WJEC (Wales) Physics A-level

Topic 4.B: Medical Physics

Notes

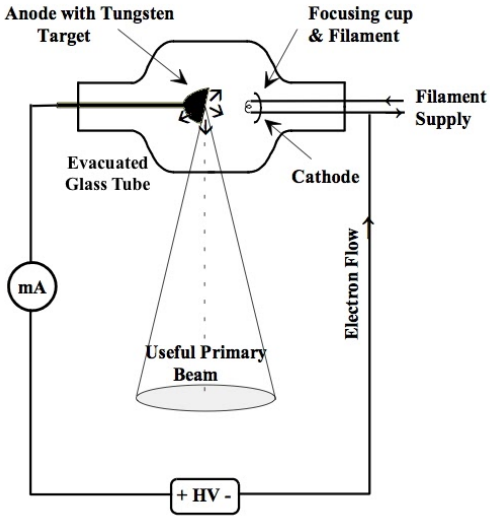
Nature & Properties of X-Rays

X-Rays are a form of **electromagnetic radiation**. They are highly **ionising**, so can knock electrons off atoms which can lead to cancer in humans.

Production of X-Rays

Thermionic emission is used to produce X-rays. This is where a metal is heated until the free electrons on its surface gain enough energy to leave the surface.

1. Electrons are emitted from a filament by thermionic emission in an **evacuated tube**.
2. They are then accelerated through a potential difference towards the **anode** (metal target).
3. Once they collide with the metal target, they decelerate rapidly and emit **X-ray photons** and form a continuous spectrum of X-ray radiation.
4. Some electrons will collide with orbital electrons of the target atoms and **ionise** the atoms, releasing energy in the form of X-ray photons. The energy of these X-ray photons depends on the difference in **energy levels** of the metal target's atoms and so will depend on the material of the metal target. This is why they are known to form a characteristic **spectrum** of X-ray radiation; these are **line spectra** because only photons at specific energies can be emitted.



The **maximum X-ray photon energy E** produced by the above method is:

$$E = \frac{hc}{\lambda_{min}} = eV_a$$

e = charge on an electron, V_a = accelerating voltage.

The minimum wavelength λ_{min} can be calculated from this equation.

Intensity of the X-ray beam is defined as the **total energy emitted per second per unit area passing through a surface (at right angles).**

Beam intensity needs to be controlled to reduce the ionising effect of the X-rays and reduce the chances of them causing cancer.

There are two methods which could be used to control the beam intensity:

1. Increasing the **anode voltage** will increase the beam **intensity**. This is because the electrons gain more kinetic energy, so X-ray photons will have higher **energies** because higher energy electrons can ionise electrons from deeper within the target atoms.

2. Increasing the current passing through the filament which is emitting electrons will increase the **intensity**. This is because this causes more electrons to be released per second, therefore more X-rays photons can be produced per second. The photons will have the same range of energies as before the current was increased; only intensity is affected by changing the current.

The **image sharpness** of an X-ray image can be increased by the following methods:

1. Placing the detection plate as close as possible to the patient, while moving the X-ray source far away.

2. Ensuring the **patient holds very still** and even holds their breath while the X-ray is taking place.

3. Using a **lead grid** between the patient and film, as it will stop **scattered X-rays** from reducing the **contrast** of the final image because lead absorbs X-rays.

The **dose of radiation** that a patient is exposed to is important. This depends on two factors:

- Intensity of the X-ray beam.

