CAIE Physics A-level

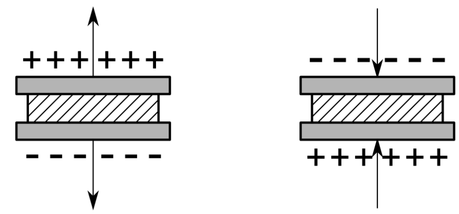
Topic 24: Medical Physics

Notes

24 - Medical Physics

24.1 - Production and Use of Ultrasound

An **ultrasound wave** is a **longitudinal** wave with 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.



When a **potential difference is applied** to a **piezoelectric** material (e.g. a quartz crystal), it will experience **mechanical deformation** (and vice versa)- this is known as the **piezoelectric effect** and it is used to produce ultrasound waves.

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 pulses of ultrasound waves to be emitted.
- and 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 and is defined as the **product of the density (ρ) and the speed of sound (c) in that material**.

$$Z = \rho c$$

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

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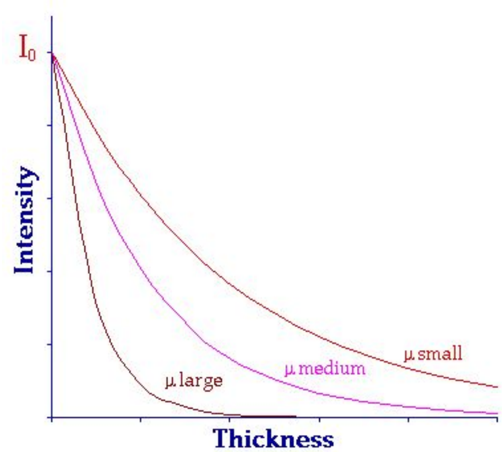
You can calculate the proportion of the incident ultrasound signal that is reflected when it moves between two specific mediums by using the formula below, this value is also known as the **intensity reflection coefficient**:

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

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.

If you look at the equation above you can see that if the acoustic impedance of both materials is the **same**, the **wave is not reflected;** and if the acoustic impedance of second material (Z_2) **is much larger** than the acoustic impedance of the initial material (Z_1), then **most of the wave is reflected back**. Due to the large difference in acoustic impedance between air and soft tissue, a **coupling medium** must be used between a transducer and the body so the ultrasound is not mostly reflected before entering the body. The coupling medium **removes the air** between the transducer and body and it is usually an **oil or gel** which can be spread across the skin. It is not possible to image structures of the body which are behind regions of air in the body (e.g the lungs) using ultrasound for this reason.

As ultrasound waves move through the body, they experience **attenuation,** meaning that they are absorbed and scattered, which decreases their amplitude. The **degree of attenuation increases as the acoustic impedance of the material the ultrasound is travelling through increases**. The **linear attenuation coefficient μ** is a measure of how easily the ultrasound wave can pass through a given material, and **describes the rate of energy loss per unit thickness**. The larger the coefficient, the quicker the **intensity** of the ultrasound will decrease as the wave passes through a medium.



The intensity of the ultrasound after it has passed a distance x through a medium is given by the following exponential equation which gives rise to graph above:

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

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:

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

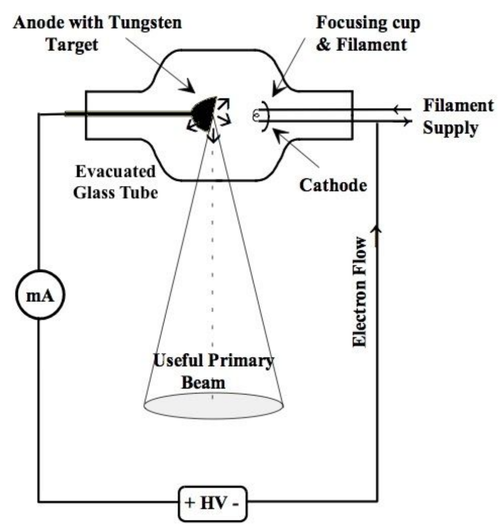
Note that you can derive this formula by substituting $0.5I_0$ for I in the first equation on this page, and rearranging for x. This is an equivalent process to determining the half life from a radioactive decay equation.

24.2 - Production and Use of X-Rays

Thermionic emission is used in the production of X-rays. This is where a metal is heated until the free electrons on its surface gain enough energy to be emitted.

