# Seeing With Sound
## - An introduction to Ultrasound



http://www.genesisobgynonline.com/ultra08.jpg



http://www.3d-4d-ultrasounds.com/images/gallery/before-after.jpg



http://www.dximaging.com/images/ultras10.jpg



http://www.nsbri.org/NewsPublicOut/Photos/20051102b.jpg
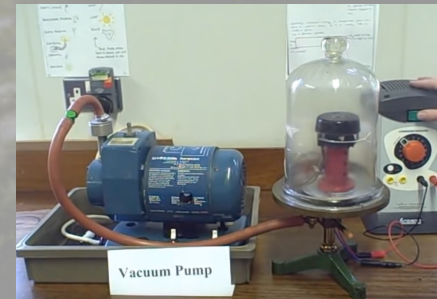
# Seeing With Sound - Outline

• Introduction to sound and sound waves.

• The velocity of sound in materials.

• Basics of ultrasound.

• Homogeneous and non-homogeneous materials.

• Reflections & echoes.

• Intensity of ultrasound – the decibel scale.

• Attenuation of ultrasound in homogeneous media.
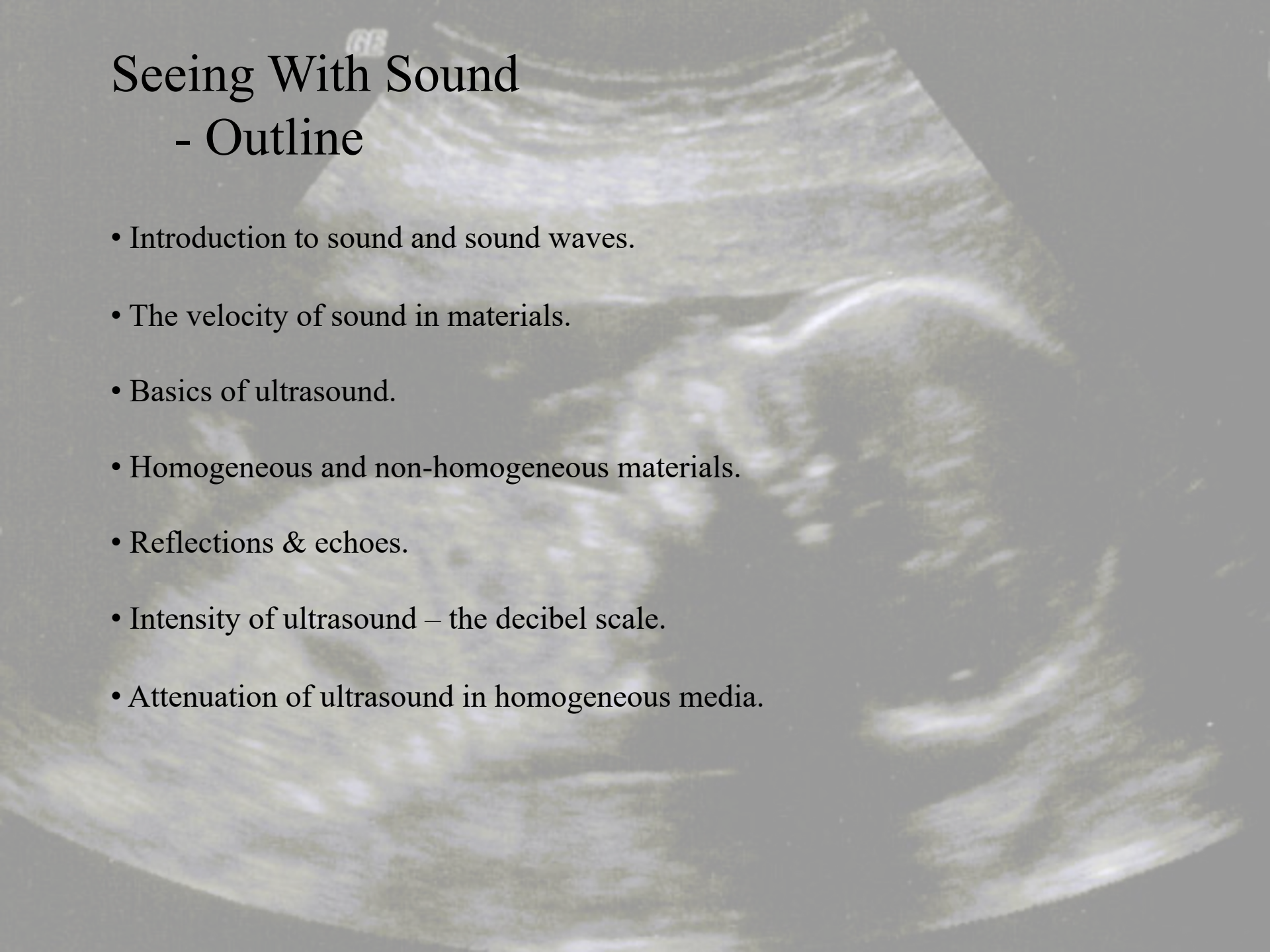
# Seeing With Sound

## - *The Physics of Ultrasound: background*

- Most imaging technologies are concerned with the interaction of ionizing radiation (UV, x-rays, γ-rays, or particles) and tissue or electromagnetic interactions with tissues in the body.

- Ultrasound (or sound in general) is different – it is not an electromagnetic wave, and it is non-ionizing. Sound is a mechanical wave – it needs a medium in order to propagate.

- Ultrasound is high-frequency sound waves in the 1 – 10MHz range.

- Ultrasound waves are traveling waves and not standing waves.



https://www.youtube.com/watch?v=ce7AMJdq0Gw

- The energy associated with the waves can be absorbed by the material and the ultrasound waves can be reflected or refracted at different tissue boundaries.

- Ultrasound *image formation is accomplished by using echoes*, or reflections from different media, such as organs, vessels or other structures.

- Refraction produces distorted images and absorption is of little clinical value.

# Seeing With Sound

## - *The Physics of Ultrasound: background*

- Sound is a *longitudinal wave* – medium oscillates parallel to the direction of propagation of the wave. There are regions of compression (higher than ambient pressure) and decompressions (lower than ambient pressure).