- **Exposure time.**

Attenuation

X-Rays are **attenuated** (lose intensity) as they pass through matter. They lose intensity according to the following equation:

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

μ - Attenuation Coefficient
***x* - Distance into the matter**
I_0 - Initial intensity
***I* - Intensity**

CT Scans

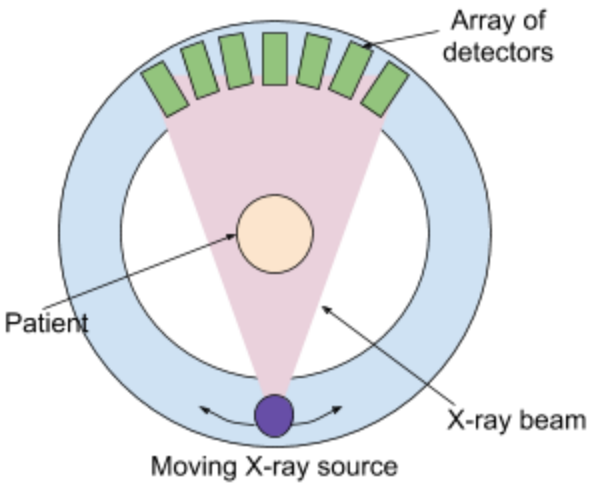
CT (Computerised Tomography) scanners produce **high-contrast** images of a **cross-section** of the body, which clearly show the depth of structures. Many of these images can be used together to form a **3D image** of the area under investigation.

A CT scanner creates an image through the following process:

1. An X-ray source is rotated around the patient, and it emits a **narrow, monochromatic X-ray beam** which passes through the body at different orientations.

2. There is an **array of detectors** arranged outside the path of the X-ray source, which detect the intensity of the X-ray beam after it passes through the body. The detectors only register the intensity of beam sources placed directly opposite to them.

3. The recorded intensities are sent to a computer, where they're processed and an image of the **cross-section** is created.



The advantages of a CT scanner:

- Can produce very **high quality** images of complicated bone fractures, and organs (e.g brain).

- It is completely **non-invasive.**

- CT scanners produce a higher quality image than ultrasound imaging.

- An image of a full cross-sectional area is formed.

The disadvantages of a CT scanner:

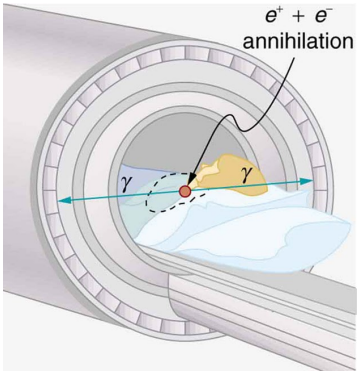
- The patient is exposed to a relatively **large dose** of ionizing radiation.
- They are quite **expensive** (in comparison to a normal X-ray).
- The contrast between materials of similar densities is very small, therefore it is possible for the images to appear **distorted**.
- It often requires patients to remain entirely still, including holding their breath, which may be difficult for some to do.

PET Scans

Positron emission tomography (PET) scans can be used to form both 3D images and cross-sections of the body through the following process:

1. The patient is injected with a **positron-emitting ($\beta+$ decaying) radionuclide** attached to a substance used by the region of the body under investigation.
2. The patient is left for around an hour to allow the radionuclide to move to the region of interest.
3. The radionuclide will then be **absorbed and broken down,** releasing **positrons** which will collide with electrons present in the body, causing them to become **annihilated**. The minimum energy of each photon emitted is equal to the rest energy of the electron/positron. The energy of the electron and positron is assumed to be shared equally between the gamma ray photons. The photon energy is $hf = E_0$.
4. This releases two **high-energy gamma rays,** moving in opposite directions, which are recorded by detectors. These signals are sent to a computer for processing, and an image of the radioactivity in that region can be formed.

The image formed depends on the metabolic activity of the cells in the region. This is because cells with a high metabolism will break down more of the radionuclide, causing more annihilation and therefore **more gamma radiation to be emitted and detected.**



The advantages of PET scanners:

- The **metabolic activity** of a region can be measured.
- **Tumours** can be detected and information about if they are spreading/malignant can be found.
- **Brain activity** can be easily investigated because gamma rays produced inside the brain can easily pass through the skull.

