BME 200
Bioimaging - Lesson 13
Oct, 6, 2020

By the end of this lesson students will be able to:

- Given two of wavelength, speed of light, and frequency, calculate the third.
- Calculate the energy or frequency associated with electromagnetic radiation, calculate the other.
- Calculate one of number of transmitted x-rays, number of incident x-rays, tissue linear attenuation, and tissue thickness, given all others.
- Calculate the half-layer value of tissue.
- Explain how x-rays can produce medical images.
- Explain how ultrasound can produce images.
- Calculate the time required for an ultrasound signal to travel through one or more tissues.
- Explain how ultrasound can estimate blood velocity.
- Given two of speed of sound in tissue, tissue thickness, and time, calculate the third.
- Calculate one of speed of sound in blood, frequency change, initial frequency of transmitted signal, velocity of blood flow, and transducer angle, given all others.

I. Biomedical Imaging
  A. In the field of biomedical imaging, we define an *image* as a representation of a measurable property that varies with space and time
  B. General imaging system components
    1. Overall block diagram of an imaging system

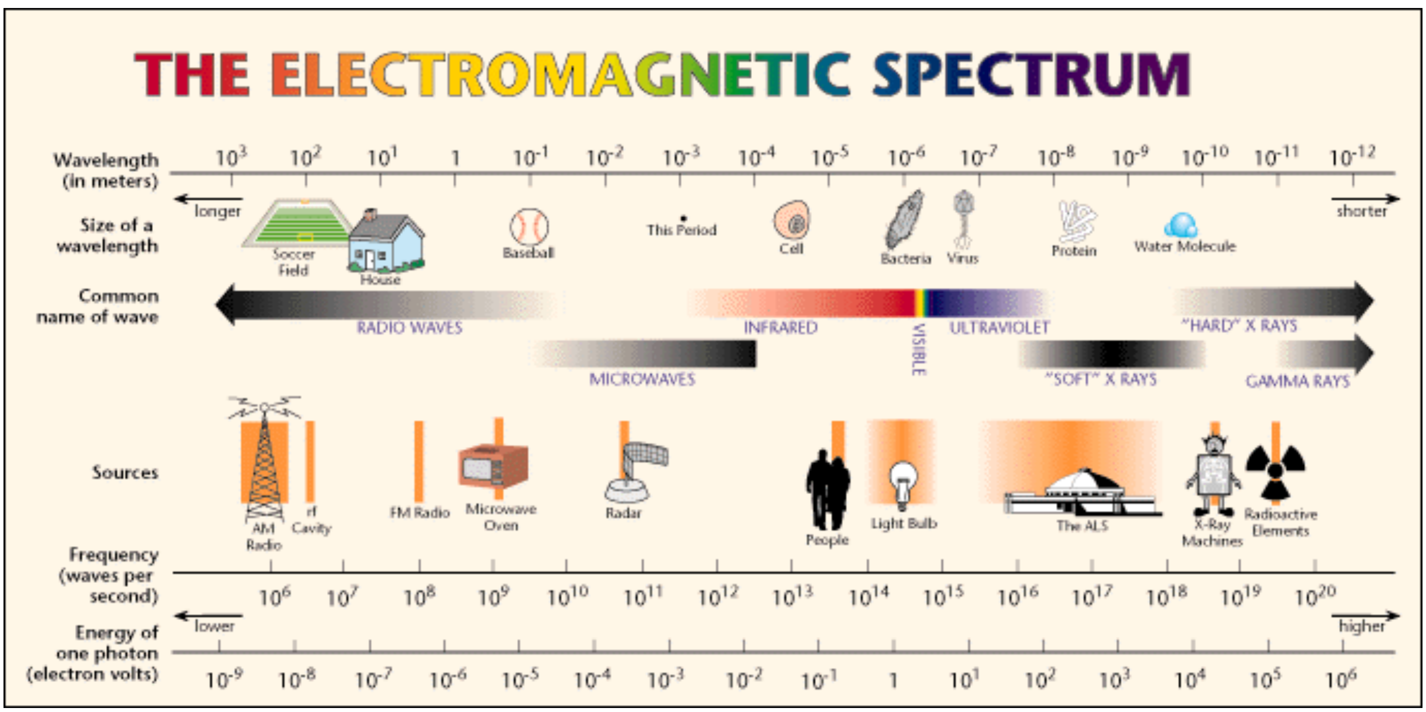
    2. Energy source interacts with target to produce a signal
      a) A contrast agent may be required to highlight a structure or function
    3. Transducer converts signal to an electrical signal (usually voltage) which is then most often converted to an image.
  C. Sometimes you will hear the term *imaging modality*. Modality is another word for method, and is used to distinguish among x-ray, MRI, ultrasound, etc.