- The human ear can hear sound in the frequency range of about 20 – 20,000 Hz.

- *Ultrasound* refers to frequencies that are higher than 20-kHz (and for comparison with light, *infrasound* refers to frequencies that are lower than 20-Hz.)

- The wave speed of a sound wave is related to its frequency and wavelength through:

$$v = f\lambda$$



http://www.physics.uc.edu/~sitko/CollegePhysicsIII/14-Sound/Sound.htm
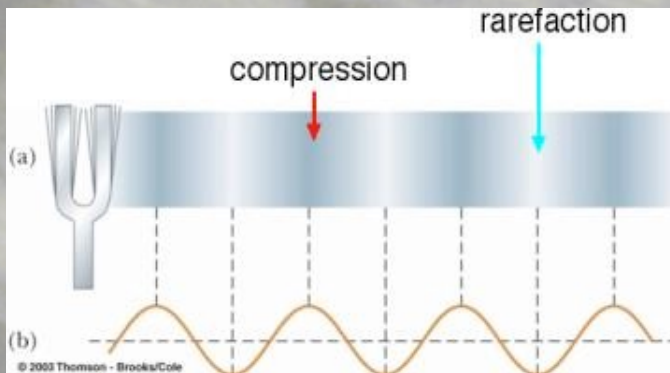
- For any material, the velocity of sound is nearly constant in the material, meaning that the velocity is independent of frequency. Or there is little dispersion of the waves.

- The wavelength of a sound wave is the physical distance between any two compressions or decompressions (rarefactions.)

# Seeing With Sound

## - *The Physics of Ultrasound: background*

- Animation of a continuously vibrating source in a column of air perhaps, or sound propagation in a material.

- Notice that the molecules do not move with the passing wave.  Waves do not transport matter, but rather energy from one location to another.
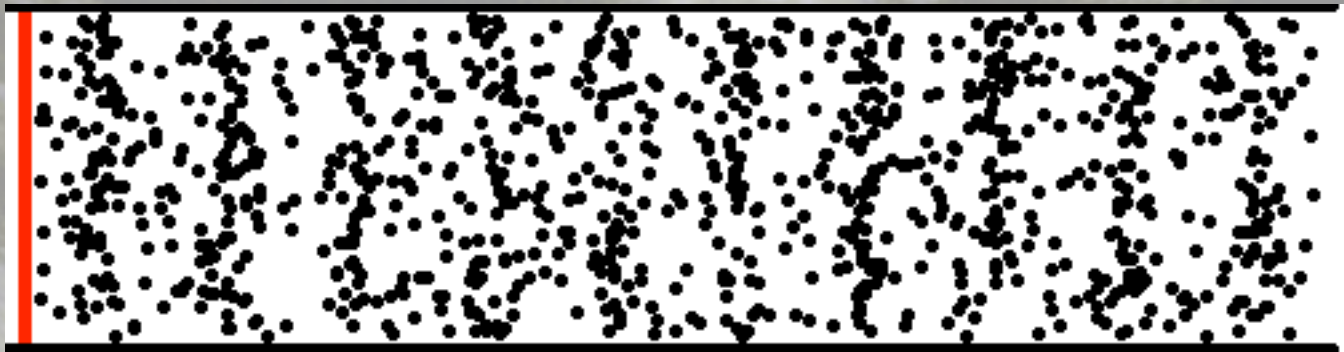
Application made using Mathematica by Dan Russell, Penn State

- For our ultrasound applications we'll actually be using a pulsed source of  sound. We'll be calling this "pulse-echo ultrasound".

- This is how bats and submarines hunt their prey.

# Seeing With Sound

### *- The Physics of Ultrasound: The Wave Equation*

- The sound waves transfer energy (and not matter) through the medium.

- The propagation is described by a function $\eta(x,t)$ in 1-dimension, where $\eta$ represents any physical property of the wave system. For example, $\eta$ could represent the wave speed, tension, pressure, temperature, etc. Any property that can be propagated. For us, this is probably the pressure of the sound wave.

- To physically model the wave propagation, consider the following 1-dimensional situation in which a uniform rod of cross-sectional area $A$ and length $L$ is struck at one end by a hammer as shown below.

- The rod experiences a *stress* (defined as the Force applied per unit area of the rod) and the rod changes length and thus experiences a *strain* (defined as the change in length per unit length of the rod.)

- Mathematically we have:

$$Stress = \tau = \frac{F}{A}$$

$$Strain = \varepsilon = \frac{\Delta L}{L}$$
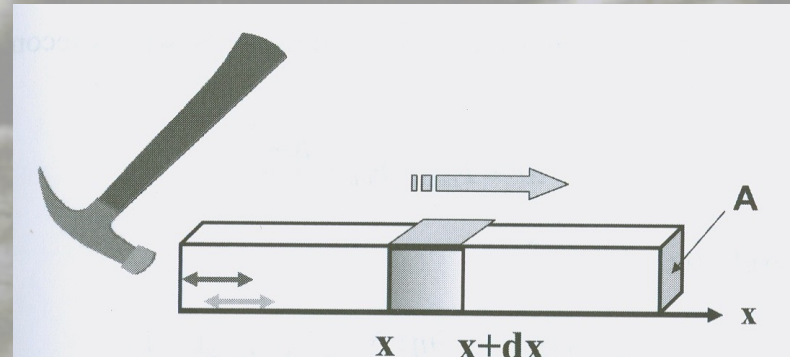
# Seeing With Sound
## *- The Physics of Ultrasound: The Wave Equation*

- For an elastic material, Hooke's Law is found to hold and defining the elastic response of the material as $E$, we have:

$$F = \text{"stiffness"} \cdot \Delta L \rightarrow \Delta L = \varepsilon L \quad \& \quad F = \tau A \Rightarrow \tau = \left(\text{"stiffness"} \frac{L}{A}\right) \varepsilon$$

$$\rightarrow \tau = E\varepsilon$$

- Or, expressing Hooke's Law as

$$Stress = E \cdot Strain$$

- Now, we examine a small piece of the rod located at a point $x$ along the length of the rod.