The disadvantages of PET scanners:

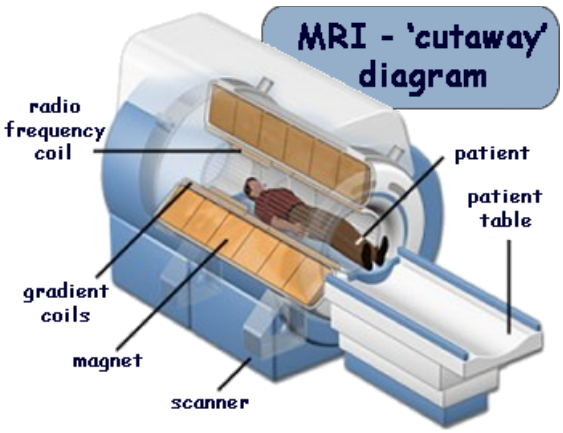
- Ionising radiation is used, which could cause **damage** to the patient's cells.
- Scans take a long time and require patients to stay very still inside the scanner, which may be uncomfortable and may cause some patients to feel **claustrophobic.**
- They are very large and **expensive**, meaning that a patient may need to travel a long distance to get to a hospital which has a PET scanner.

MRI Scans

Magnetic Resonance Imaging (MRI) works by measuring the way that hydrogen atoms **absorb** and then **relax and re-emit** electromagnetic energy.

Most of the human body is made up of water molecules, which consist of only **hydrogen** and **oxygen** atoms and fat, which also contains hydrogen atoms.

The nucleus of a hydrogen atom is a proton, and protons are very sensitive to **magnetic fields.** When the proton spins it generates a magnetic field, and therefore the nucleus of a hydrogen atom is like a **tiny magnet**. When your body is in a strong magnetic field all of your hydrogen nuclei aline - just like a row of compass needles lining up with a magnetic field.



MRI scanners use powerful magnets. When the powerful magnets that are used in magnetic resonance imaging (MRI) are switched on, all the protons in your body are pulled so that they **spin in the same direction,** in the same way that a magnet can pull the needle of a compass. The scanner contains several **electric coils**. This produces **variations in the strength** of the magnetic field at different points in your body.

This variation means that each hydrogen nucleus experiences a slightly different magnetic field strength. This is important for detecting the **position** of a particular hydrogen nucleus.

The **frequency** of these waves depends on the strength of the magnetic field where each nucleus is and this means that the scanner can work out the location of each nucleus.

The **Larmor or precessional frequency** in MRI refers to the rate of precession of the magnetic moment of the proton around the external magnetic field. The frequency of precession is related to the strength of the magnetic field, B_0.

$$f = 42.6 \times 10^6 B_0$$

The precessional frequency of nuclei of a substance placed in a static magnetic field B0 is calculated from the Larmor Equation:

$$\omega = \gamma B_0$$

The **T1 relaxation time**, also known as the spin-lattice relaxation time, is a measure of how quickly the net magnetisation vector (NMV) recovers to its ground state in the direction of B_0.

Advantages:

- MRI provides better **soft tissue** contrast than CT
- Can differentiate better between fat, water, muscle, and other soft tissue than CT
- **Non-invasive**
- Does not use **ionizing radiation**

Disadvantages:

- Because of the small bore of the magnet, some patients experience **claustrophobia**

- Some patients, particularly acutely ill patients, cannot cooperate and movement artifacts may result.

- MRI units require careful **siting and shielding**.

Radiation

There are four major types of radiation: alpha, beta, neutrons, and electromagnetic waves such as gamma rays.

Alpha particles:

Alpha particles cannot penetrate most matter. A piece of paper or the outer layers of skin is sufficient to stop alpha particles.

Radioactive material that emits alpha particles (alpha emitters) can be very harmful when **inhaled, swallowed, or absorbed** into the bloodstream through wounds.

Beta particles:

Beta particles can be stopped by a layer of clothing or by a **few millimeters** of a substance such as aluminum.

Beta particles are capable of **penetrating the skin** and causing radiation damage, such as skin burns.

As with alpha emitters, beta emitters are most hazardous when they are inhaled or swallowed or absorbed into the **bloodstream** through wounds.

