Module 6 Particles & Medical Physics

Module 6: Particles and medical physics

In this module, learners will learn about capacitors, electric field, electromagnetism, nuclear physics, particle physics and medical imaging.

Module 6 Particles & Medical Physics

Unit 5 Medical Imaging

6.5 Medical imaging

This section provides knowledge and understanding of X-rays, CAT scans, PET scans and ultrasound scans. This section shows how the developments in medical imaging have led to a number of valuable non-invasive techniques used in hospitals.

Not all hospitals in this country are equipped with complex scanners. Learners have the chance to discuss the ethical issues in the treatment of humans and the ways in which society uses science to inform decision making (HSW9,10,12).

Module 5 – Newtonian world and astrophysics

5.1 Thermal physics

5.2 Circular motion

5.3 Oscillations

5.4 Gravitational fields

5.5 Astrophysics and cosmology

Module 6 – Particles and medical physics

6.1 Capacitors

6.2 Electric fields

6.3 Electromagnetism

6.4 Nuclear and particle physics

You are here! → 6.5 Medical imaging

6.5 Medical Imaging

- 6.5.1 Using X Rays
- 6.5.2 Diagnostic Methods in Medicine
- 6.5.3 Using Ultrasound

6.5.1 Using X Rays

6.5.1 Using X-rays

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) basic structure of an X-ray tube; components – heater, cathode and target metal

(b) production of X-ray photons from an X-ray tube

(c) X-ray attenuation mechanisms; simple scatter, photoelectric effect, Compton effect and pair production.

(d) attenuation of X-rays; $I = I_0 e^{-\mu x}$, where μ is the attenuation (absorption) coefficient

(e) X-ray imaging with contrast media; barium and iodine

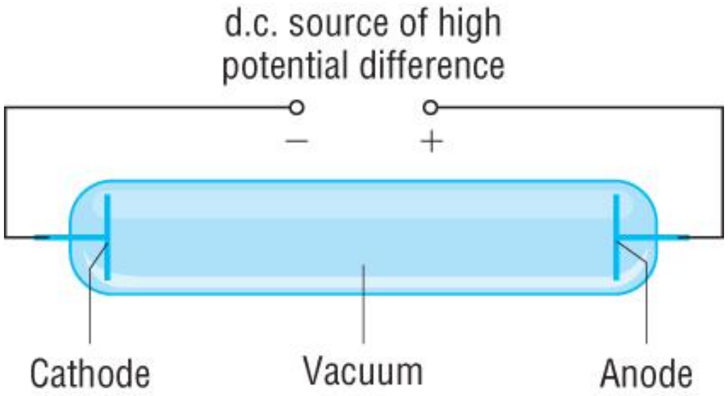
(f) computerised axial tomography (CAT) scanning; components – rotating X-tube producing a thin fan-shaped X-ray beam, stationary ring of detectors, computer software and display

(g) advantages of a CAT scan over an X-ray image.

What are X-rays and where do they come from?

X-Rays

- First discovered by Wilhelm Roentgen in 1895.
  - He was using equipment similar to that used to produce the first electron beams – a discharge tube.
  - He was investigating the light emitted by different gases inside the tube.
  - He noted that if the pressure inside the tube was very low, a fluorescent plate near the tube started to glow.
  - He also saw a shadow on the plate in the shape of his bones if he put his hand in front of it.



Roentgen's new finding

- He realised that something must be being produced which passes through the soft tissues of his hand but is stopped by the denser bones.
- He placed a photographic plate near the discharge tube instead of the fluorescent screen and asked his wife to place her hand in front of it.
- The photo he took is the first X-Ray image

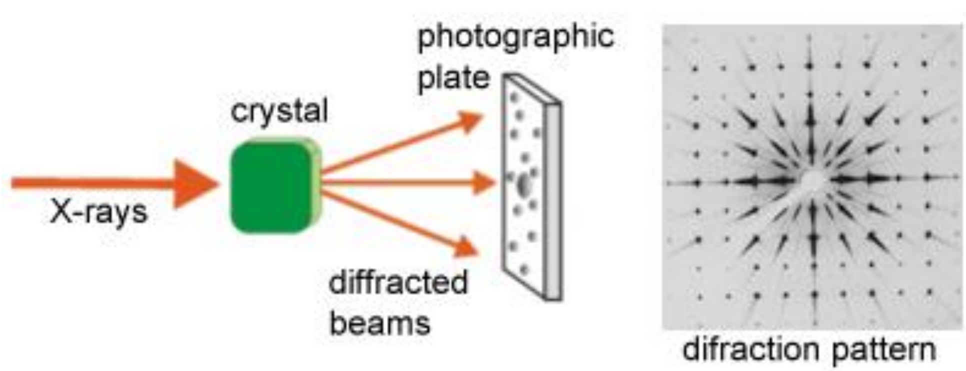
Are Roentgen's Rays (now known as X-Rays) Waves or Particles?

- Following his discovery, this was the next question to be answered.

1906 – Charles Barkla showed that X Rays could be polarised.

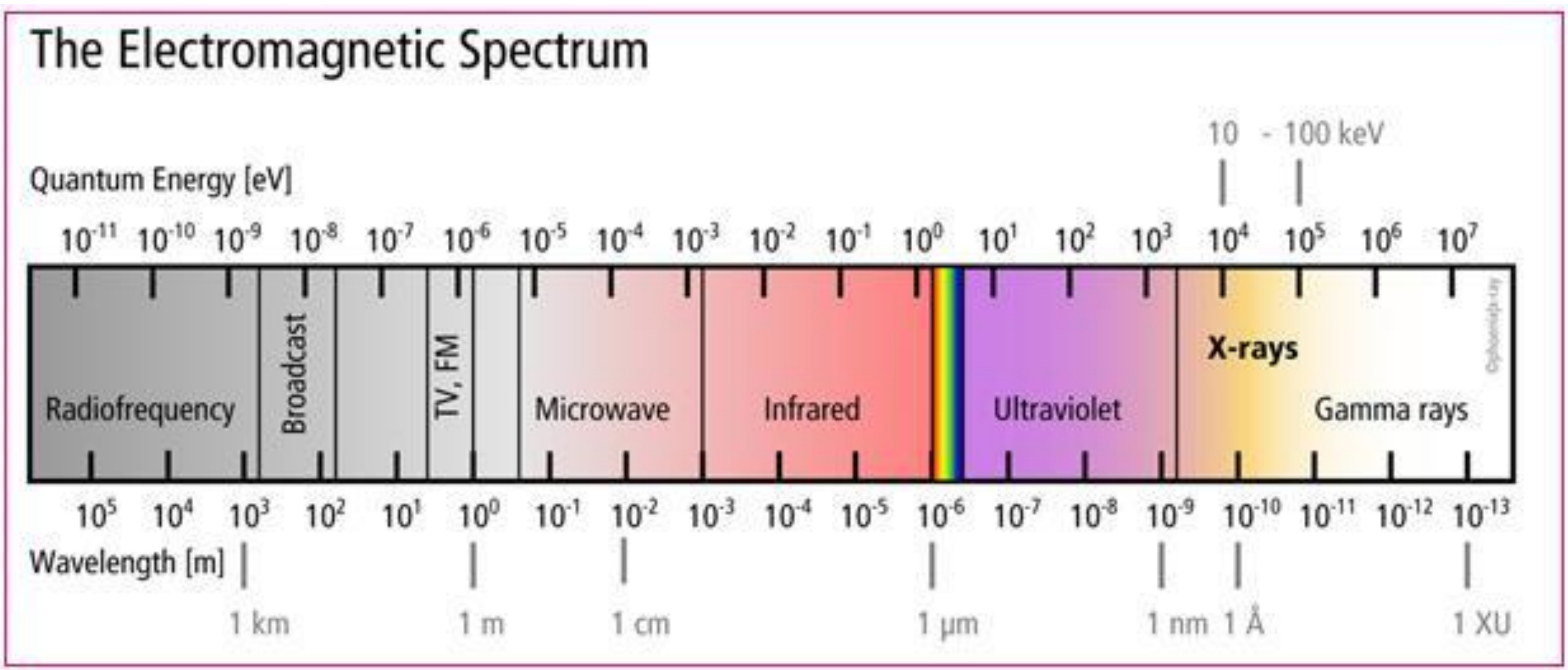
1912 – Arnold Sommerfeld estimated their wavelength.

Later, Max von Laue managed to cause diffraction of X-Rays using the regular array of atoms in a crystal as the diffraction grating (the distance between the atomic nuclei needs to be similar to the wavelength of the X-Rays).



We now know X-Rays are Electromagnetic Waves

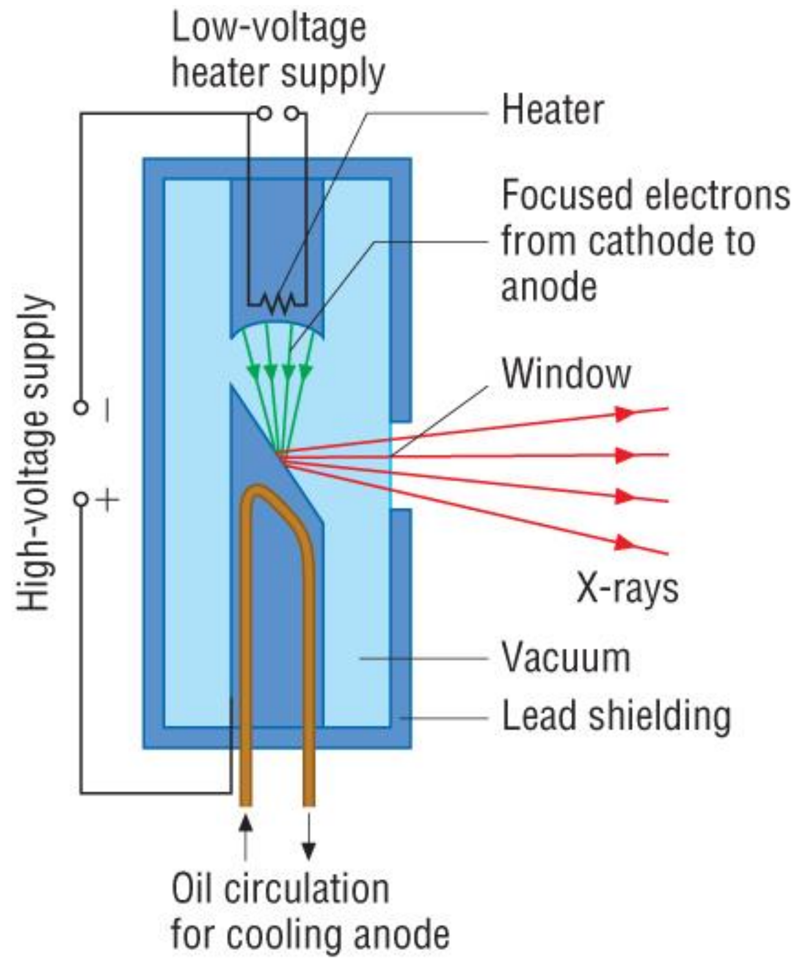
- X-Ray Wavelength: 10^{-12} to 10^{-9}m



(An Angstrom (1Å) = 10^{-10}m) (An X unit (XU) = 0.1pm)

Production of X-Rays

- X-Ray tubes are similar to the discharge tube Roentgen originally used:
  - They use a large voltage between a heated cathode and an anode in a vacuum.
  - The anode is angled to direct the X-Rays out through a window in the lead casing.
  - The energy output of the X-Rays is roughly 1% of the energy of the electron beam. The 99% wasted energy heats the anode which therefore needs to be cooled.