- The stress created by the hammer blow, causes one side of the rod to be displaced by an amount $\eta_x$ on the left face and $\eta_{x+dx}$ on the right face due to the wave taking time to travel along $dx$ and related to the elastic properties of the material.

- $\eta$ is the physical property of interest (say the pressure).
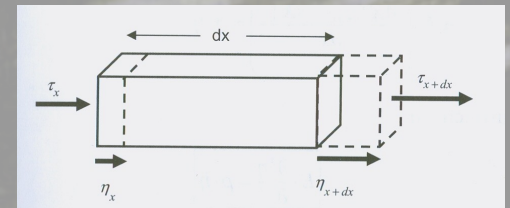
# Seeing With Sound

## - *The Physics of Ultrasound: The Wave Equation*

The force on the left face is given as (using the definition of stress):

$$F_{left} = A\tau_x = AE\varepsilon = AE \left.\frac{\partial \eta}{\partial x}\right|_x$$

While the force on the right side is:

$$F_{right} = A\tau_{x+dx} = AE\varepsilon = AE \left.\frac{\partial \eta}{\partial x}\right|_{x+dx}$$

The net force is the difference between the left and right sides and of course is equal to the mass times the acceleration of the segment.

$$F_{net} = F_{left} - F_{right} = m\frac{\partial^2 \eta}{\partial t^2}$$

Or, more explicitly

$$AE \left( \left.\frac{\partial \eta}{\partial x}\right|_x - \left.\frac{\partial \eta}{\partial x}\right|_{x+dx} \right) = \rho A dx \frac{\partial^2 \eta}{\partial t^2}$$

# Seeing With Sound

### *- The Physics of Ultrasound: The Wave Equation*

- Rearranging the previous equation, we have:

$$E\left(\frac{\left.\frac{\partial \eta}{\partial x}\right|_x - \left.\frac{\partial \eta}{\partial x}\right|_{x+dx}}{dx}\right) = \rho \frac{\partial^2 \eta}{\partial t^2}$$

- This represents a 1-dimensional wave equation for the propagation of a longitudinal wave through an elastic homogeneous medium as a function of position and time.

$$\frac{\partial^2 \eta}{\partial x^2} = \frac{\rho}{E}\frac{\partial^2 \eta}{\partial t^2}$$

- With $v$ representing the wave speed through the medium and comparing this to the standard form of the wave equation we have

$$\frac{\partial^2 \eta}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 \eta}{\partial t^2} = \frac{\rho}{E}\frac{\partial^2 \eta}{\partial t^2}$$

# Seeing With Sound
### - *The Physics of Ultrasound: background*

- We've determined the speed of a sound wave in a 1-dimensional medium by applying Newton's laws to a small segment of material and we find that that the speed of sound depends further on its density, $\rho$ and the elastic properties of the medium, or equivalently in terms of the compressibility, $K$, through

$$v = \sqrt{\frac{E}{\rho}} = \frac{1}{\sqrt{K\rho}}$$

- The compressibility $K$ is defined as the fractional change in volume of material per unit increase in pressure

$$K = -\frac{1}{V}\frac{dV}{dP}$$

- Thus, a large compressibility, $K$, means that it is easier to squeeze something.

- $E$ is called the elastic (or Young's) modulus of the material and is a measure of the stiffness (or elastic response) of the material.

# Seeing With Sound
## - *The Physics of Ultrasound : background*

- Ultrasound imaging is particularly useful in studying soft tissues that are not able to be contrasted with say by using x-rays. For contrast using x-rays we usually use a very dense material like iodine which is preferentially taken up by vascular structures.

- Doppler ultrasound can detect and monitor the flow of fluids, such as blood flow in arteries and veins.

- Ultrasound is used (almost extensively) in obstetric, gynecologic, renal, hepatic, cardiac, vascular and abdominal imaging.

- Ultrasound equipment is relatively cheap and portable, unlike and MRI or X-ray equipment.

- Ultrasound does not produce ionizing radiation in the body.

- Believed that the risks of using ultrasound as a diagnostic tool are low.

# Seeing With Sound

*- The Physics of Ultrasound : background*

$10000 − $80000

$4000

# Seeing With Sound
### - *The Physics of Ultrasound : an example*

- The fundamental frequency of a piano's middle C key is $261.6\,Hz$. What is its wavelength in air? What is its wavelength in tissue?

- What is the wavelength of a $1MHz$ ultrasound signal in soft tissue?

- What frequency ultrasound would be needed to image features that are $0.5mm$ in diameter?

# Seeing With Sound
## - *The Physics of Ultrasound*

- Sound waves are periodic mechanical disturbances that need a medium to propagate through.

- Sound waves are longitudinal waves made up of repeating cycles of compression and decompression.

- Disturbances due to sound radiate outward radially from the source causing disturbances in the local surrounding media. For example, a hammer hitting a nail.

- Ultrasound imaging makes use out of the reflections of high frequency sound waves.

- The orientation of the ultrasound beam at the time of the pulse gives a bearing, or heading for the beam, toward a target.

- From the echoes that are received back distances to the target can be determined, if the return time of the echo and velocity of sound in the medium are known.

- This process is known as *SONAR* (**SO**und **N**avigation **A**nd **R**anging.)

# Seeing With Sound

## - *The Physics of Ultrasound*

- The basics of ultrasound are to send out a well defined, high frequency pulse of sound energy in a known direction, from a source (a transducer) and to detect the resultant fainter echoes.

- The echoes are turned into an electrical signal (a voltage) and the voltages are processed and displayed on an oscilloscope (or TV screen.)

- The transducer is constructed of a piezoelectric material.

- A piezoelectric is a material that has a well-defined oscillation frequency, and the material is put into oscillation by an oscillating electric field (or by an oscillating current or voltage source.)

- The piezoelectric material can not only generate but also detect sound vibrations.