Gamma rays:

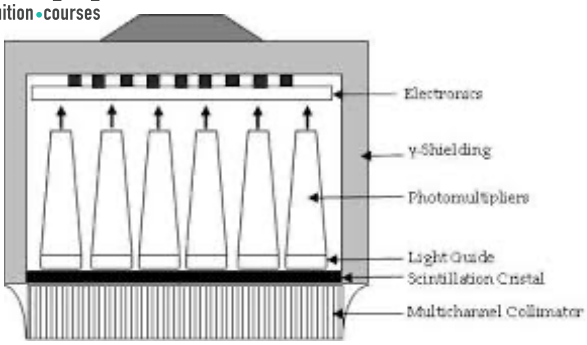
Gamma rays are penetrating. Several feet of **concrete** or a few inches of **lead** are required to stop them. Gamma rays are the reason why it is best to shelter in a basement or a centrally located room in a high rise.

Gamma rays and X-rays are a **radiation hazard** for the entire body.

While gamma rays can easily pass completely through the **human body**, some fraction of the energy will always be absorbed by body tissue.

The Gray, the unit of **absorbed dose of ionizing radiation**, was defined in the 1980s by the International Commission on Radiation Units and Measurements. One gray is equal approximately to the absorbed dose delivered when the energy per unit mass imparted to matter by ionizing radiation is **one joule per kilogram**.

Sievert is the unit for measuring ionizing radiation effective dose, which accounts for relative sensitivities of different tissues and organs exposed to radiation. The radiation quantity measured by the sievert is called effective dose.



Equivalent Dose = Absorbed Dose × (Radiation) Weighting Factor

$$H = DW_R$$

Effective Dose = Equivalent Dose × Tissue Weighting Factor

$$E = HW_T$$

Nuclear medicine uses **radioactive isotopes** in a variety of ways. One of the more common uses is as a **tracer** in which a radioisotope, such as **technetium-99m**, is taken orally or is injected or is inhaled into the body.

The radioisotope then circulates through the body or is taken up only by certain tissues. Its distribution can be tracked according to the radiation it gives off. The emitted radiation can be captured by various imaging techniques, such as positron emission tomography (PET), depending on the radioisotope used.

Gamma camera

The gamma ray is electromagnetic radiation of very **high penetration** power. Therefore more rays exit the body and are available for detection than interact with the patient's tissue. These can be detected by a gamma camera and the **concentration** of radioactive tracer in various parts of the body can be ascertained.

Gamma rays cannot be focused by refraction. Therefore, a **lead collimator** is used to direct rays from a point on the patient towards a single point on a sodium iodide crystal. The collimator **absorbs** gamma rays emanating from other parts of the body before they activate the crystal.

To detect the gamma photons we use a large crystal of sodium **iodide**. The crystal gives a tiny flash of visible light every time a gamma photon hits it. This flash is picked up by **photomultipliers** which convert the flash into an **electrical signal.** The electrical signals from the photomultipliers are analysed by a computer to construct an image.

A photomultiplier works by causing an increasing avalanche of electrons. The photomultipliers are quite large and may have a diameter of a few centimetres. So if each flash of light was only detected by one photomultiplier, the **resolution** of the image would be very poor.

The light guide, which is made of transparent plastic, spreads the light from each flash around several photomultipliers. By comparing the **intensity** of each signal you can compute more accurately where on the crystal the flash occurred.

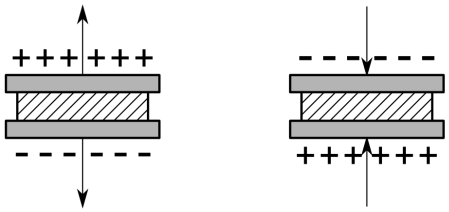
In reality each bright patch in the tumour emits gamma photons in all directions. This means each bright patch could 'illuminate' the whole crystal and we couldn't tell them apart.