The Maximum Energy of an X-Ray Photon

- If an electron of charge e is accelerated through a potential difference V it will gain 1eV of energy.
- The energy of an X-Ray photon produced cannot be more than this (actually its a lot less).
- Since the energy of a photon is E=hf we get:

  $\mathbf{E_{max} = hf_{max} = eV}$
- Rearranging, we can get an equation for the maximum frequency of the photon:

  $\mathbf{f_{max} = eV/h}$
- Since the speed of EM radiation c = λf, we have an equation for the minimum wavelength as well:

  $\mathbf{\lambda_{min} = hc/eV}$

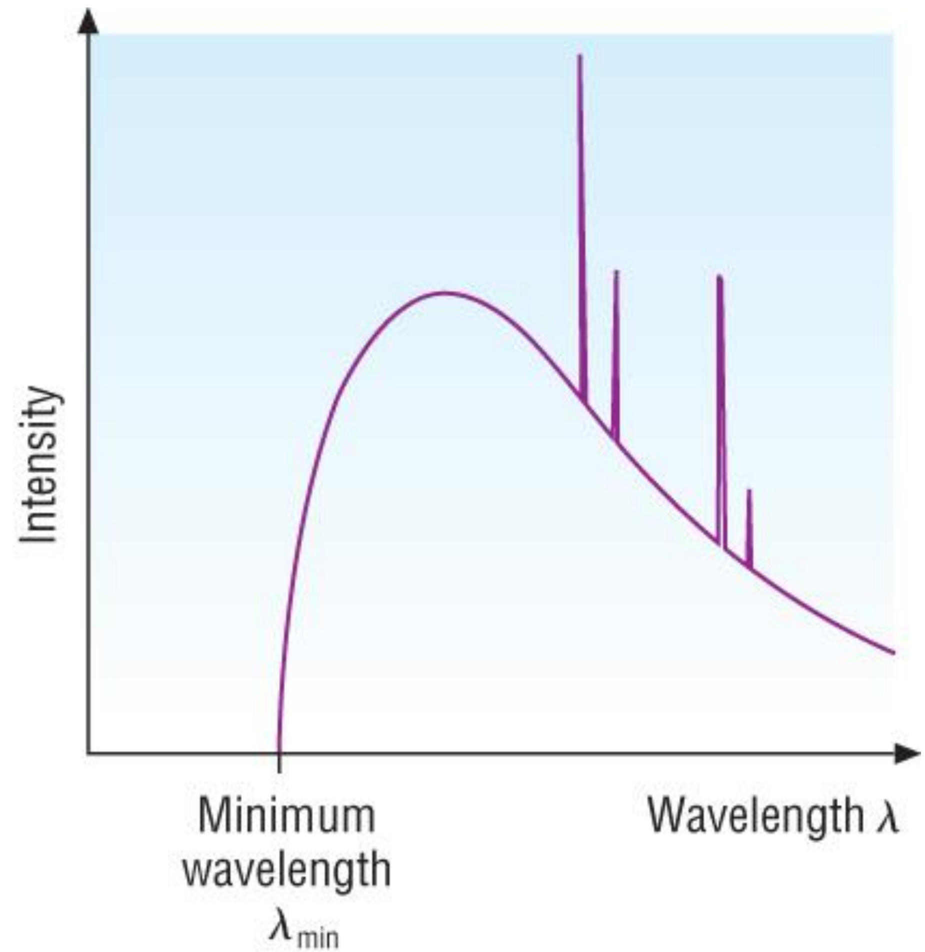
Minimum & Maximum Wavelength

- We now have a way of calculating the minimum wavelength of an X-ray photon produced by a fixed voltage in an X-ray tube ($\lambda_{min} = hc/eV$).

- So what is the maximum wavelength that could be emitted?

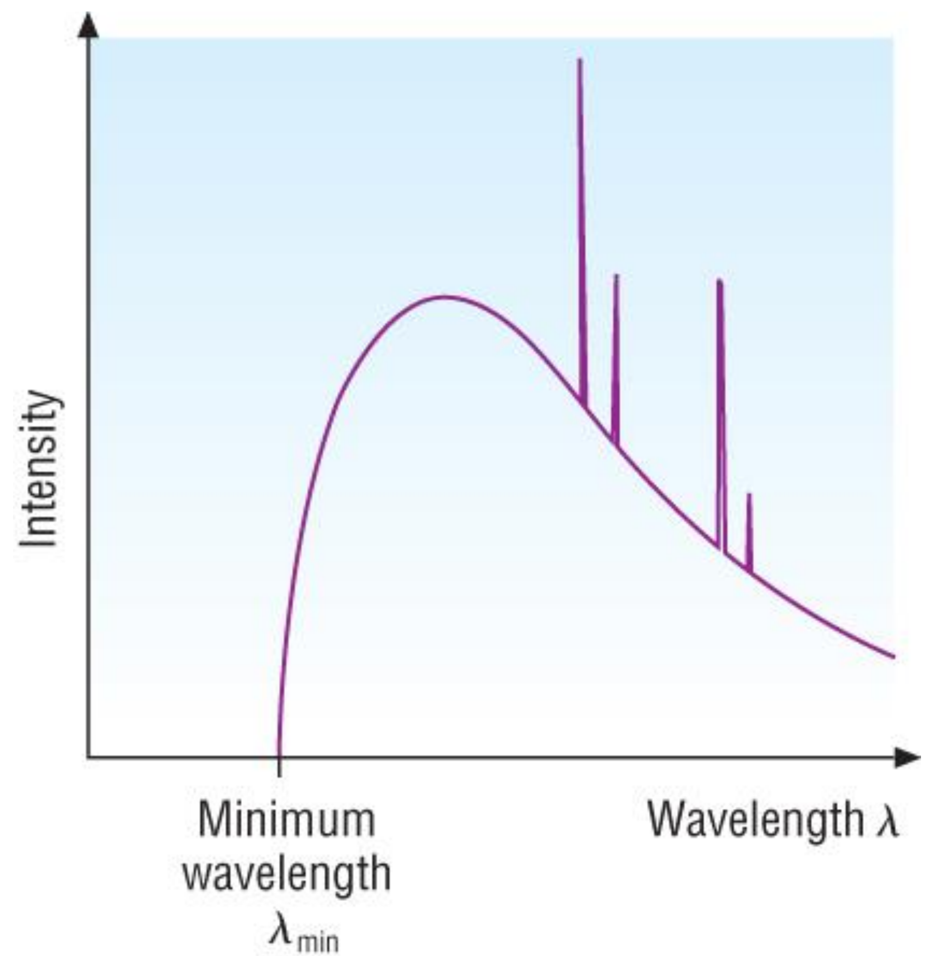
The wavelengths of X-rays

- Actually, there is a variation of wavelengths produced from the X-ray tube.
  - The intensity of each wavelength is zero below the minimum value (obviously) and also tails off at higher wavelengths.



The wavelengths of X-rays

- The graph also shows several peaks of intensities at particular wavelengths.
  - These peaks are similar to line spectra of light, these peaks are characteristic of the elements contained in the anode.
    - The high speed electrons hitting the anode dislodge electrons from its atoms. As electrons fall back into their original positions they emit X-rays at a particular wavelength.

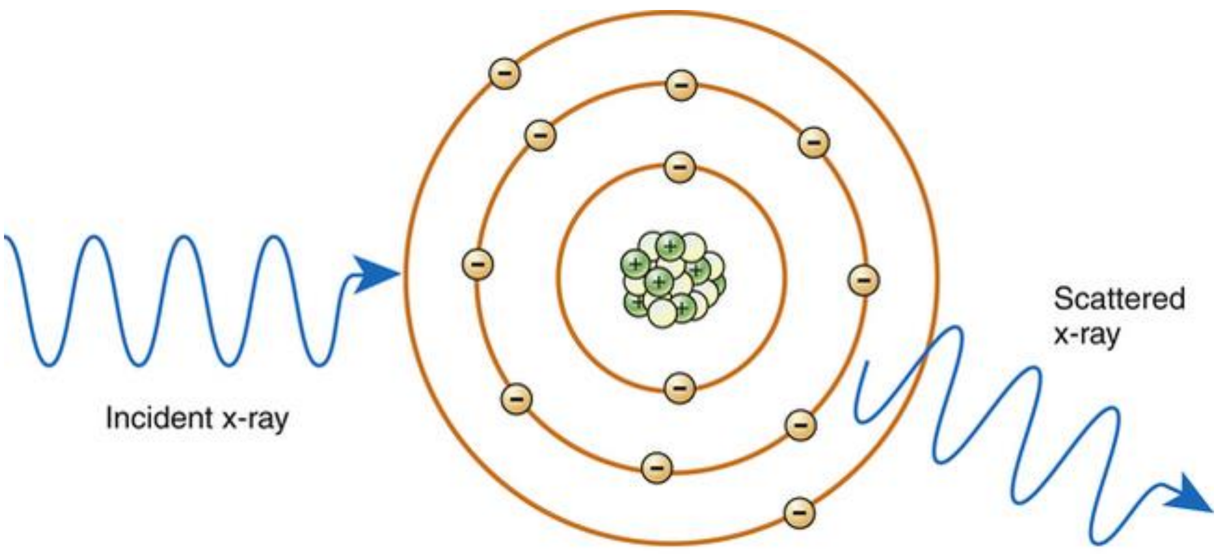


X-rays interacting with matter

- When X-rays pass through matter they are attenuated (intensity is reduced) in one of 4 ways:
  - The following 4 examples show X-rays behaving as particles:
    - **Simple scattering**
    - **The Photoelectric Effect**
    - **The Compton Effect**
    - **Pair Production**

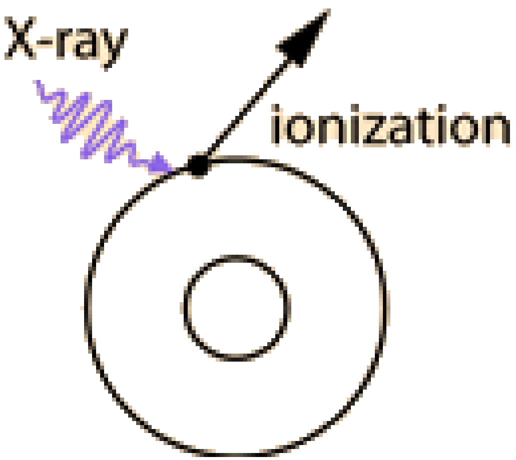
Simple Scattering

- Low energy X-ray photons (1-20keV) bounce off and are deflected by electrons in an atom.
- Their energy is not high enough to interact any more than this.



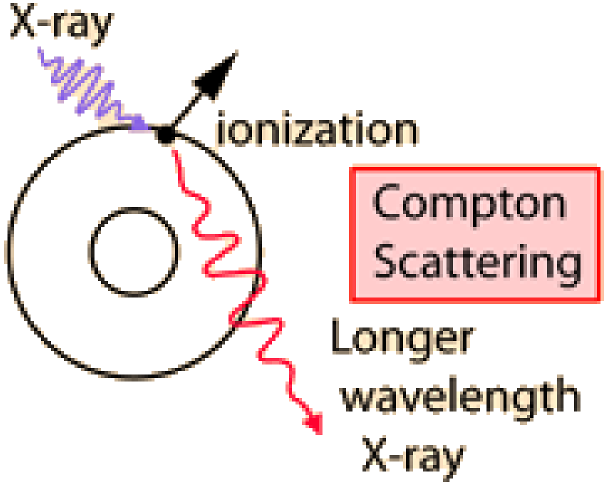
Photoelectric effect

- X-ray photons with higher energies (20-100keV) become absorbed by an electron.
- As this happens the electron escapes the atom.
- Hospitals use X-rays in this energy range.



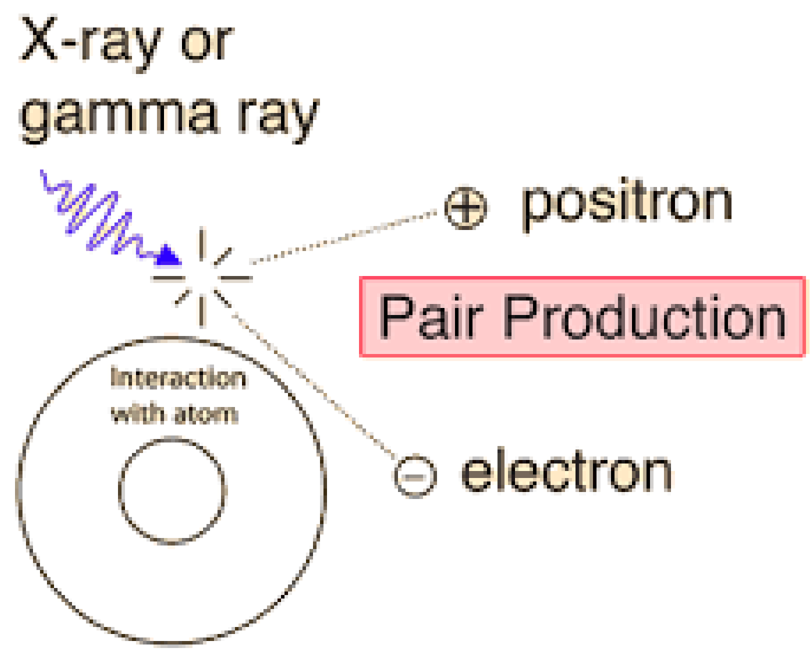
Compton Scattering

- Shown by X-rays with energies in the range 0.5-5.0 MeV.
- The incoming photon causes ejection of an electron and the photon is scattered with reduced energy.