- Planar vs. other geometries – maybe a curved surface piezoelectric would be better?



http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/radiatedfields.htm

# Seeing With Sound
## - *The Physics of Ultrasound*



metal outer casing — backing block — electrodes apply an alternating potential difference — piezoelectric crystal — plastic 'nose' — acoustic insulator — power cable

http://www.genesis.net.au/~ajs/projects/medical_physics/graphics/transducer.jpg

Backing Material — Wear Plate — Sound Field — Electrical Leads — Piezoelectric Element — Near Field — Far Field

http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/radiatedfields.htm

- The transducer head contains the piezoelectric material, and the transducer is acoustically coupled to the body by using a gel.

- The gel minimizes reflections of the ultrasound at the skin's surface and a beam of ultrasound pulses are delivered to the body.   (Acoustic impedance matching.)

- The velocity of sound in soft tissue is approximately $1540\frac{m}{s}$.

- The ultrasound pulse has an intensity $I$ that decreases exponentially as it passes through the body's tissues and organs.  This can be experimentally verified.

# Seeing With Sound
## - *The Physics of Ultrasound - Echoes*

Material types:

- *Homogeneous medium* – the medium is the same throughout – like a fluid filled bladder or cyst.

  Medically these are uninteresting materials since fluid in the bladder/cyst will usually produce no echoes.

- *Non-homogeneous medium* – the medium has a sharp boundary, and the boundary will produce an echo.

  Medically more interesting and the boundary could be different tissue densities or different tissue elasticities.
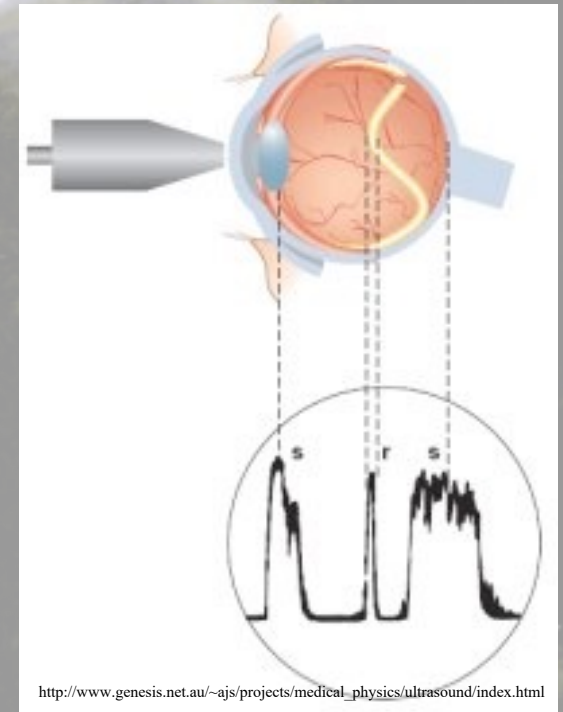
# Seeing With Sound
## *- The Physics of Ultrasound - Echoes*

- The time lapse from transmission of pulse to detection of echo is proportional to the depth within the tissue. This is called an Amplitude or A-type (or single line) scan.

  A-type scans are used to measure distances. The transducer emits an ultrasonic pulse and the time taken for the pulse to be reflected and return to the transducer is graphed in order to determine how far away the object is. A-type scans only give one-dimensional information and therefore are not useful for imaging.

- There are several other scan types that we'll look at B-Type, M-mode & Doppler.



http://www.genesis.net.au/~ajs/projects/medical_physics/ultrasound/index.html

- The intensity of the echo signal increases with the amount of physical difference between the two tissues. Compare for example a tennis ball thrown off a wall that is made from brick to one made from a blue tarp.

# Seeing With Sound

## - *The Physics of Ultrasound - Echoes*



https://courses.washington.edu/bioen508/Lecture6-US.pdf
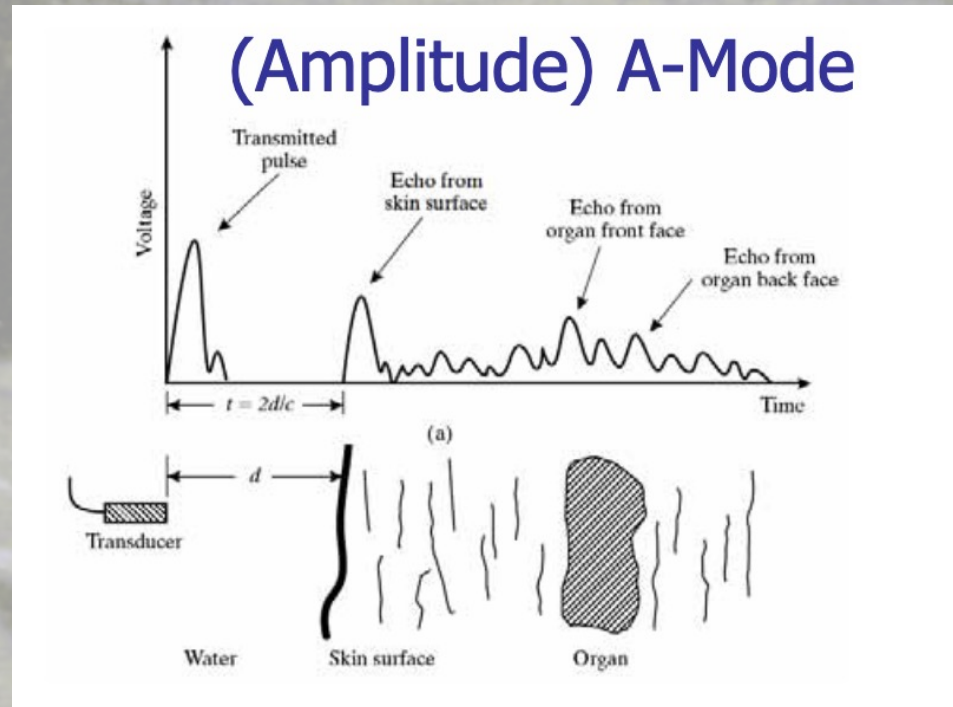
If you measure the time it takes for the echo to return, you can, knowing the wave speed of sound in the material, determine the distance to the surface that caused the reflection.