II. X-rays and CT
  A. Electromagnetic radiation
    1. EM basics

a) Wavelength

b) Energy

2. Spectrum of different wavelengths
   a) Visible light
   b) Radio waves
   c) Microwaves (don't damage DNA)
   d) x-rays (can damage DNA); wavelength 0.1 nm



3. Ionizing radiation
   a) EM radiation has enough energy to knock electrons out of atoms within a material (i.e., to ionize them)

b) In biological organisms, ionizing radiation damages the DNA (from minor damage to double strand break); this is why ionizing radiation is sometimes used to treat cancer—you're basically trying to damage the cancer DNA beyond repair
    (1) Radiation therapy

4. X-rays
    a) Two properties useful for imaging:
        (1) They are the ideal wavelength to go through the human body and they are partially absorbed by whatever they hit.
        (2) An x-ray photon will create a spot on photographic film; you can take a "picture" using x-rays as the light source.
            (a) This is the hand of Röntgen's ("Rent-gen") wife.

b) Image properties
   (1) Compared to the original work by Röntgen, today's x-ray images are reversed. Here is a broken arm:

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   (2) Features of note:
      (a) Darker = less dense
      (b) Brighter = more dense
      (c) Is a shadow of a 3D object; this is called a *projection.*

c) Model for x-rays
   (1) Here is a setup for an average x-ray system:

   (2) We can model the number of x-rays that make it through tissue with the equation

- μ is tissue linear attenuation
- N_0 is the number of incident x-rays
- N is the number of x-rays transmitted through a tissue of thickness x

(3) HVL = half-value layer. This is the tissue thickness that attenuates (reduces) incident x-rays by 50%

(4) But what if you have more than one tissue type? You can model how x-rays travel through it using this strategy.

(5) Student exercise. Assume the upper arm of a body-builder has a diameter of 16 cm and consists of only muscle tissue (no skin, bone, etc.). If the incident x-ray energy is 45 keV and the HVL of muscle is 3.5 cm, what percentage of x-rays would be transmitted through the tissue?

d) Terms often used with x-ray imaging
   (1) **Contrast** = difference in density between two materials
   (2) **Contrast agent** = agent that can be added to create a difference in density
   (3) **Fluoroscopy** = dynamically changing x-rays (e.g., stent delivery); called this because used to use a fluorescent screen instead of film to visualize

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https://edc2.healthtap.com/ht-staging/user_answer/reference_image/9428/large/Fluoroscopy.jpeg?1386670479

5. CT
   a) **CT** = Computed Tomography
   b) CT uses computers and many images from 2D x-rays to create a 3D representation
   c) A CT machine images slices by rotating around a patient and then slides the table (patient) to get the next slice
   d) **Radiodensity** = the degree of x-ray attenuation caused by the local density and composition of tissue (e.g., bone has high radiodensity, water very low)