Below is the process through which X-rays for diagnostic use are produced:

1. Electrons are emitted from a filament by **thermionic emission** in an **evacuated** tube, and are **accelerated through a potential difference** towards the anode (metal target).
2. Once they **collide with the metal target**, they **decelerate and emit part of their energy as EM radiation**, in the form of X-ray photons - this is called the **bremsstrahlung (braking radiation)** and forms a **continuous spectrum** of X-ray radiation.
3. Some electrons will collide with orbital electrons of the target atoms and **ionise the atoms**, causing electrons from **higher energy levels to move down and occupy the gaps** left by the ionised electrons, releasing energy in the form of X-ray photons. The energy of these X-ray photons depend 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 equal to the **product of the charge of an electron and the accelerating voltage** because this is the value of the kinetic energy of the electrons as they hit the target. The minimum wavelength λ_{min} can be calculated from this equation.

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

where e is the charge on an electron, and V_a is the accelerating voltage.
The **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). There are two methods which could be used to **control the beam intensity**:

1. As mentioned above, **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 amount of **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. Putting the detection **plate as close as possible** to the patient, while moving the **X-ray source far away.**
2. Making sure 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 (by darkening random areas of the film) because lead absorbs X-rays very well.

As X-rays are a form of **ionising radiation**, excessive exposure could cause a great deal of harm and could lead to the development of cancer, therefore the **dose** of radiation that a patient is exposed to is monitored and adjusted accordingly. The dose of radiation depends on two factors:

- **intensity** of the X-ray beam.
- and **exposure time**.

Generally, the larger the exposure time, the higher the resolution of the final image. However, the high resolution can also be retained by **intensifying the image** or by **using a more sensitive detector** (e.g electronic detector instead of film). The intensity of the X-ray beam can be adjusted by changing the **anode voltage** and the **cathode current**. As **X-rays with higher energies form higher contrast images**, the **cathode current is usually decreased in order to decrease the intensity** of the X-ray beam.

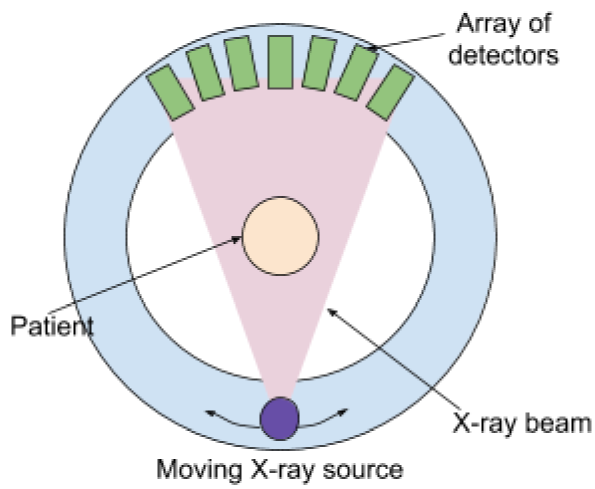
The **dose can also be decreased by filtering out low-energy X-ray photons** because they are unlikely to reach the detector and more likely to be absorbed by the skin of the patient, therefore increasing the radiation dose unnecessarily. This is usually done through the use of an **aluminium filter**, which absorbs a larger amount of low-energy than high-energy radiation.
The intensity of the X-rays after they have passed a distance x through a medium is given by the same exponential equation as for ultrasound:

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

The types of X-ray imaging described above produce **2D images**, meaning they give no indication of the depth of a structure. **CT scanners** produce **high-contrast** images of a **cross-section of the body**, which clearly shows the depth of structures and many of these 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. The **X-ray tube 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 tube, 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 can be formed.**



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.

24.3 - PET Scanning

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.

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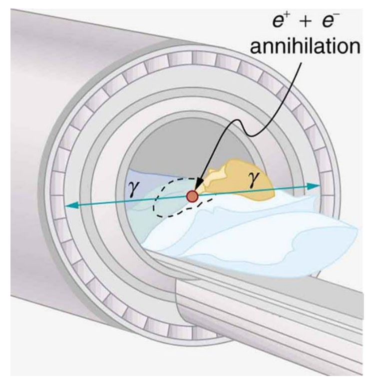

The **advantages** of PET scanners:

- 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.