The collimator helps to 'focus' the image so that we can tell the bright patches apart. It's just a lead sheet with holes in it. Only gamma photons travelling perpendicularly to the crystal manage to hit it. All the other photons are absorbed by the collimator.

This is quite wasteful of photons because most never cause a flash. More sophisticated gamma cameras have collimators that allow gamma photons from one point to go through several holes. Clever software and clever arrangement of the holes allows a brighter image to be reconstructed.

Production and Use of Ultrasound

An ultrasound wave has a frequency greater than **20 kHz**. However, when used for medical purposes, the frequency of ultrasound waves is usually between 1 MHz and 20 MHz.



A transducer containing **piezoelectric** material is used to **transmit and detect** ultrasound waves. This is because:

- When an **alternating potential difference** is applied to a piezoelectric material, it will cause the material to vibrate at the same frequency as the applied p.d. If the frequency of the alternating p.d. is equal to the natural frequency of the piezoelectric material, there is resonance and the vibrations reach their **maximum amplitude**. These vibrations cause ultrasound waves to be emitted.

- When a piezoelectric material is hit by an ultrasound wave, it will **deform**, producing a potential difference which can be **amplified** and displayed (usually on an oscilloscope).

In order to increase the resolution of the transducer, it is heavily damped in order to produce short pulses of ultrasound waves, meaning transmitted and received signals do not overlap.

Ultrasound is reflected when it reaches a **boundary** between two **mediums** and the amount of reflection that takes place depends on the difference in acoustic **impedance** of the two mediums. The acoustic impedance (Z) is a measure of how difficult it is for an acoustic wave to travel through a medium.

$$Z = \rho c$$

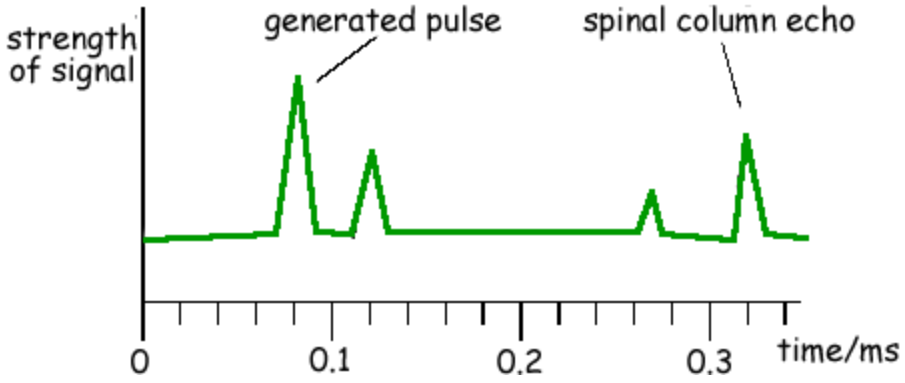
A **coupling medium** is used to reduce impedance and **reflections** at the boundary and as ultrasound has difficulty travelling in air, it is normally in the form of a gel.

The **half-value thickness ($x_{1/2}$)** is the thickness of a material at which the intensity is reduced to half of the initial value and can be measured by using the following formula:

$$x_{1/2} = \frac{ln\,2}{\mu}$$

A-Scans and B-Scans

An A-scan gives an image of **voltage peaks** on a cathode-ray oscilloscope screen from which the internal dimensions of cysts and organs can be determined.



The ultrasound transducer sends **pulses** into the patient and detects the reflections from various boundaries within an organ.

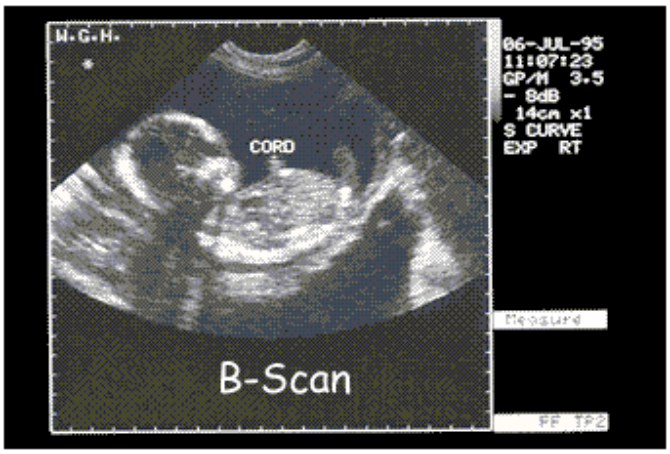
The simplified diagram above shows an A-scan.