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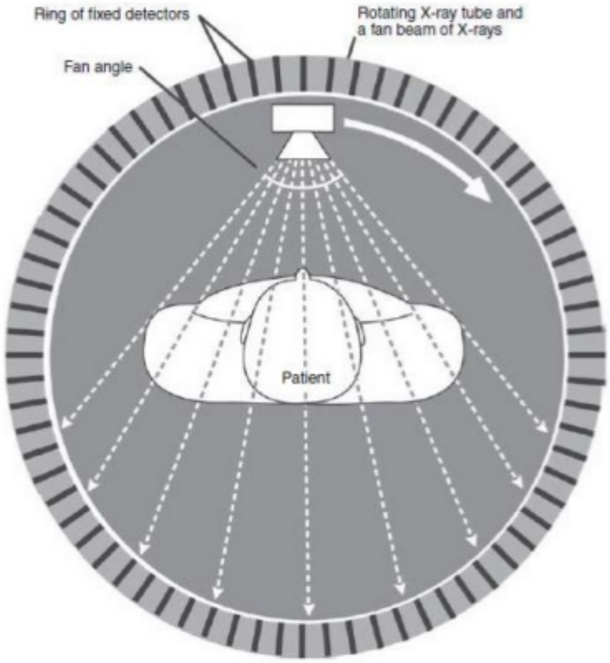
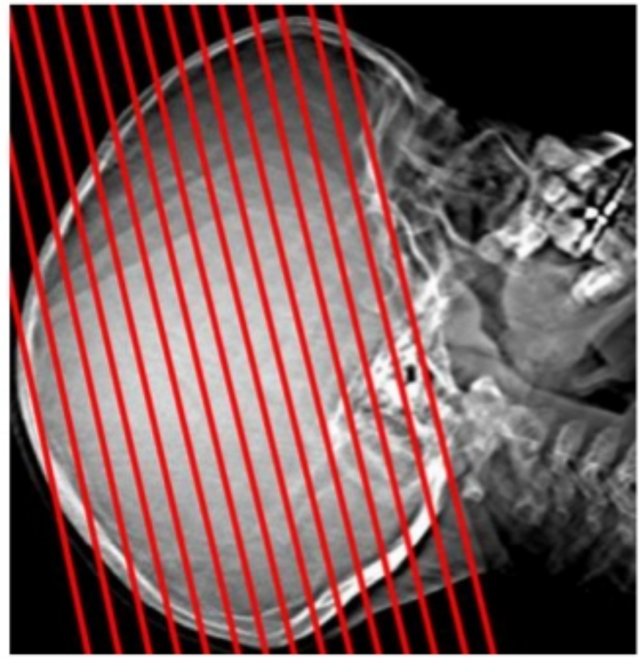
PRINCIPLES OF CT………