# Seeing With Sound

*- The Physics of Ultrasound - Intensity*

- The intensity of sound is described by the decibel scale.

- We generally define the intensity level of sound in terms of the intensity with which the ear is just barely sensitive to: $I_{threshold} = 1 \times 10^{-12} \frac{W}{m^2}$.

- The intensity ratio for two sounds as heard by your ear is given by: $dB = 10 \log \left( \frac{I_{sound}}{I_{threshold}} \right)$

- For ultrasound, the threshold intensity is the US beam intensity, $I_{US}$ and the echo has an intensity, $I_{echo}$.

- Thus, we have: $dB = -10 \log \left( \frac{I_{echo}}{I_{US}} \right)$

- Alternatively, and coincidentally more useful, we could write this in terms of the ratio of the intensities:
$$\frac{I_{echo}}{I_{US}} = 10^{-\frac{dB}{10}}$$

- It two signals differ in intensity by $20 dB$, what is the ratio of their intensities?

# Seeing with Sound

### *Ultrasound – Intensity*

- The attenuation, or loss of sound energy, is due to frictional forces at the atomic/molecular level as the atoms/molecules vibrate and return to their relaxed state.

- The intensity of the ultrasound is proportional to the square of the amplitude of the wave so that

$$dB = -10\log\left(\frac{I_{echo}}{I_{source}}\right) = -10\log\left(\frac{A_{echo}}{A_{source}}\right)^2 = -20\log\frac{A_{echo}}{A_{source}}$$

- Solving for the intensity ratio we have

$$\frac{I_{echo}}{I_{source}} = 10^{-\frac{dB}{10}} \quad \& \quad \frac{A_{echo}}{A_{source}} = 10^{-\frac{dB}{20}}$$

- Suppose that an echo is ½ as intense as the original US pulse, what is the intensity drop in decibels?

# Seeing With Sound
### - *The Physics of Ultrasound – Intensity*

- So how strong of an echo will be produced? I need this because it's the intensity of the echo is what we're going to use to form the image.

- It depends on many factors.

- If the beam passes through a homogeneous medium like a fluid filled cyst or a large blood vessel, the ultrasound pulse simply propagates through and its intensity will simply decrease exponentially with increasing distance, $x$. This is experimentally verifiable in the laboratory with any fluid.

$$I(x) = I_{incident}e^{-\mu_s x}$$

- $\mu_s$ is called the *ultrasound intensity attenuation coefficient* in units of distance$^{-1}$.

- $\mu_s$ is a combination of the energy loss due to absorption by the tissue (and turned into heat) and energy loss due to scattering of the beam by irregularities.

- If we take the base 10 logarithm of the equation above, (and then multiply by -10) we get

$$-10\log\left(\frac{I(x)}{I_{incident}}\right) = -10\log(e^{-\mu_s x})$$

# Seeing With Sound

*- The Physics of Ultrasound – Attenuation of US*

- The left-hand side of this equation is the definition of the dB. Thus, we have

$$dB = -10\log\left(\frac{I(x)}{I_{incident}}\right) = -10\log(e^{-\mu_s x}) = 10\mu_s x\log(e) = 4.3\mu_s x$$

- And now we define a more useful quantity, decibels of intensity loss per unit distance (in dB per cm) as

$$dB = \text{``absorption coefficient''} \cdot x$$

- The absorption coefficients are frequency dependant and for the most part that frequency dependence is linear in frequency.

- To find the decibels of intensity loss (per cm) we use a graph (or a computerized data file which is programmed on an actual US machine) to determine the absorption coefficient at a particular frequency in a particular tissue.

- Then the number of decibels of intensity loss is easily calculated and this is easier than calculating actual intensities.

# Seeing With Sound

## - *The Physics of Ultrasound – Attenuation of US*

- The attenuation given is for a one-way travel.

- As the ultrasound reflects it is further attenuated.

- Suppose that a $5 MHz$ ultrasound source is used to image a muscle, how many decibels of intensity are lost as the ultrasound passes one way through $2 cm$ of muscle?