Pair Production

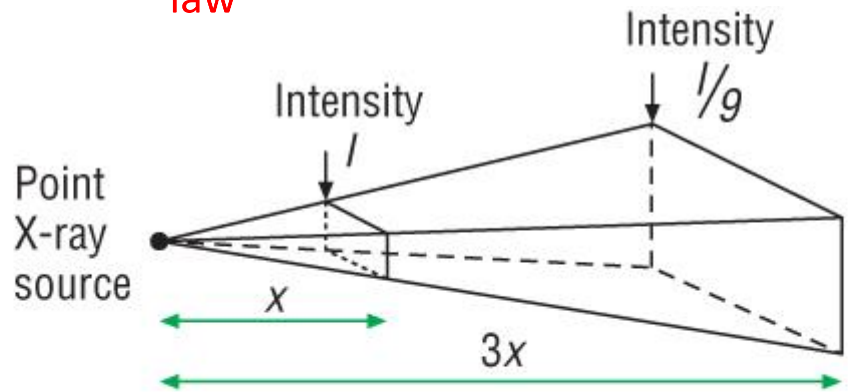
- For X-ray energies over 1.02MeV (recall the minimum energy required to create a positron-electron pair).



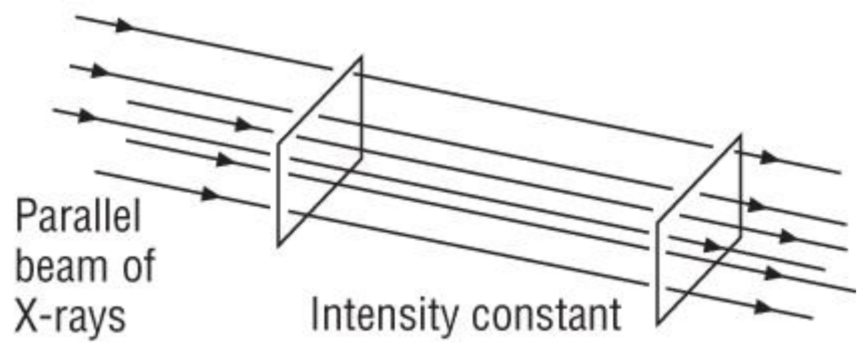
X-ray intensity

- The intensity of EM radiation is defined as power per unit cross sectional area.

Intensity follows inverse square law



- TAKE CARE
  - X-ray beams can either spread out from a point source or can be made to be collimated (run parallel to each other).
    - This will affect the intensity calculations



Intensity remains constant over distance

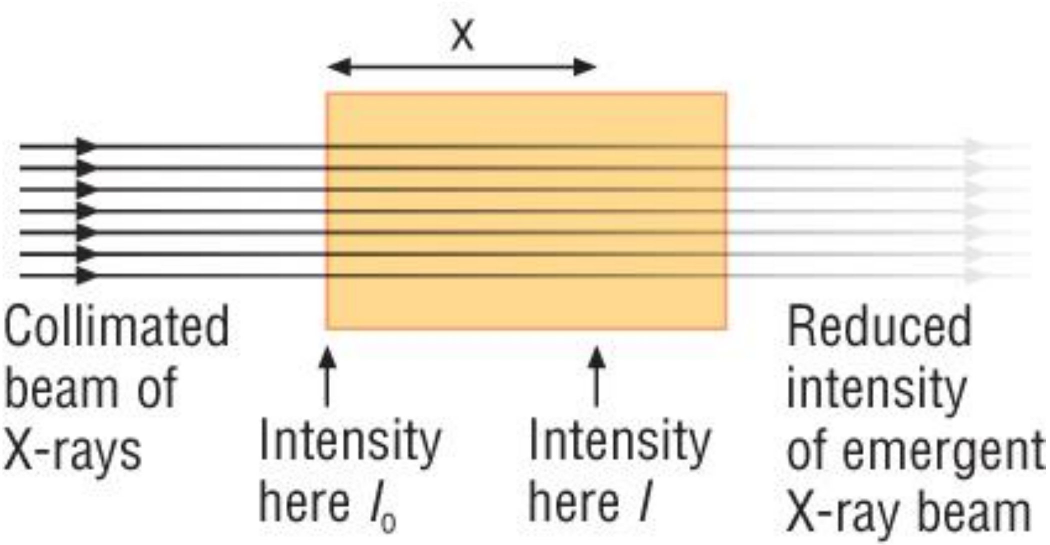
X-ray absorption

- The intensity of a collimated beam of X-rays decreases with distance as it passes through a substance.
  - The X-rays become absorbed.
- The method of absorption varies with X-ray frequency:
  - **Low frequency X-rays are absorbed by the photoelectric effect – causing electron emission.**
  - **Higher frequencies are absorbed by the Compton effect – being deflected.**
  - **Very high frequencies become absorbed by pair production – the appearance of electron-positron pairs.**

The rate of X-ray absorption

- The reduction in X-ray intensity is exponential (like radioactive decay) and obeys the equation:

$$I = I_0 e^{-\mu x}$$



Where:
I = Intensity at a particular distance from source.
I_0 = Initial intensity.
μ = The attenuation coefficient.
x = The distance through the medium.

Attenuation Coefficient

- A quantity which describes how easily a material can be penetrated.
  - A large attenuation coefficient causes an X-ray beam to attenuate (weaken) very quickly.
  - Low attenuation coefficients indicate a relatively transparent substance.
- Attenuation coefficients vary with the wavelength of the X-rays.

Half-Value Thickness

- The half-value thickness is the thickness of the material which causes the intensity of X-rays to decrease by half.
  - This is similar to the half life of a radioactive decay curve.

Medical X-ray image enhancement

- Modern medical X-ray images of body parts are much clearer than the original image of Roentgen’s wife’s hand.

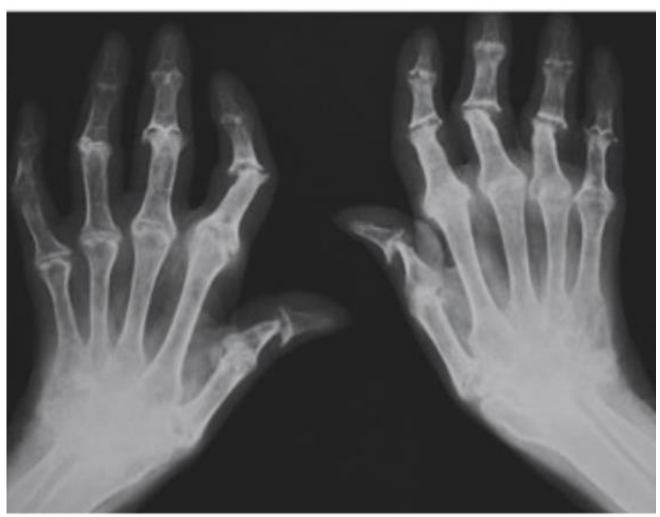


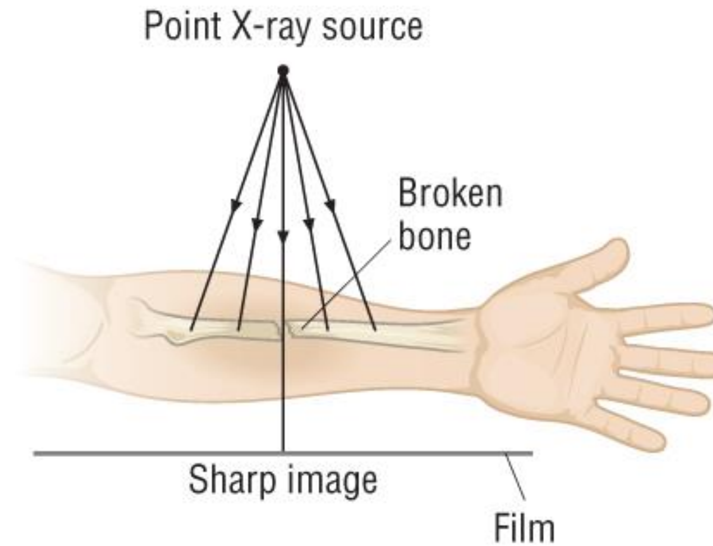
Image enhancement techniques

- Medical images can be enhanced by:
  - Using more sensitive photographic film or put a fluorescent plate behind the film.
    - Not only makes a clearer image but reduces exposure to the patient.
  - Use an X-ray absorbing material to improve contrast.
    - Barium sulfate can be given to improve contrast of the intestines (barium meal).
  - Use of digital imaging software.
    - HD digital equipment can now be used to capture motion images or still images, which are stored electronically or can be emailed/printed as required by any medical practitioner involved in a patient’s care.

Medical X-ray images

- 2D X-rays
- Angiograms
- CAT Scans

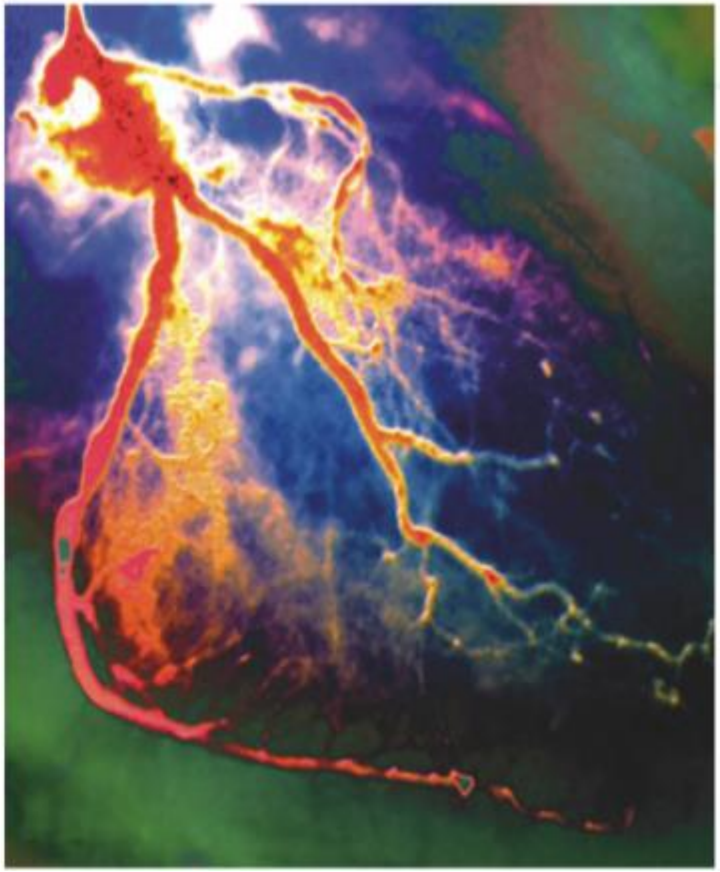
2D X-rays



- X-rays from a point source produce a sharp, clear shadow on photographic plate below.
  - Point source X-rays are used rather than extended X-ray sources.
- The radiographer needs to position the arm carefully to ensure the 2 forearm bones do not obscure one another.
  - Chest/abdominal X-rays are difficult for this reason.

Angiograms

- An X-ray image using a contrast medium to view otherwise X-ray transparent arteries.
- This image of the heart used the subtraction method:
  - A first X-ray image is taken of the heart and digitised.
  - A contrast medium is then injected into the patient's blood (iodine is often used).
  - A second digital X-ray image is then taken.
  - A computer superimposes both images, adjusts for slight movements of the patient and the subtracts one image from the other.
  - The final image shows the differences between the two, Ie. the arteries filled with contrast medium.



