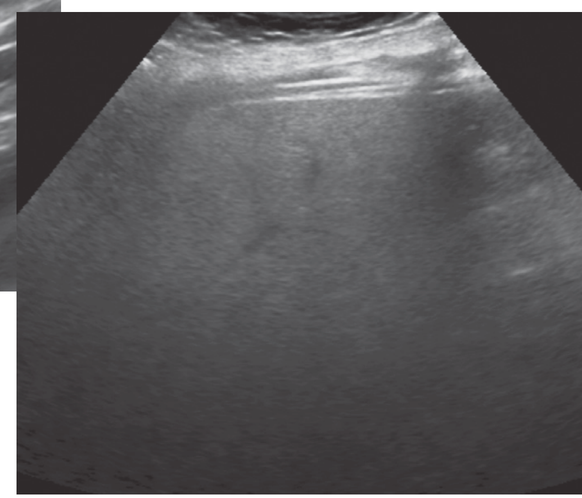
Poorly adjusted Time-Gain Compensation

Artifact 2:
What is causes increasing loss of liver signal?

increasing fat content







more reflections from inhomgeneous fat/water liver

attenuation of fat compared to aqueous liver

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- Intensity
- Attenuation
- Speed of Sound
- Acoustic Impedance
- **Intensity**

Intensity

Intensity is the power transferred per unit area (W/m²)
Intensity = power density

$$powerdensity = \frac{power}{area} = \frac{work}{area * time} = \frac{force * dis\tan ce}{area * time}$$

$$powerdensity = P * particlevelocity$$

$$Z = \frac{P}{u}$$

$$I = \frac{P^2}{Z}$$

Instantaneous

Intensity

$$I = \frac{P^2}{Z}$$ Instantaneous

$$I_{ave} = \frac{P^2}{2Z}$$ time average