- How about through $2 cm$ of blood?
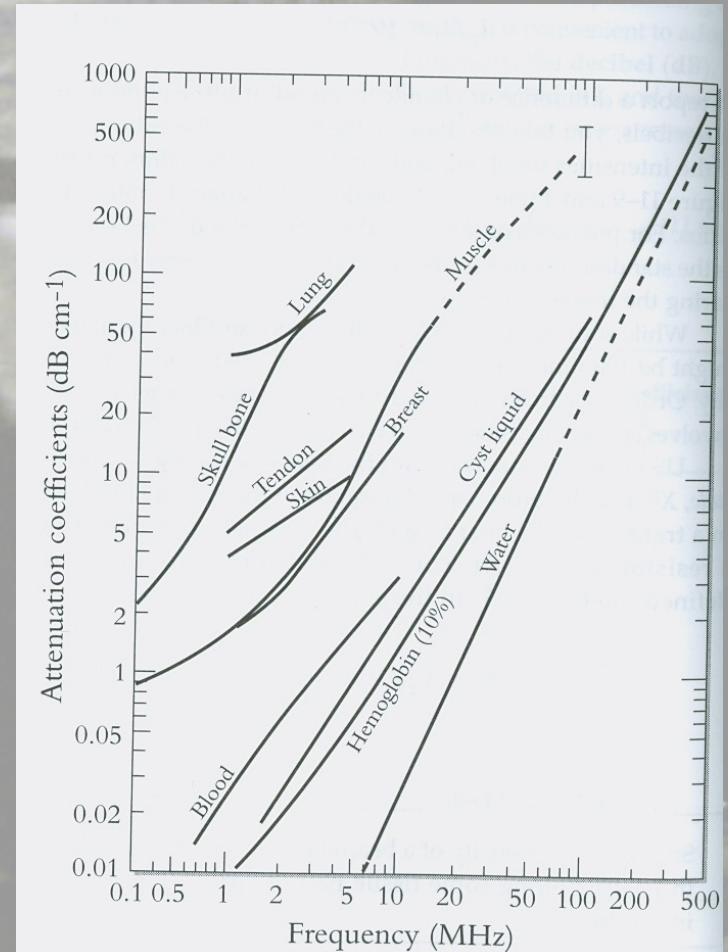


Wolbarst, Physics of Radiology, Ch. 11

**Figure 11–10** The attenuation coefficient (in dB/cm) for
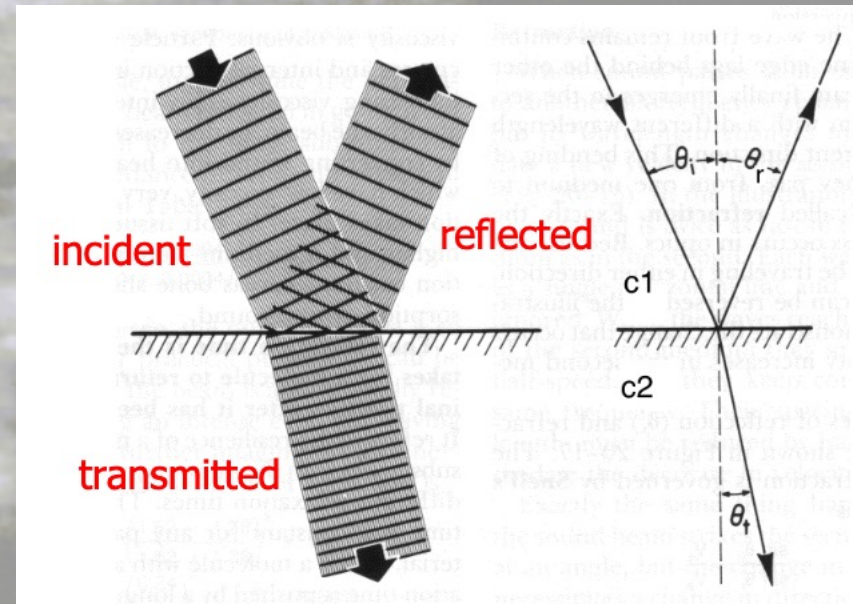
# Seeing With Sound

## - *The Physics of Ultrasound – Reflection & Refraction*

- Just like light, whenever sound energy passes from one medium in which the speed of sound is $v_1$ to another medium in which the speed of sound is $v_2$, the waves refract.

- Using the geometry of the system, the law of refraction for sound is given as:

$$\frac{\sin \theta_2}{v_2} = \frac{\sin \theta_1}{v_1}$$

- Here, like light, the frequency is constant across the interface so that the wave passes continuously from one medium to the other.

- Thus, we have a relation between the velocity and wavelength in the two media:

$$\frac{\lambda_2}{\lambda_1} = \frac{v_2}{v_1}$$



https://courses.washington.edu/bioen508/Lecture6-US.pdf

- Refraction causes distortions in the images generally leading to displacements in the image of objects in the scan and cause some loss in resolution.

# Seeing With Sound

*- The Physics of Ultrasound – Reflection at Acoustic Media Interfaces*

- So, let's return to the question of how strong an echo will be?

- For a homogeneous medium – a fluid filled cyst or a large blood vessel, US propagates and is attenuated but no echoes are formed.

- If US propagates through dissimilar tissues or organs, then multiple reflections are possible, and energy is reflected towards the transducer.

- The return time is proportional to the the distance the object is away and the velocity of sound in that material.

- The intensity of the echo depends on this distance since it will be attenuated exponentially with distance but also on the difference in physical properties of the materials (density or elasticity.)

- Sharp echoes are produced from a large flat boundary between materials that have significant physical differences.

- The reflected waves obey the law of reflection.

# Seeing With Sound

*- The Physics of Ultrasound – Reflection at Acoustic Media Interfaces*

- The elasticity of a material ($E$) along with its density ($\rho$) determine the speed of sound in the medium.

- Thus, where the velocity of sound changes abruptly is where the strongest echoes will be produced.

- This means that more intense US waves will be reflected.

- However, if two materials have similar elastic properties then the US waves will produce small reflections and most of the US will propagate into the second medium.

- The amount of reflection of sound at an interface is determined by the acoustic impedance, $Z$, of the materials.

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

- Using the definition of the velocity of sound $Z = v\rho$, where the units are $1\frac{kg}{m^2 s} = 1Rayleigh = 1Rayl$.

# Seeing With Sound

*- The Physics of Ultrasound – Reflection at Acoustic Media Interfaces*

- Why the acoustic impedance?

    Analogous to an index of refraction

- Thus, we can write the reflection coefficient in terms of the acoustic impedance (and we would most likely turn this into some number of dBs of energy loss after the US beam reaches the receiver).

$$\frac{I_{reflected}}{I_{incident}} = R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

- And the transmission coefficient: $T = 1 - R$

- The greater the difference in $Z$'s the larger the reflection coefficient, $R$ and the strongest echoes are from the largest changes in density, since $Z$ is proportional to $\rho$.

- How much of an US wave is reflected at a muscle-fat interface?  How much is transmitted? $\left(Z_{muscle} = 1.7 \times 10^6 \frac{kg}{m^2 s}; \; Z_{fat} = 1.38 \times 10^6 \frac{kg}{m^2 s}\right)$

- Compare to muscle-bone or muscle-air. $\left(Z_{air} = 400 \frac{kg}{m^2 s}; \; Z_{bone} = 5 \times 10^6 \frac{kg}{m^2 s}\right)$

# Seeing With Sound

*- The Physics of Ultrasound – B or Brightness-type Scans*
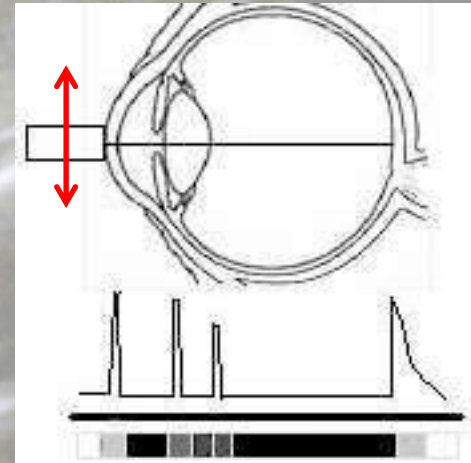
- From before, we've had A –or amplitude-type scans and these give a one-dimensional view of an object. We'd like more spatial information.