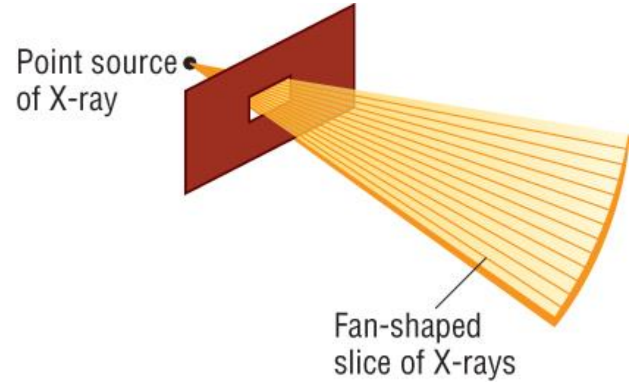
Computerised Axial Tomography

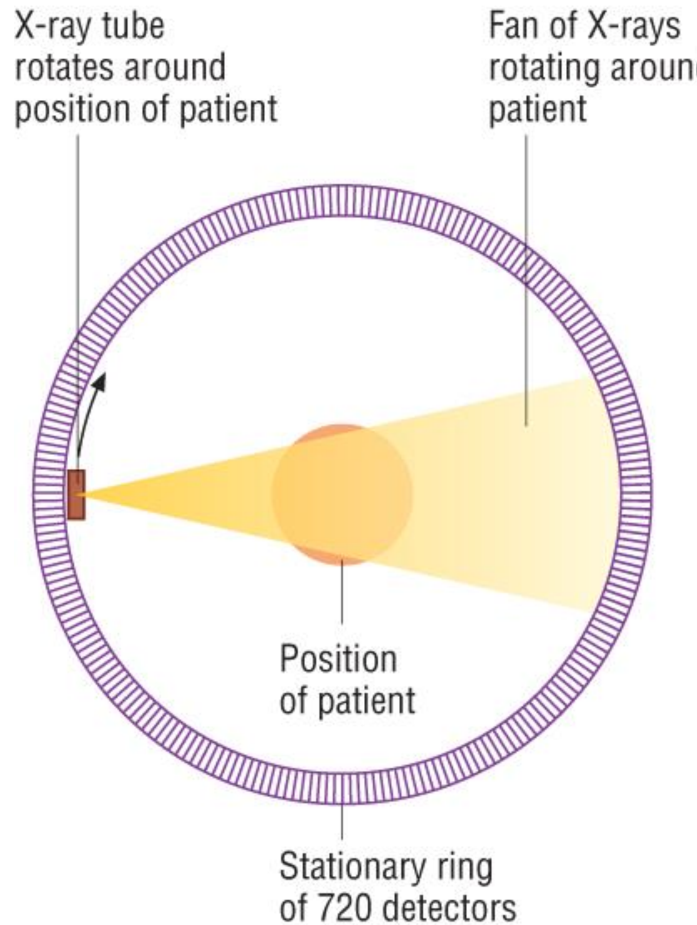
- CAT scans (or CT scans) produce 3D images of the body.
- A number of "slices" of the body are imaged and then the 3D image is constructed by a computer.

How it works

- The X-ray point source is shielded to produce fan shaped rays.
- The source rotates around the body, irradiating a thin slice of the patient, with X-ray detectors opposite.
- After a complete rotation the whole ring moves so another slice can be taken.
- The computer assembles the images into a 3D view.
- Medical staff can then rotate or zoom in on any part of the digital 3D image on the screen.

- Tomography comes from the Greek word Tomos meaning slice.





6.5.1 Using X Rays (review)

6.5.1 Using X-rays

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) basic structure of an X-ray tube; components – heater, cathode and target metal

(b) production of X-ray photons from an X-ray tube

(c) X-ray attenuation mechanisms; simple scatter, photoelectric effect, Compton effect and pair production.

(d) attenuation of X-rays; $I = I_0 e^{-\mu x}$, where μ is the attenuation (absorption) coefficient

(e) X-ray imaging with contrast media; barium and iodine

(f) computerised axial tomography (CAT) scanning; components – rotating X-tube producing a thin fan-shaped X-ray beam, stationary ring of detectors, computer software and display

(g) advantages of a CAT scan over an X-ray image.

6.5.2 Diagnostic Methods in Medicine

6.5.2 Diagnostic methods in medicine

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) medical tracers; technetium–99m and fluorine–18

(b) gamma camera; components – collimator, scintillator, photomultiplier tubes, computer and display; formation of image

(c) diagnosis using gamma camera

(d) positron emission tomography (PET) scanner; annihilation of positron–electron pairs; formation of image

(e) diagnosis using PET scanning.

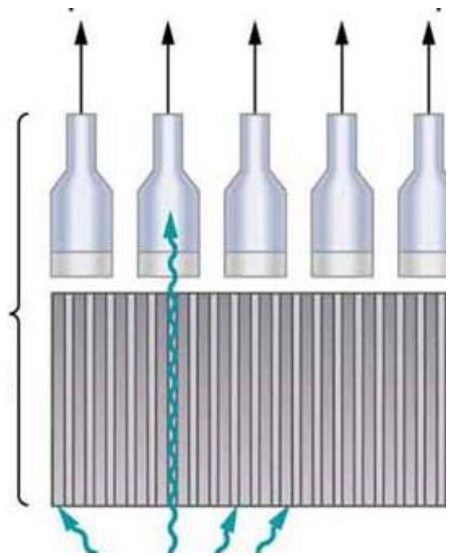
How do we use physics to diagnose biology?

Radioactive Tracers

- Radioactive chemicals which can be injected or ingested into the body to monitor various organ functions.
  - These chemicals are not poisonous to the patient and are chosen so the radiation will move to the area which is to be studied.
- Radio tracers are gamma sources with a half life long enough to carry out the test but not so long to cause unnecessary damage.
  - However, the patient will be exposed to some level of radiation (as will nurses and the patient’s family).
  - Alpha & Beta radiation is far too ionising to use.

How is the radiation detected

- Gamma (Anger) Cameras are used to detect position of the radiation emitted from the tracer.
- Collimator ensures only horizontal/vertical rays reach the camera.
- Sodium iodide scintillator flashes when gamma photons hit.
- Flashes are detected by photomultiplier tubes.
- Tubes send electrical signal to the computer.
- With two cameras at right angles, computer can calculate exact position of gamma source.



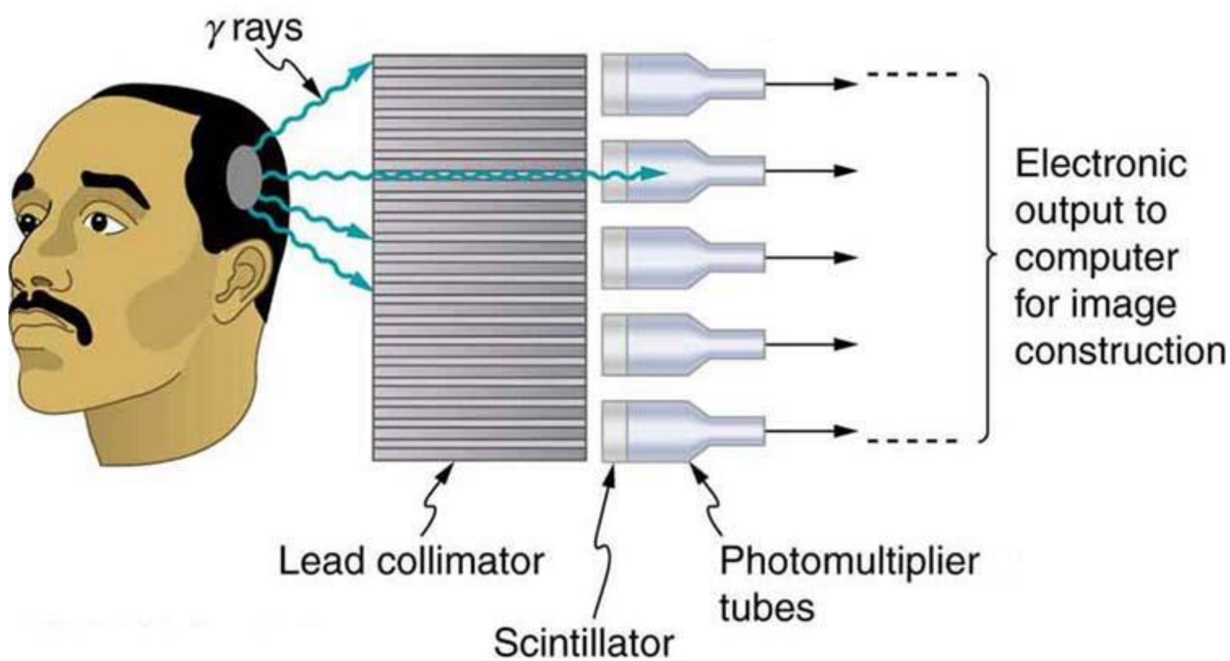


Figure 1 A patient being positioned to undergo a gamma camera scan

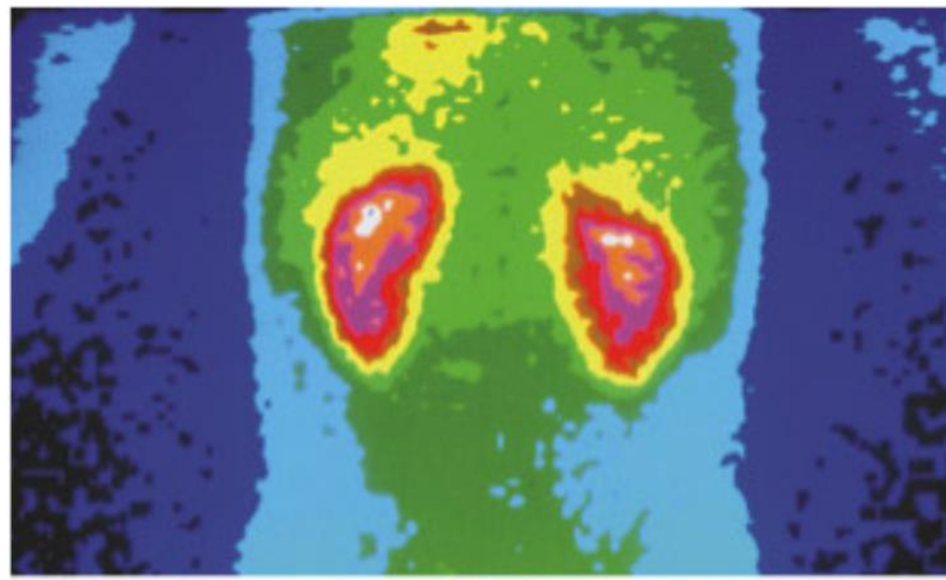


Figure 3 A gamma camera photograph showing healthy human kidneys

How can radio tracers diagnose conditions?