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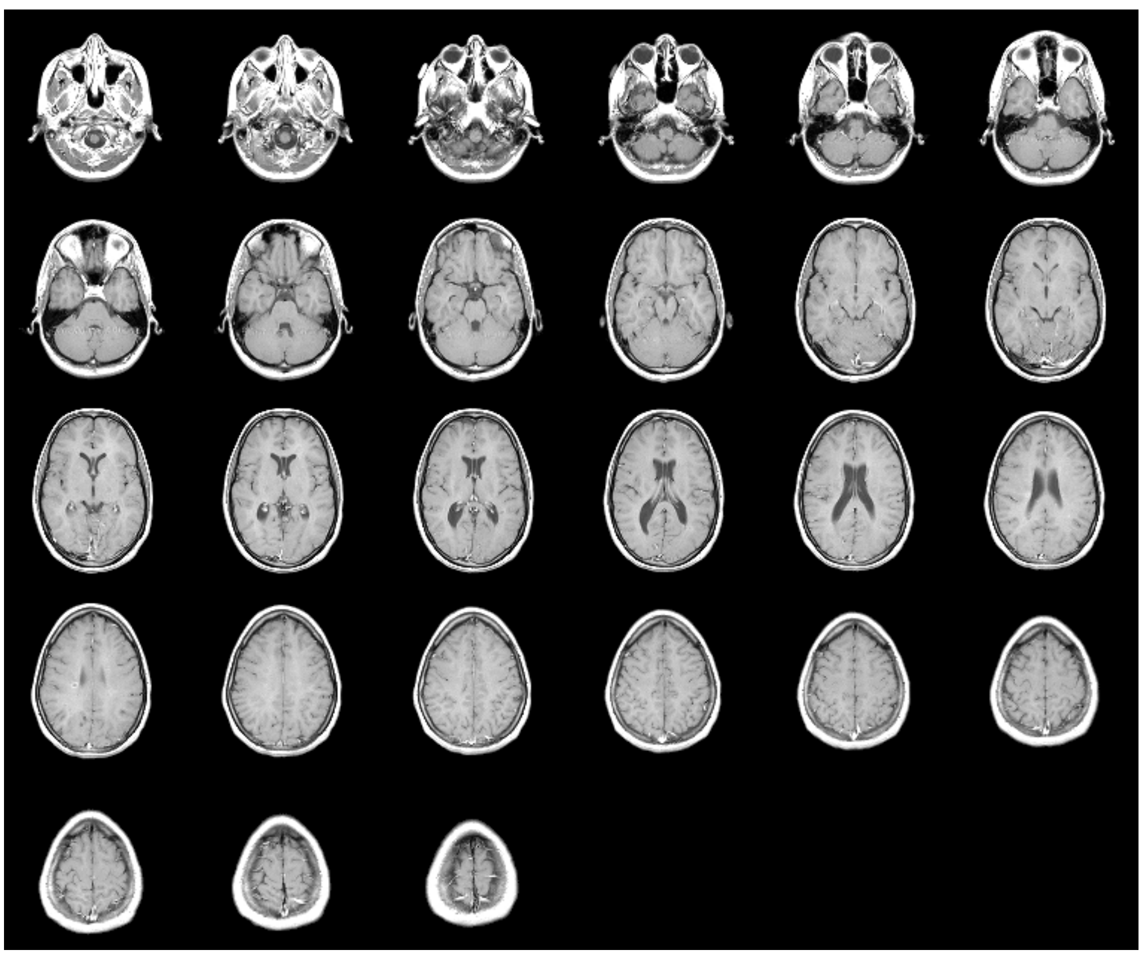

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III. Ultrasound Imaging

A. Whereas x-rays and CT use electromagnetic radiation to create images, ultrasound uses sound waves to create images.

B. Pros and cons

1. Pros
    a) Can make images quickly, and at the point of care (e.g., in a battlefield or at a patient's house)
    b) Portable
    c) Does not use ionizing radiation to create an image; generally safer than x-rays/ct
    d) Can be used therapeutically to treat disease (e.g., lithotripsy)
2. Cons
    a) Cannot image through very dense tissue (e.g., bone)
    b) Cannot image through air (e.g., lungs)
    c) Cannot image as deep into tissue as x-ray/ct
    d) Can cause tissue damage (heat & mechanical disruption) if the energy is too high

C. 1D Image Generation

1. Ultrasound can be used to generate different types of images. A 1D image may not seem useful, but it can be used to image blood flow velocity within vessels.
    a) Helps physicians diagnose narrowed arteries
    b) Also called Doppler velocimetry.
2. How ultrasound transducers work
    a) Piezoelectric crystals convert voltage to mechanical vibrations (sound)
    b) These crystals can also convert sound to voltage
        (1) In short, the crystals act as both a speaker and a microphone
    c) Typical ultrasound frequencies: 2–13 MHz
        (1) What is the typical upper limit on human hearing?
    d) The ultrasound transducer alternates b/w transmit and listen many times (up to millions of times) per second

3. Velocimetry makes use of the Doppler effect and measures the change in frequency, or the *frequency shift*, of the signal.
4. Doppler effect: coming toward you, wavelength shorter (higher frequency); moving away wavelength longer (lower frequency)