- We would still like distance information, but we'd also like to see the variation in US intensity from place to place.

- To do this we fan the US beam out across the transducer and then move the transducer across an area of the body producing what's called a B-type (or Brightness) scan.

- B-type scans are a combination of many A-type scans that are displayed on a computer or TV screen.

- The shades of gray from the A-type scans, when placed next to each other in a plane, form the B-type scan and this then forms the image in a 2D plane.
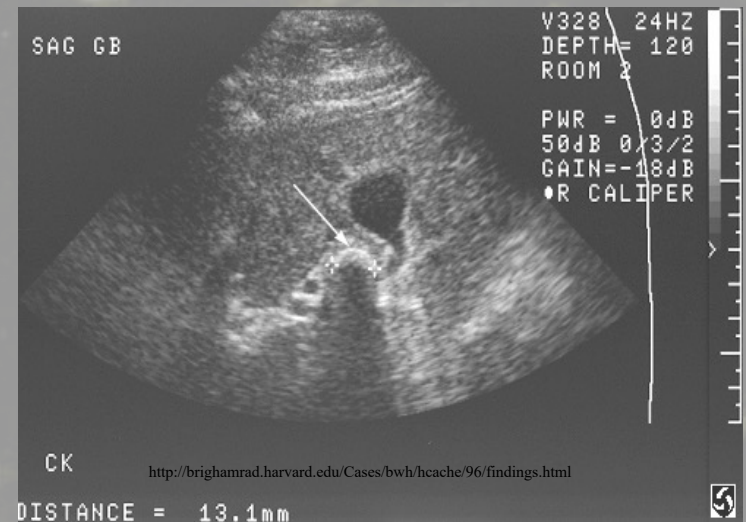


http://www.genesis.net.au/~ajs/projects/medical_physics/ultrasound/index.html
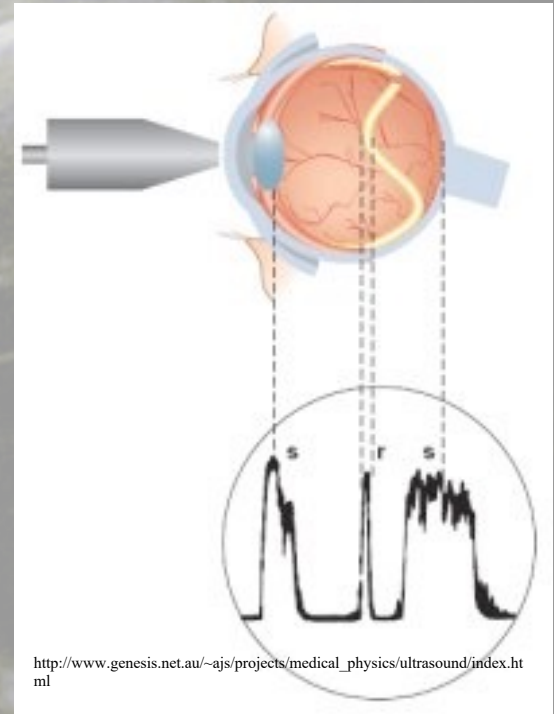
# Seeing With Sound

*- The Physics of Ultrasound – B or Brightness-type Scans*

- A single pulse of ultrasound passing into a series of tissues will give rise to a series of spots, with the brightness of the spots corresponding to the amplitude of the reflection from different layers.

- The largest amplitude gives rise to a spot with the greatest brightness, and this corresponds to white.

- The smallest amplitude corresponds to a black spot.

- Intermediate amplitudes give us various shades of gray.

- The area that does not give rise to any spike for example, the aqueous and the vitreous of the eye will appear black. (No echoes)
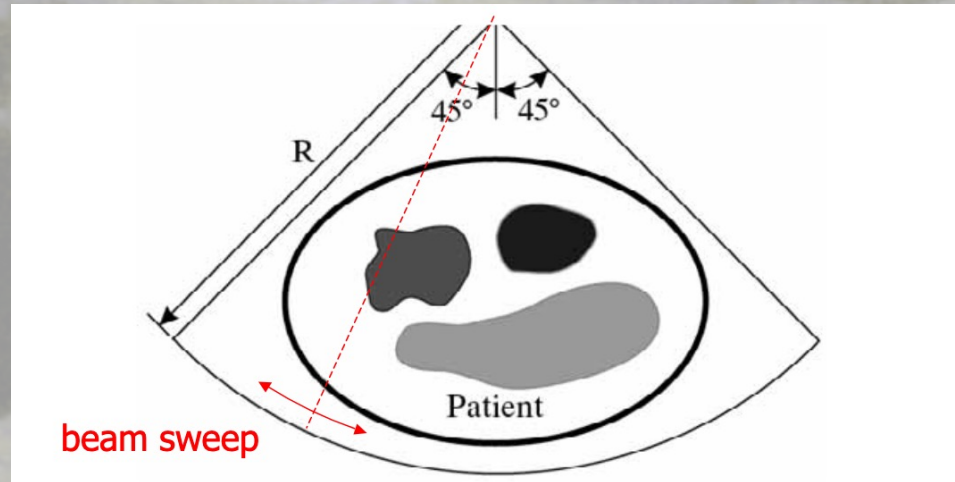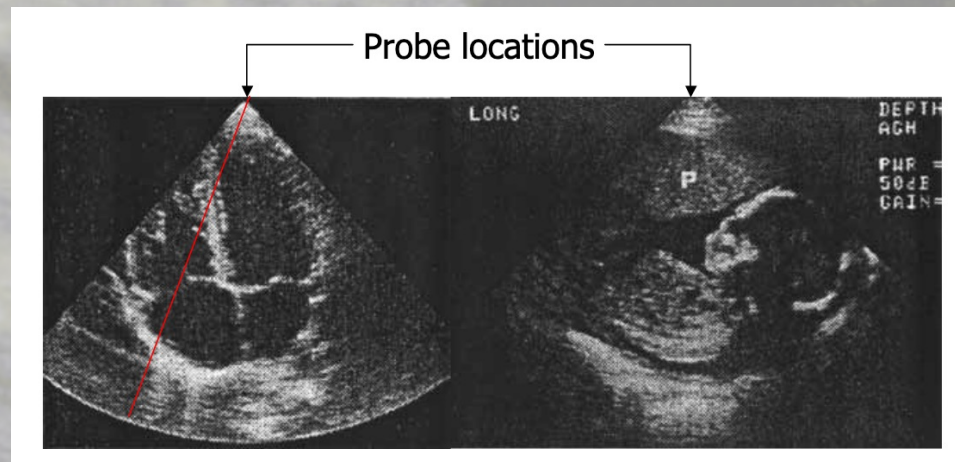