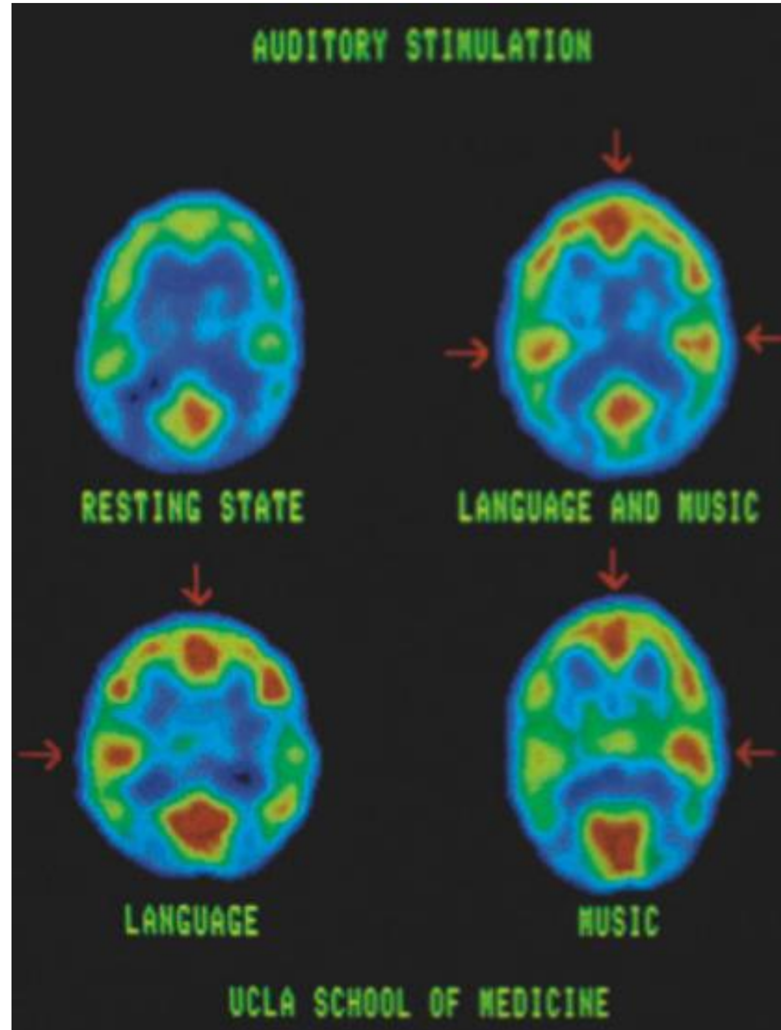
- A radioactive nucleus (often technetium 99) can be incorporated into a variety of different biomolecules.
  - An emission of 140keV gamma photons with a half life of 6 hours.
- Examples are:
  - Iodine compounds concentrate in the thyroid gland.
    - The thyroid gland produces a hormone called thyroxine, which regulates the rate of metabolism. Thyroxine contains 4 iodine atoms. If a patient drinks an iodine compound doped with Te99, most of it will end up in the thyroid gland. The gamma camera can image the gland. An assessment can then be made about its shape, size and functioning.
  - Phosphorus compounds concentrate in the bones.
  - Potassium concentrates in the muscles.

Other uses of radiotracers

- Some radioactive chemicals are being developed with longer half lives which are absorbed into cancer cells – and so destroy the cells without causing damage elsewhere.
- Radiotracers are also used in non medical ways:
  - Checking for leaks in gas/water pipes.

Positron Emission Tomography (PET)

- Radiolabelled glucose molecule which undergoes positron emission decay is injected into the blood.
- Glucose is used by respiring cells.
  - More active cells use more glucose.
- When positrons are emitted they quickly annihilate with electrons to produce a pair of gamma photons.
- A ring of gamma detectors surround the patient and the location of the gamma emission can be calculated.
- The concentration of gamma emission indicates activity of cells.



Brain PET scan shows active areas

Advantages/Disadvantages of PET

- Advantages:
  - Non invasive
  - Versatile diagnoses

- Disadvantages:
  - Expensive
  - Not all hospitals have them
  - Used for complex diagnoses only

6.5.2 Diagnostic Methods in Medicine (review)

6.5.2 Diagnostic methods in medicine

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) medical tracers; technetium–99m and fluorine–18

(b) gamma camera; components – collimator, scintillator, photomultiplier tubes, computer and display; formation of image

(c) diagnosis using gamma camera

(d) positron emission tomography (PET) scanner; annihilation of positron–electron pairs; formation of image

(e) diagnosis using PET scanning.

6.5.3 Using Ultrasound

6.5.3 Using ultrasound

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) ultrasound; longitudinal wave with frequency greater than 20 kHz

(b) piezoelectric effect; ultrasound transducer as a device that emits and receives ultrasound

(c) ultrasound A-scan and B-scan

(d) acoustic impedance of a medium; $Z = \rho c$

(e) reflection of ultrasound at a boundary;

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

(f) impedance (acoustic) matching; special gel used in ultrasound scanning

(g) Doppler effect in ultrasound; speed of blood in the patient; $\frac{\Delta f}{f} = \frac{2v\cos\theta}{c}$ for determining the speed v of blood.

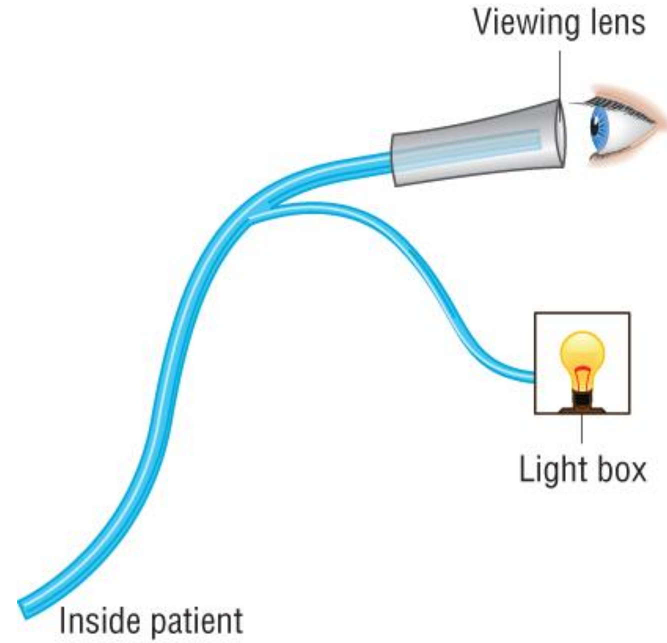
How can we use sound waves to diagnose?

Other Non Invasive Techniques

- Non invasive diagnostic techniques are those which do not have undue adverse effects on the patient:
  - For example:
    - Non surgical
    - No involvement of ionising radiation
  - Non invasive techniques include:
    - MRI Scans
    - Endoscopy
    - Ultrasound Scans
  - Invasive techniques include:
    - Surgery
    - X-rays (including CAT Scans, angiograms)
    - Radio tracer imaging (including PET Scans)

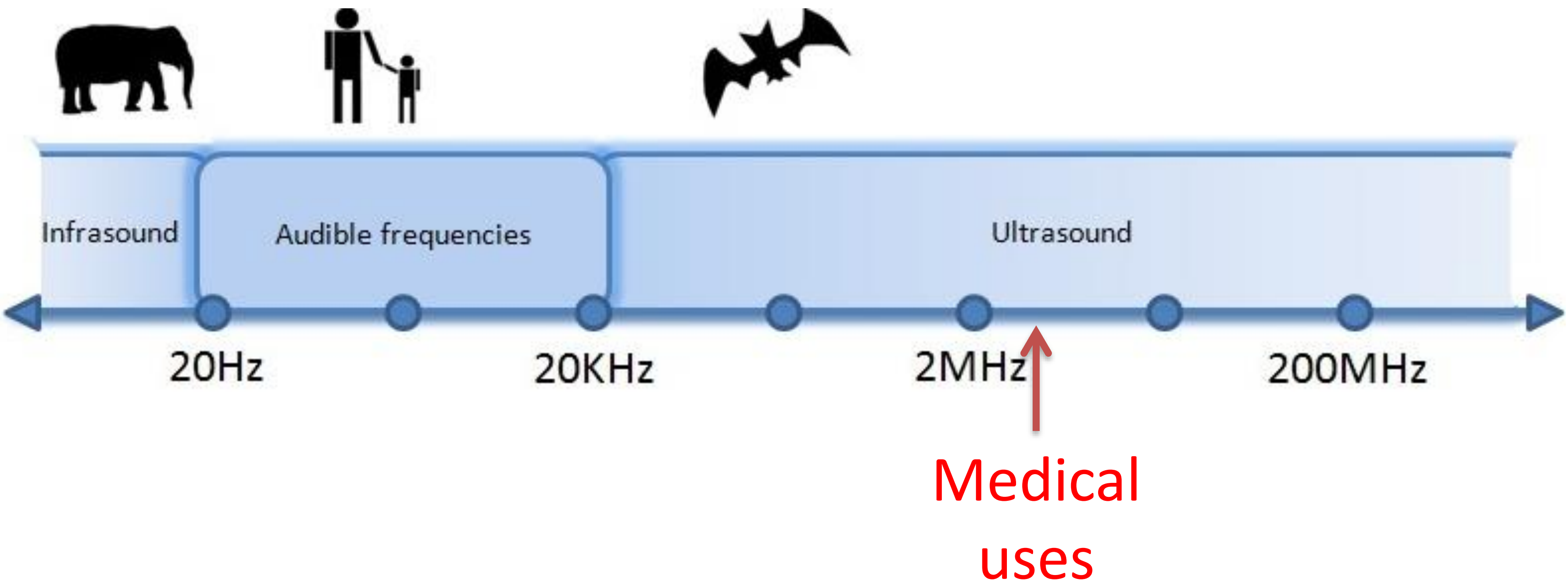
Endoscopy

- An endoscope uses optical fibres which are inserted into the body and allows medics to see inside.
  - Optical fibres are arranged in two layers:
    - One allows light to be transmitted from a source into the body.
    - The other allows reflected light to be transmitted back to the doctor.
  - Control wires allow the tip of the endoscope to move to guide it through the body and view the various parts (some have controllable tools).



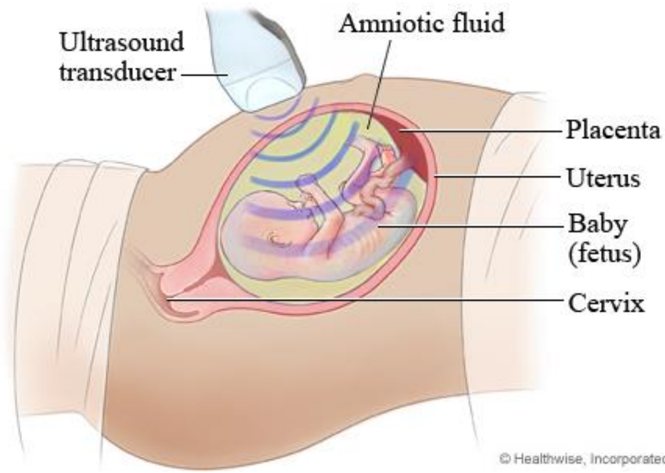
Ultrasound

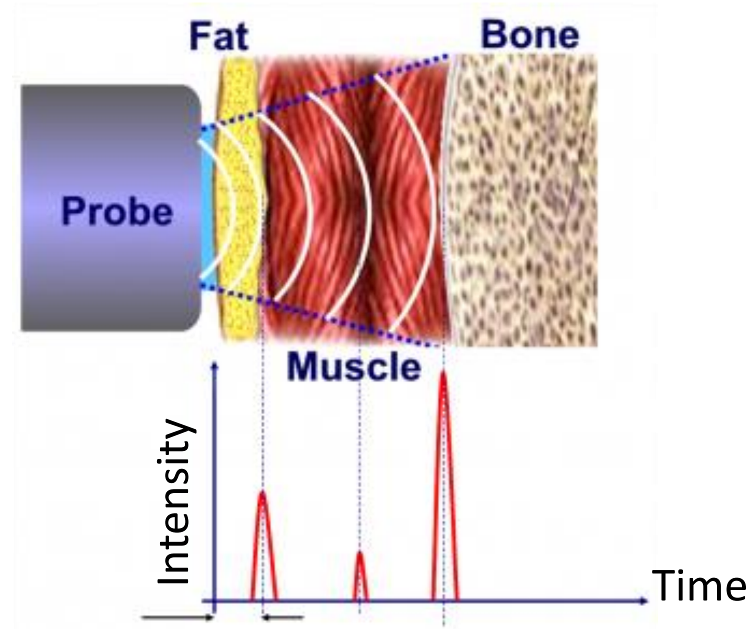
- The name given to sound frequencies higher than those heard by humans.



Ultrasound in Diagnosis

- As ultrasound meets a boundary, a proportion is reflected.
- These echoes can be analysed and an image produced.