Time, Δt = the time taken for the ultrasound to travel from the back of the eye lens to the retina and back again.

The process by which the acoustic impedances of the two substances on either side of a boundary are made nearly equal in order to ensure effective ultrasound transmission is called impedance (or acoustic) matching. This is achieved using a coupling gel.

B-scans are composed of many A-scans and produce a detailed **2-dimensional image** of the inside of a patient. Pre-natal (fetal) scans are the most common example of a B-scan.

The transducer is swept to and fro over the part of the patient's body under investigation (in the case of a pregnant woman, the abdomen) and a computer determines the **position and orientation** of the transducer. Each reflected pulse is analysed and the depth and nature of the reflecting boundary is determined.



The B-scan image is built up from the superimposition of a large collection of A-scans. Since this takes several seconds, any movements within the organ being scanned will degrade the quality of the image obtained. For example a B-scan of a pulsating heart would yield a **blurred** and virtually useless image. This is why fetal scans are usually quite blurry.

Advantages:

- No ionising radiation
- **Portability**, facilitated by laptop sized ultrasound machines.

Disadvantages:

- Increased depth means a lower frequency is required for optimal imaging. As a consequence there is a **lower resolution**.
- **Artefacts** are common. If a structure can only be seen in one plane it is likely to be an artefact.

Doppler Effect

The **Doppler effect** is a change in the frequency of a wave which occurs if one is in a different frame of reference from the emitter of the wave. Relative to us, we observe such a change if an emitter of a wave is moving relative to us.

All waves travel in a **medium**. So, they have a velocity relative to this medium v. They also have a velocity **relative** to their source v_s and a velocity relative to the place where they are received v_r. The frequency at which they are received f is related to the frequency of transmission f_0 by the formula:

$$\frac{\Delta\lambda}{\lambda 0} = \frac{\Delta f}{f0} = \frac{2v}{c}\cos\Theta$$

λ = Wavelength

$\lambda 0$ = Original Wavelength

f = Frequency

$f0$ = Original Frequency

v = Relative speed between source and observer

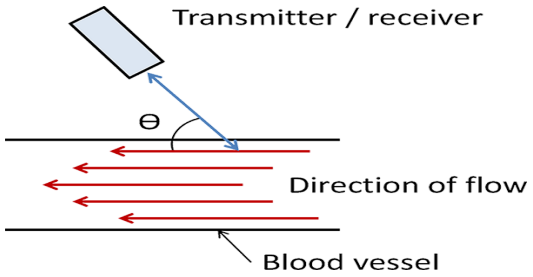
c = Speed of the wave

Below is a table of values of acoustic impedance for various materials.

Medium	Density (kg m^{-3})	Speed of ultrasound (m s^{-1})	Acoustic impedance (kg $m^{-2}s^{-1}$)
Air	1.3	330	429
Water	1000	1500	1.5×10^6
Fat	925	1450	1.34×10^6
Muscle	1075	1590	1.70×10^6
Bone	1400-1900	4080	5.7×10^6 to 7.8×10^6

You can calculate the **proportion** of the incident ultrasound signal that is reflected when it moves between two specific mediums by using the formula below. This value is also known as the intensity reflection coefficient:

$$\frac{I_r}{I_i} = \left(\frac{z_2 - z_1}{z_2 + z_1}\right)^2$$



where I_r is the intensity of the reflected wave, I_i is the intensity of the incident wave, Z_1 is the acoustic impedance of the initial material, and Z_2 is the acoustic impedance of the second material.