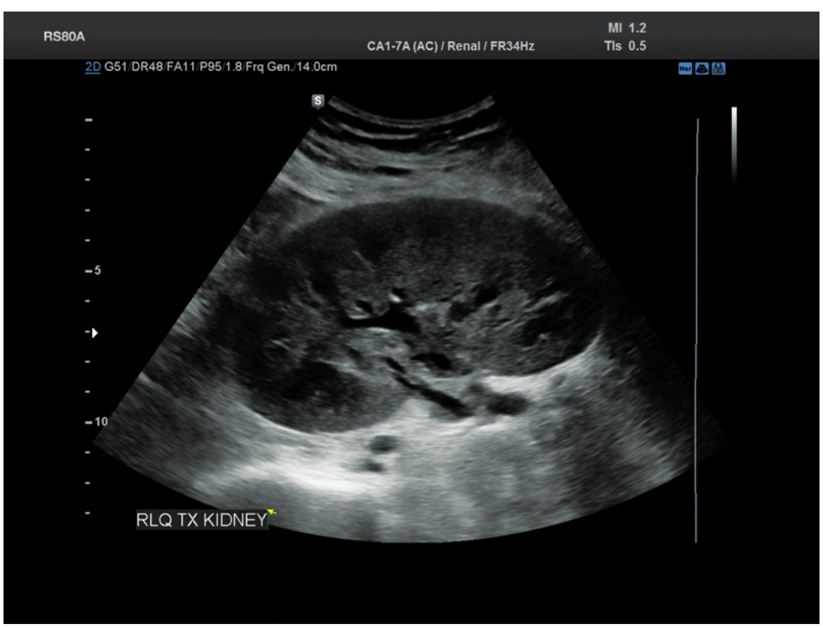
5. We use this principle to measure frequency of blood flow in vessels

6. Can calculate velocity with this formula:

7. Student example. Assume that you measure the flow velocity of blood in a patient using an ultrasonic probe with $f_i = 5$ MHz and a probe angle of 45°. Assume $c_{blood} = 1540$ m/s and that the observed frequency shift is $f_D = 1.7$ kHz.
   (a) What is the velocity of blood?
   (b) Assume that you give the patient a bag of saline and this changes the frequency shift to $f_D = 1.9$ kHz. What is the new speed of sound in blood?

D. 2D Image Generation
   1. 2D ultrasound images are created by sending out signals and listening for the time it takes to receive an echo
   2. Different tissue types have different speeds of sound and we can use this information to piece together the thicknesses and kinds of tissue the ultrasound has traveled through.
   3. Whenever ultrasound hits a tissue interface (e.g., between muscle and fat), some of the wave is reflected back and can be measured by the ultrasonic transducer
   4. Here's an example
   5. 2D ultrasound produces plane images (e.g., slices of things or a cross-section) because it's only listening for waves from a particular plane
   6. In order to form an image, it needs to measure many planes and then display them all together
   7. B-Mode imaging
      a) B-Mode imaging is a mode of ultrasonic imaging that uses a sweeping motion to measure a range of locations within tissue

b) This mode of imaging is used to check on the health of a fetus (fetal ultrasound)
c) Each radial line (100 or more) contains pixels of different brightness (hence B-mode)
d) Brightness is proportional to the echo amplitude (higher echo means more reflected), and indicates different types of tissues or in the case of fetal ultrasound, also amniotic fluid



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8. Speed of sound in body must be known to gauge different types of tissue
9. We assume that in general it is approximately 1540 m/s (i.e., the speed of sound in water) but in reality it will +/- 100 m/s or so depending on material
10. Each interface has its own reflection coefficient, e.g.,
    a) Liver-fat will appear brighter than liver-kidney
11. Student example. How long would it take to get an echo back from the surface of an artery if it sits under 5 mm of fat and 3 mm of muscle? Assume $c_{fat} = 1430$ m/s and $c_{muscle} = 1540$ m/s.