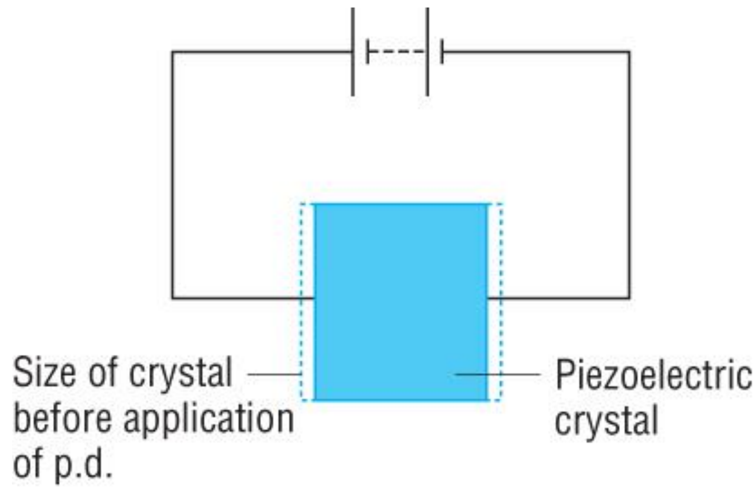


Advantages/Disadvantages of ultrasound

- Advantages:
  - No ionising radiation is used.
    - So safe to use for pregnant women.
  - X-rays of soft tissues just show an outline shape (very little resoultion), Ultrasound can distinguish between different tissues (muscle, blood) and can even show blood movement.
- Disadvantages:
  - High intensity ultrasound can cause tissue damage.

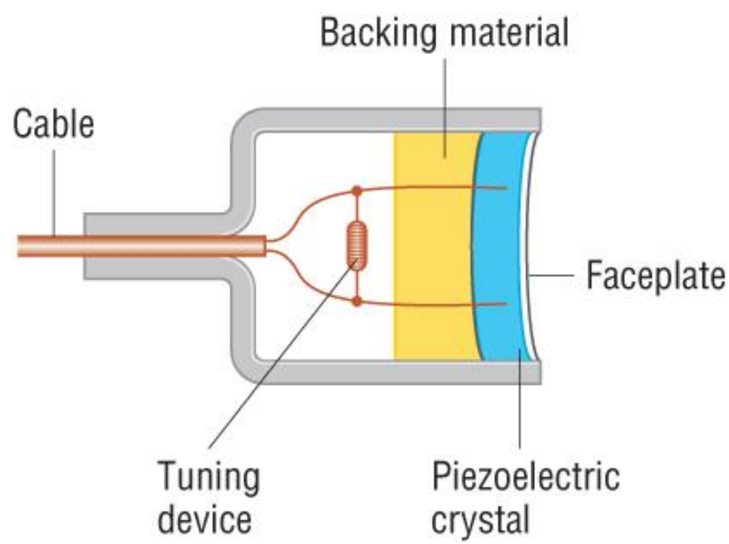
How ultrasound is produced

- The piezoelectric effect:
  - When certain crystals (eg. Lead zirconate titanate) have a pd applied to them they contract slightly.
  - With a high frequency alternating pd we can make the crystals oscillate at these high frequencies.
  - Oscillating crystals produce sound waves.
  - The process works in reverse too.
    - Sound waves can cause the crystal to resonate (particularly if its thickness is cut to match the wavelength of the sound.
    - An oscillating crystal will produce a voltage which can be detected and amplified electronically.



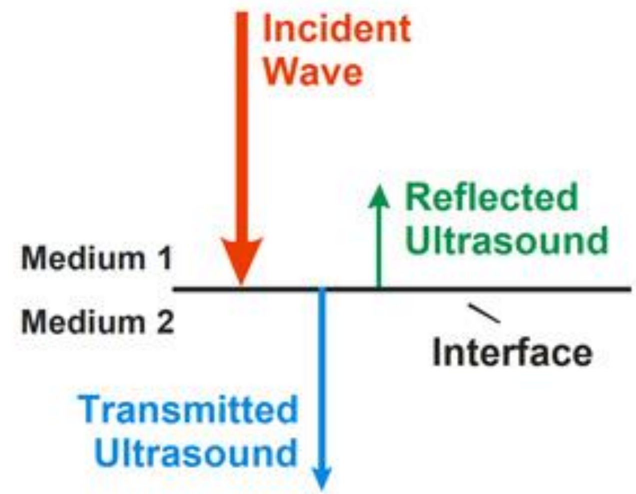
The Transducer

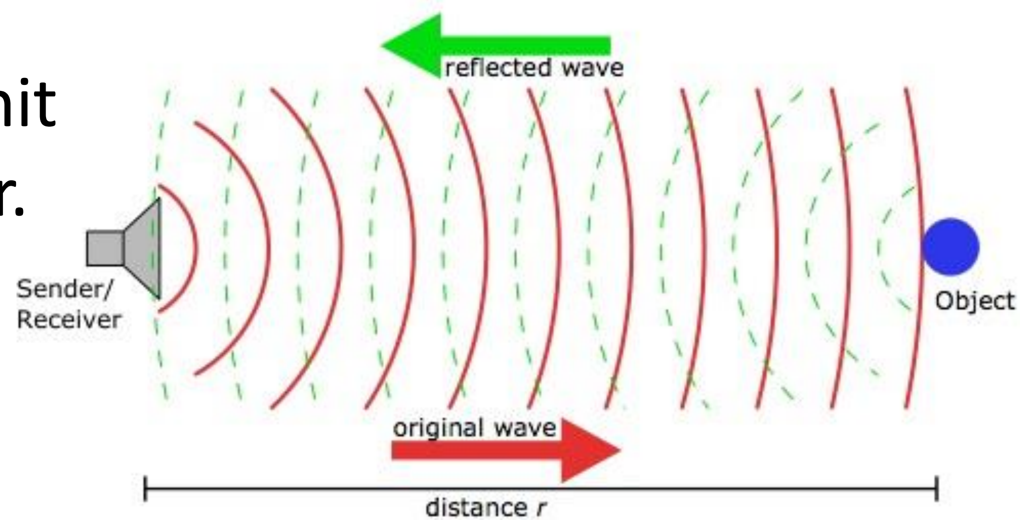
- The transducer is the hand held device placed on the patient which produces the ultrasound.
- The curved faceplate focuses the ultrasound into a narrow beam.
- The transducer acts as transmitter and receiver.



Ultrasound scanning

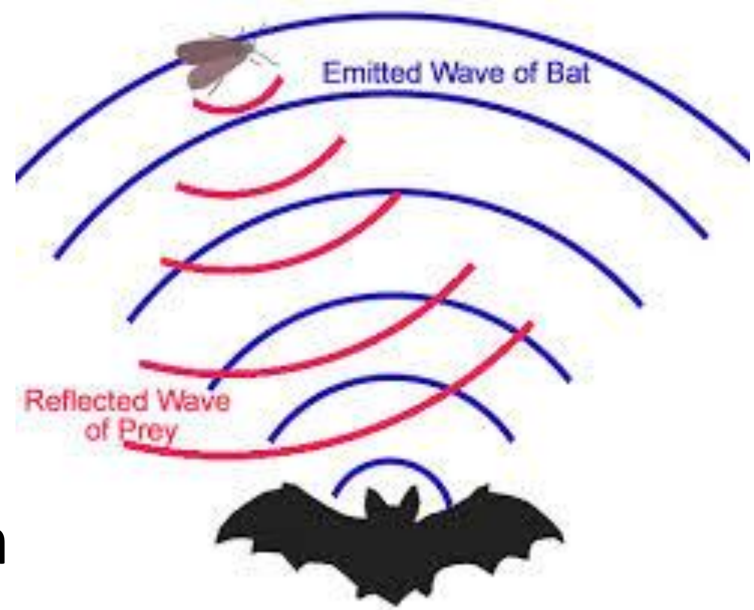
- Ultrasound doesn't just travel through a body.
  - Some reflects from different boundary surfaces in the within the body.
  - Some will transmit through however.

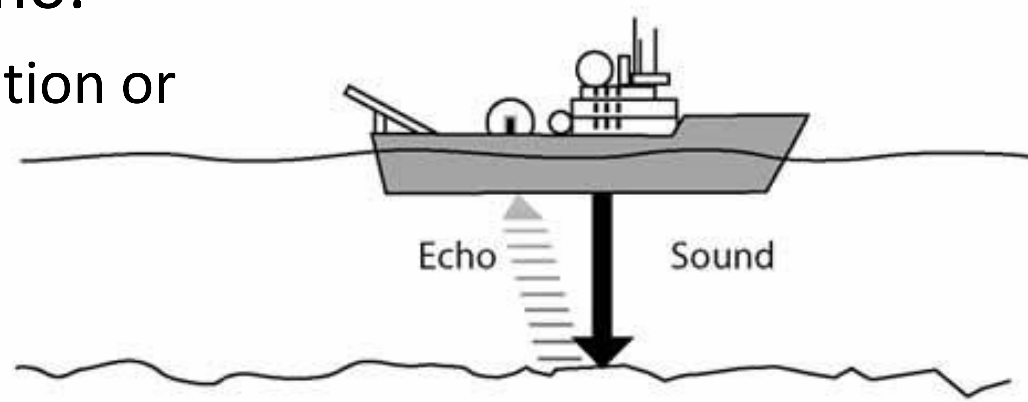




Ultrasound scanning

- Ultrasound scanning must be pulsed.
  - The transducer acts as transmitter and receiver so there must be a pause after transmission to wait for the echo.
    - Just like echolocation or sonar detection.





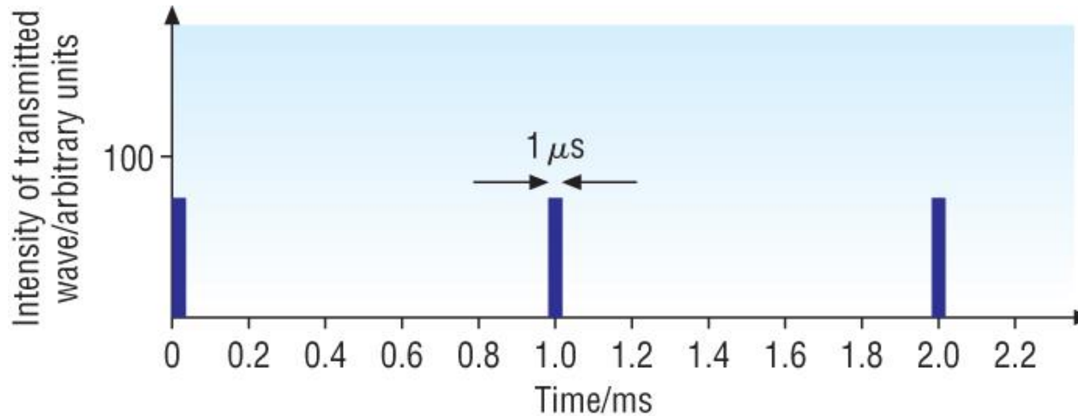
Pulse Repetition Frequency

- The minimum time delay from one pulse to the next.
  - Allows time for the echoes to be received.

- If :
  - Speed of ultrasound in muscle is $1600ms^{-1}$
  - Need to scan 20cm of muscle.
  - What is the time taken and therefore the minimum pulse repetition frequency?
    - **Time = $0.40m/1600ms^{-1}$ = 0.00025s = 0.25ms**
    - **Max PRF = 1/0.00025s = 4000Hz.**

Pulse timing

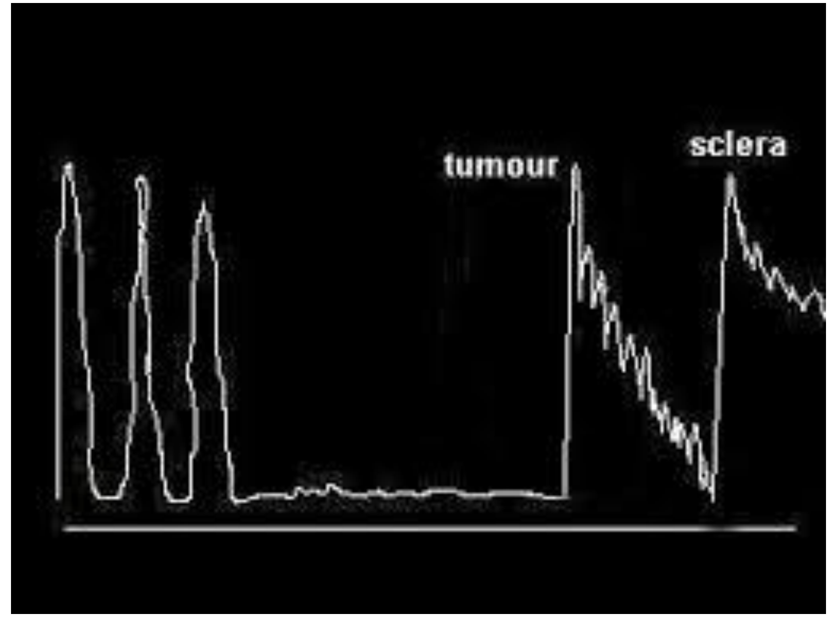
- The ultrasound pulse needs to be short & sharp.
  - Likely to contain just a few wavelengths.
  - Of the order of microseconds



- The echo will contain many different reflections of different intensities from different surfaces at different distances from the transducer.