http://www.mrcophth.com/commonultrasoundcases/principlesofultrasound.html#B%20in



http://brighamrad.harvard.edu/Cases/bwh/hcache/96/findings.html

US image of a gallstone lodged in the cystic duct.

# Seeing With Sound

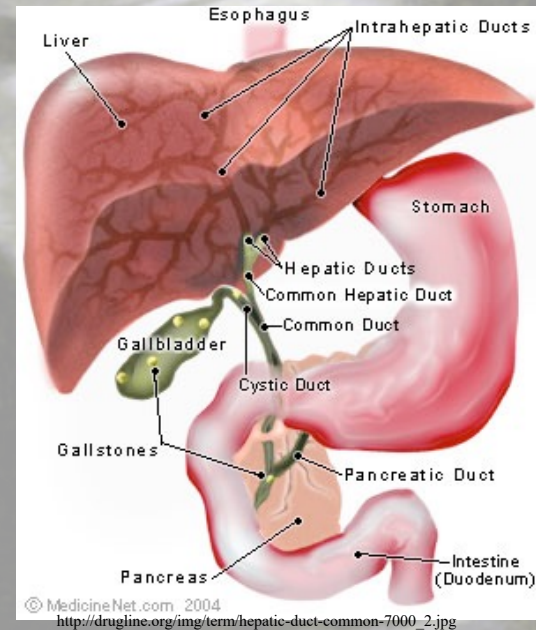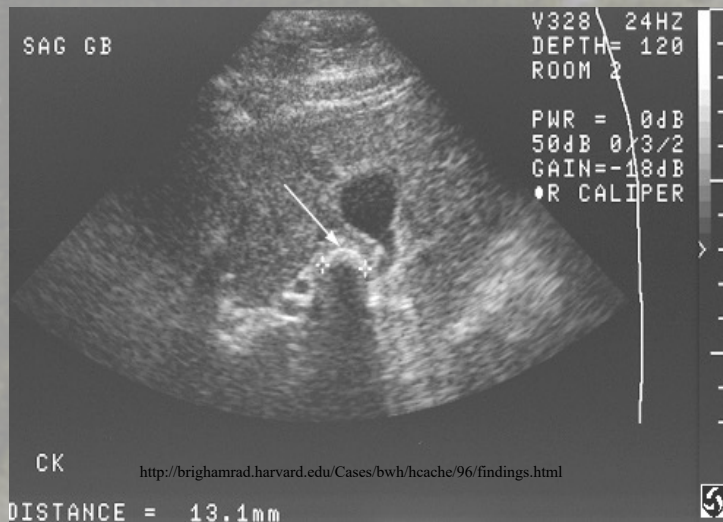*- The Physics of Ultrasound – B or Brightness-type Scans*



beam sweep

https://courses.washington.edu/bioen508/Lecture6-US.pdf



https://courses.washington.edu/bioen508/Lecture6-US.pdf

# Seeing With Sound

*- The Physics of Ultrasound – B or Brightness-type Scans*



http://brighamrad.harvard.edu/Cases/bwh/hcache/96/findings.html



http://drugline.org/img/term/hepatic-duct-common-7000_2.jpg

How is the transducer oriented in the image and with respect to the patient?

What do you think you are seeing in this image?

# Seeing With Sound

*- The Physics of Ultrasound – B or Brightness-type Scans*



https://www.youtube.com/watch?v=-Z5066OO-oI&t=86s

https://www.gtsimulators.com/products/fast-exam-real-time-ultrasound-training-model-bp-fast1800

# Seeing With Sound

*- The Physics of Ultrasound – Advantages of US*

- Ultrasound examinations are non-invasive i.e., they do not require the body to be opened, or anything to be inserted into the body. This is a major advantage compared to fiber optic endoscopy, for example, which may involve much more patient discomfort as the probe is inserted.

- Ultrasound methods are relatively inexpensive, quick and convenient, compared to techniques such as X-rays or MRI scans. The equipment can be made portable, and the images can be stored electronically.

- No harmful effects have been detected, at the intensity levels used for examinations and imaging. This contrasts with methods based on X-rays or on radioactive isotopes, which have known risks associated with them, and ultrasound methods are preferred whenever possible. This is particularly relevant to examination of expectant mothers.

- Ultrasound is particularly suited to imaging soft tissues such as the eye, heart and other internal organs, and examining blood vessels.

# Seeing With Sound

*- The Physics of Ultrasound – Disadvantages of US*

- The major disadvantage is that the resolution of images is often limited. This is being overcome as time passes, but there are still many situations where X-rays/MRI produce a much higher resolution.

- Ultrasound is reflected very strongly on passing from tissue to gas, or vice versa. This means that ultrasound cannot be used for examinations of areas of the body containing gas, such as the lung and the digestive system.

- Ultrasound also does not pass well through bone, so that the method is of limited use in diagnosing fractures. It is possible to obtain quite good ultrasound scans of the brain, but much greater detail is obtained by an MRI scan.

- If the sound waves are focused in one area for a long time, this can lead to heating in that area.

- Also, focused sound waves incident on gas bubbles, for example, can lead to cavitation, or the expanding and collapsing of the bubble.  This is a very powerful process.  This could be helpful say in dissolving a blood clot or not helpful and could lead to damage in tissue cells.