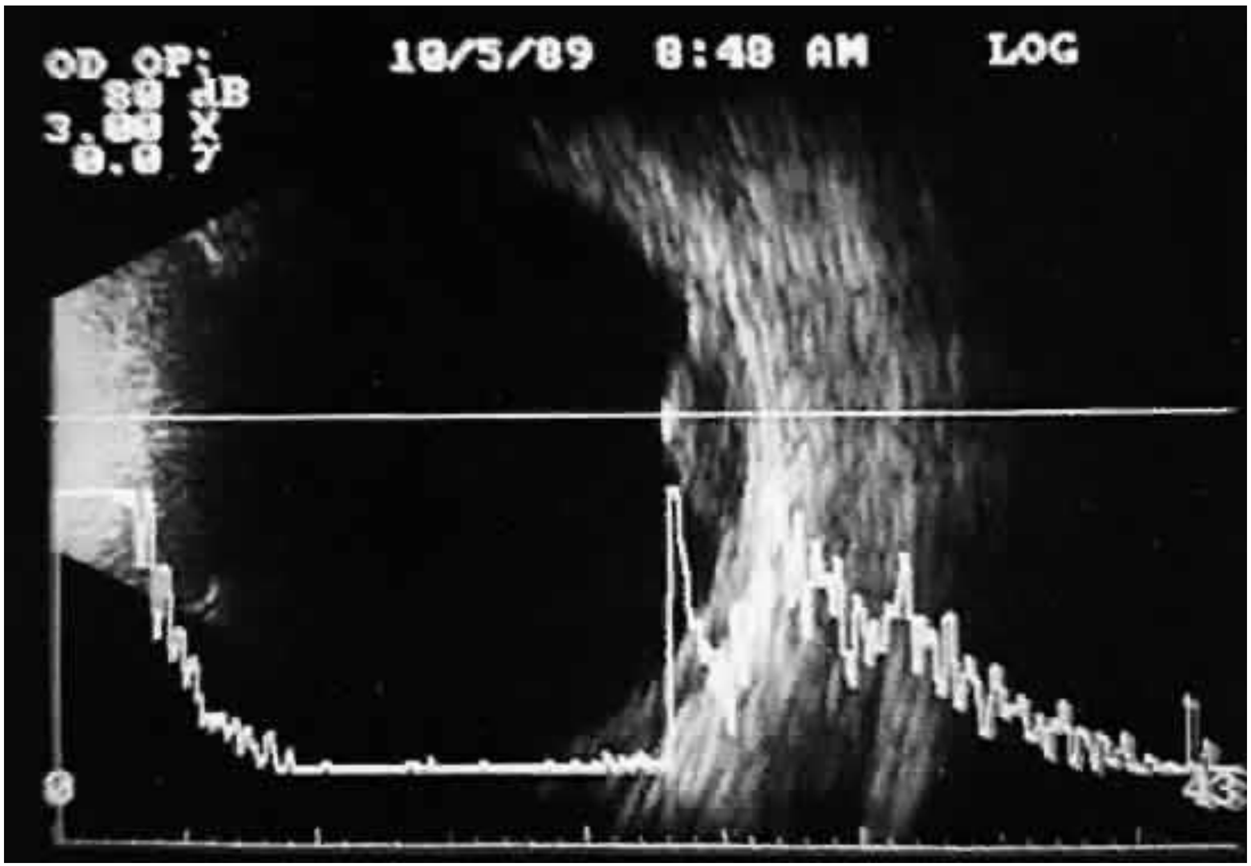
Types of Ultrasound Scan

- A-Scans
  - No image produced.
  - Shows reflected intensities over time.
  - Measurements can be taken to nearest mm.
- B-Scans
  - Uses an array of transducers.
  - Many echoes collected and collated.
  - Images produced.



Sometimes A & B scans are combined

- Allows measurement and visualisation.



Acoustic Impedance

- The resistance to sound travelling through a substance.
- Different substances have different acoustic impedances.

- Acoustic Impedance, Z is the product of density of the substance and the velocity of sound through it.

$$Z = \rho c$$

Where:

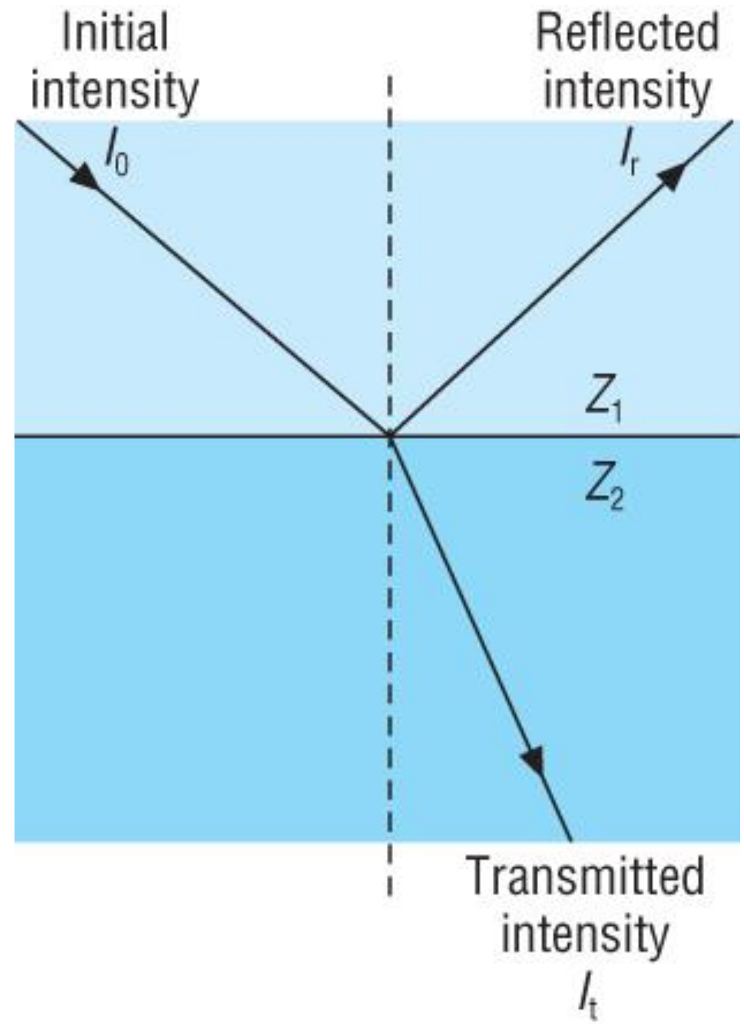
Z is Acoustic impedance

ρ is the density of the material

c is the velocity of sound through the material

Calculating the amount of reflection

- Acoustic impedances of materials can be used to determine the ratio of sound intensity reflected at a boundary to that transmitted through the boundary.



$I_r : I_0$ Ratio

- We can calculate the ratio of intensity reflected at a boundary, I_r, to the initial incident intensity, I_0, where the initial material has an acoustic impedance of Z_1 and the second material has an AI of Z_2 using the following equation:

$$\frac{I_r}{I_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

What percentage of ultrasound is reflected at the boundary between the air and the body (muscle)?

$$\frac{I_r}{I_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

Material	c/m s^{-1}	ρ/kg m^{-3}	Z/kg m^{-2} s^{-1}
Air	340	1.3	440
Bone	3500	1600	5.6×10^6
Muscle	1600	1000	1.6×10^6
Soft tissue	1500	1000	1.5×10^6
Fat	1400	1000	1.4×10^6
Blood	1600	1000	1.6×10^6

What percentage of ultrasound is reflected at the boundary between the air and the body (muscle)?

$$\frac{I_r}{I_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

I_r/I_0 = 0.9995 or 99.95%

Which means almost all ultrasound wound be reflected at this boundary

This is why the transducer is covered in gel first.

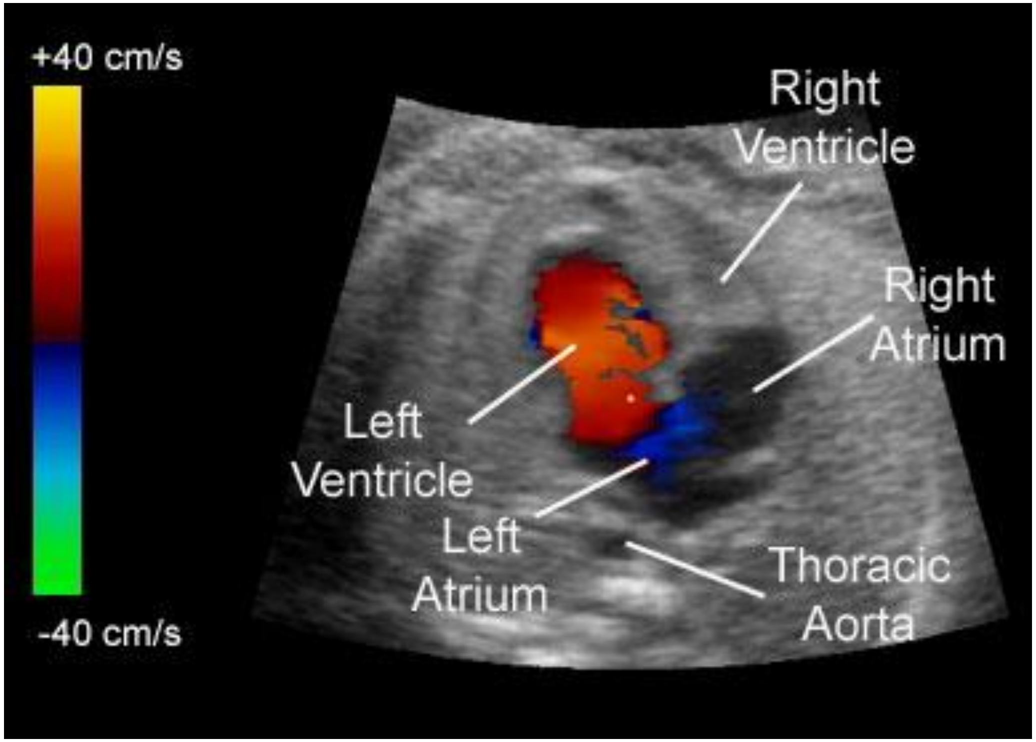
Impedance Matching

$$\frac{I_r}{I_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

- If impedances at a boundary are similar, most sound is transmitted through the boundary.
- If impedances are different, more sound will be reflected at the boundary.
- To get a good transmission of ultrasound from the transducer to the body we need to match the impedance of the skin with a gel.

Doppler Scans

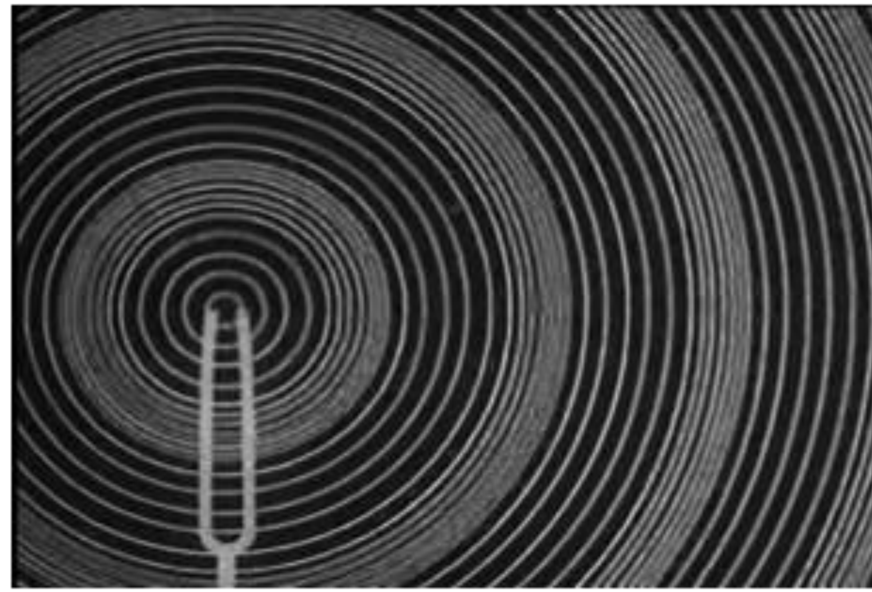
- These ultrasound scans can be used to measure the speed of moving objects (blood for example).
- They use the principle of the Doppler Effect to do this



The Doppler Effect

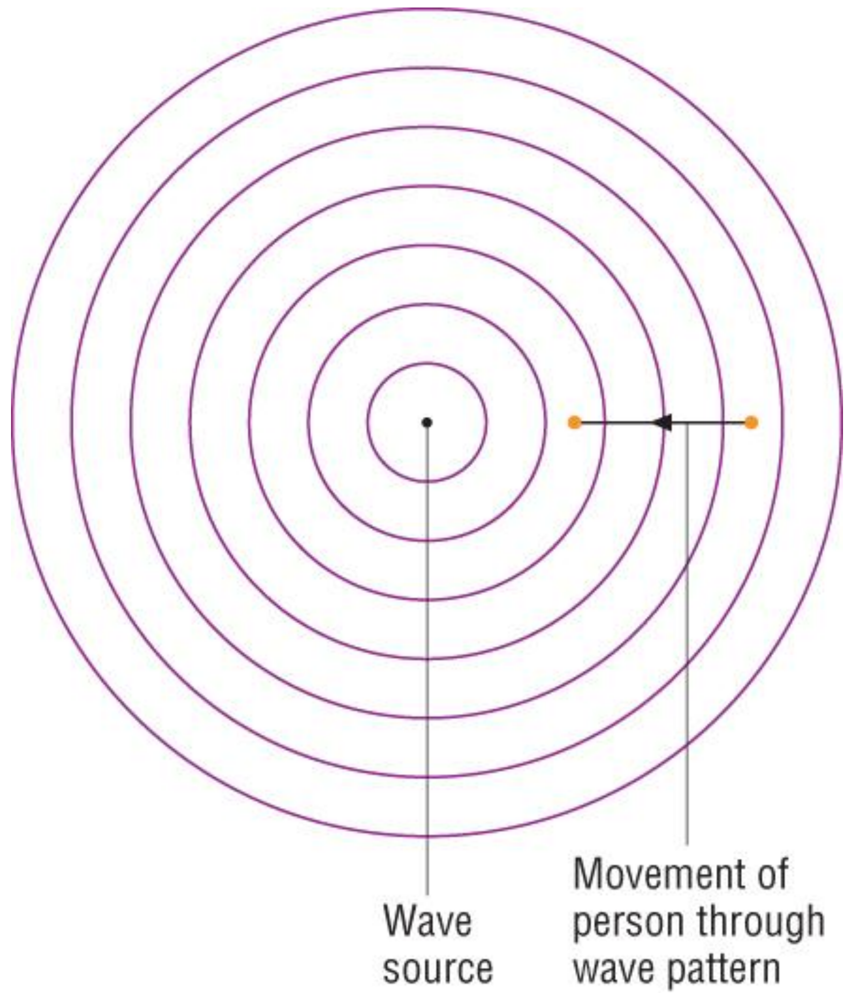
- When a sound is emitted from a stationary source, the waves spread out in concentric circles.
- The speed of the wave, c, is given by the usual formula:

$$c = f\lambda$$



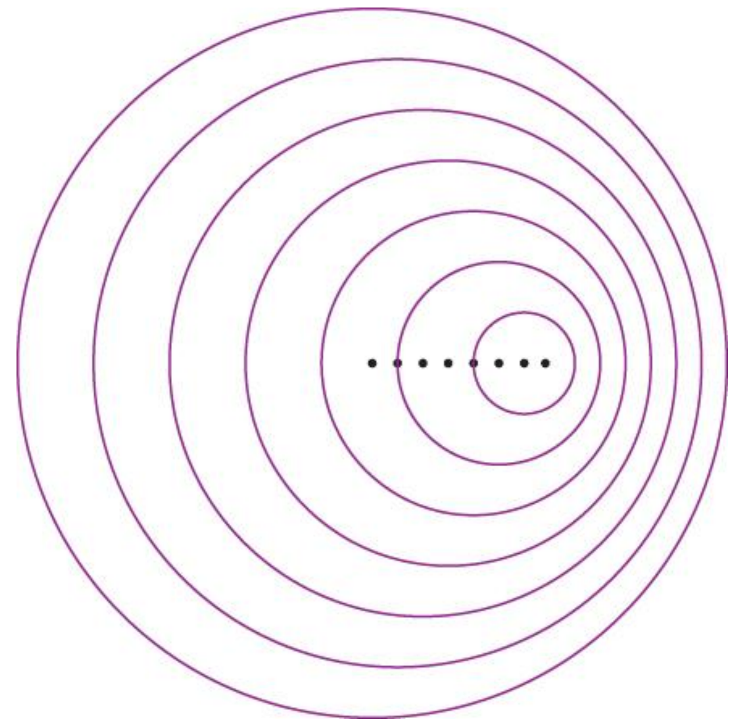
However...

- If we move towards the source of the sound we do not hear the same frequency since more waves pass us in the same time.



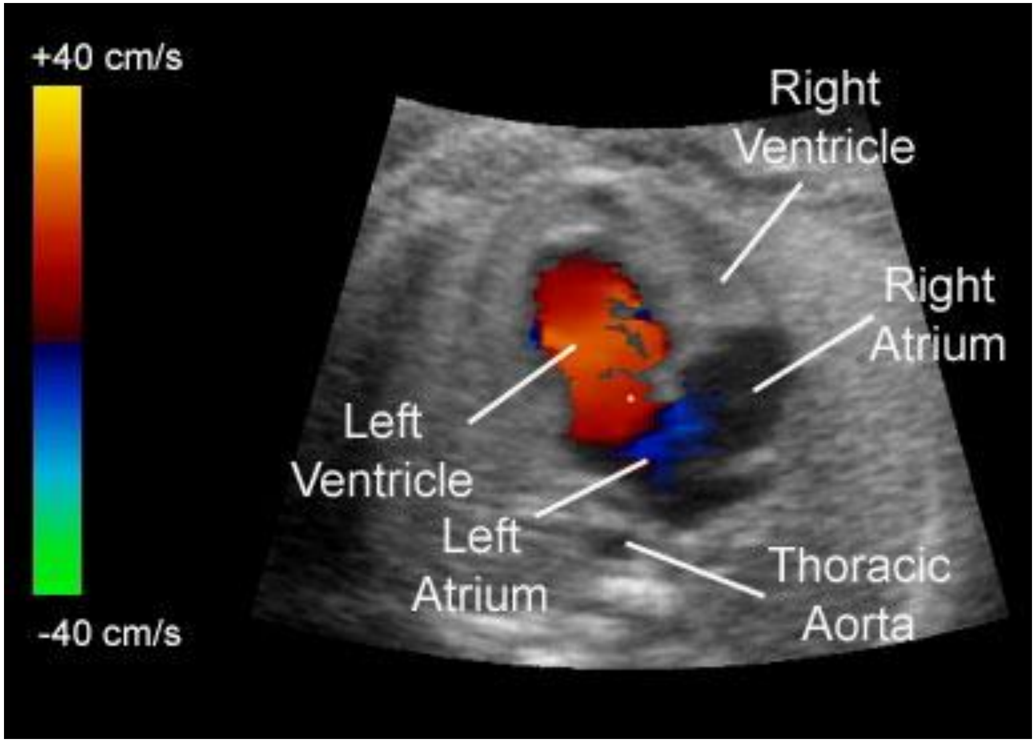
If the source is moving and the observer is stationary...

- The wavefronts are still circular, but each is produced from a different point as the source moves forward.
- This reduces the frequency behind the source but increases it in front.



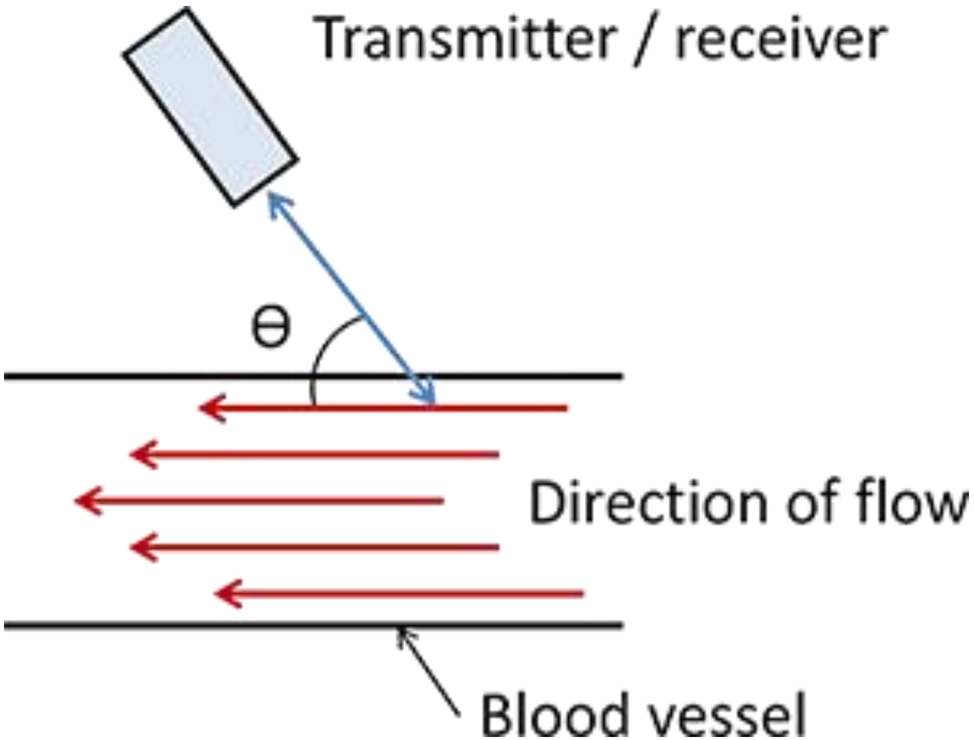
Doppler Scans

- These ultrasound scans can be used to measure the speed of moving objects (blood for example).
- They use the principle of the Doppler Effect to do this



Calculating the speed of blood

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



Where:
f = ultrasound frequency
v = speed of moving blood
θ = angle of transducer to blood direction
c = speed of ultrasound in through blood.

6.5.3 Using Ultrasound (review)

6.5.3 Using ultrasound

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) ultrasound; longitudinal wave with frequency greater than 20 kHz

(b) piezoelectric effect; ultrasound transducer as a device that emits and receives ultrasound

(c) ultrasound A-scan and B-scan

(d) acoustic impedance of a medium; $Z = \rho c$

(e) reflection of ultrasound at a boundary;

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

(f) impedance (acoustic) matching; special gel used in ultrasound scanning

(g) Doppler effect in ultrasound; speed of blood in the patient; $\frac{\Delta f}{f} = \frac{2v\cos\theta}{c}$ for determining the speed v of blood.

Module 5 – Newtonian world and astrophysics

5.1 Thermal physics
5.2 Circular motion
5.3 Oscillations
5.4 Gravitational fields
5.5 Astrophysics and cosmology

Module 6 – Particles and medical physics

6.1 Capacitors
6.2 Electric fields
6.3 Electromagnetism
6.4 Nuclear and particle physics
6.5 Medical imaging

Complete! → 6.5 Medical imaging