AQA Physics A-level
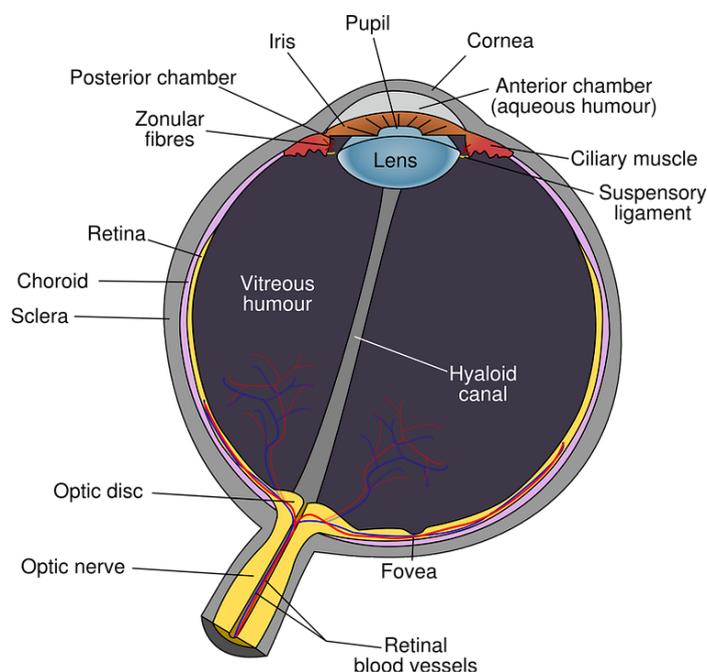
Section 10: Medical physics

Notes

3.10.1 Physics of the eye

3.10.1.1 - Physics of visions

The eye is surrounded by a tough protective layer known as the **sclera**; this is lined with the **choroid,** which is a tissue that supplies the eye with food and oxygen and contains dark pigment which **reduces reflection and therefore blurring** of images.

At the edges of the **cornea** (this is the transparent part of the sclera) you will find **ciliary muscles**, which control the shape of the lens. **Accomodation** is where the lens of the eye changes shape in order to focus on a certain object. When the **ciliary muscles are relaxed**, the eye can focus clearly on objects at a distance of **5 m to infinity**, however when an object closer than this must be viewed clearly the **ciliary muscles contract**, causing the lens to become **more curved** and so its **focal length** (explained in more detail in 3.10.1.2) decreases, and the object can be seen clearly.

The **iris** is a ring of muscle which controls the amount of light which enters the pupil. In low light levels, the **iris dilates** to **allow as much light to enter as possible** and in high light levels the **iris contracts**, so that the **image can be focused onto the fovea** and so that the outermost rays of light are removed as they will not produce a sharp image.

At the back of the eye (inside the choroid) is the **retina**, this is where images are brought to focus by the lens. The retina is formed of two types of **photodetectors** (light-sensitive cells), which produce electrical signals when light is shone on them (like a photoelectric cell), these signals are then transferred to the brain allowing you to see.

The two types of photodetectors are:
- **Rods** - These are activated by **low light levels**, but because many rods many be connected to one nerve fibre, the image they produce is not very clear and as they do not differentiate between wavelengths of light, the image is also gray-scale. They contain a substance called **rhodopsin**, which is destroyed by light, however this process can be reversed by enzymes, though this process takes some time. In very low-light levels, the enzymes will **reform the rhodopsin fully** allowing the eye to reach its **maximum sensitivity** (this is known as dark adaptation).
- **Cones** - These are activated by much **higher light levels**, however they are each connected to an individual nerve fibre, allowing for greater detail in the image they produce. Cones also contain **three types of light-sensitive material**, each of which can **detect one of the primary colours**, the intensity of all of the three colours detected will produce an image of the light observed.

The **fovea (yellow spot)** is a part of the retina, directly behind the pupil and is made up of only **cones**, as you move away from this spot the density of cones greatly decreases, while the density of rods increases. Therefore, if you are **looking directly at an object** (in high light levels) you will see it in the **greatest possible detail**, however in **low light levels the fovea cannot be used** as the cones are not activated and so you will notice greater detail at the peripherals of your vision.

Spatial resolution is what you use to observe small details, this is best on the fovea in high light levels, and at the peripherals of your vision in low light levels. The conditions necessary for two details/images to be distinguished is at least **one rod or cone between the light from each of them**.

The eye is known as an **optical refracting system**, because light refracts through it at several points, such as the cornea and lens. You can calculate the **power** of the eye, which is **a measure of its ability to bend light**, by finding the **sum of the powers of the individual refracting parts**.

The **near point** (around 25 cm for healthy eyes) is the **closest distance** which the eye can focus on and the **far point** (infinity for healthy eyes) is the **furthest distance** at which an object can be focused.

The eye acts as a **converging lens**, meaning it causes light to focus at a point as shown in the diagram below.
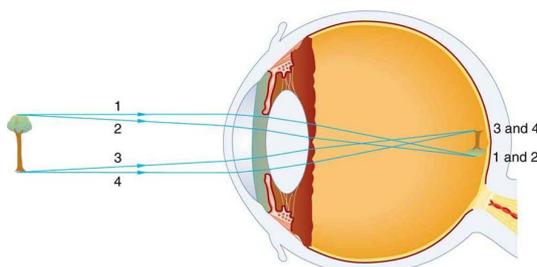

Image source: OpenStaxCollege, CC BY 4.0

When the object is further than 5 m away, the lens doesn't need to change shape in order to focus an image onto the retina. However, if the image is closer than 5 m, the **ciliary muscles will**

contract causing the lens to become **more curved** causing its **focal length to decrease** and **power to increase**.
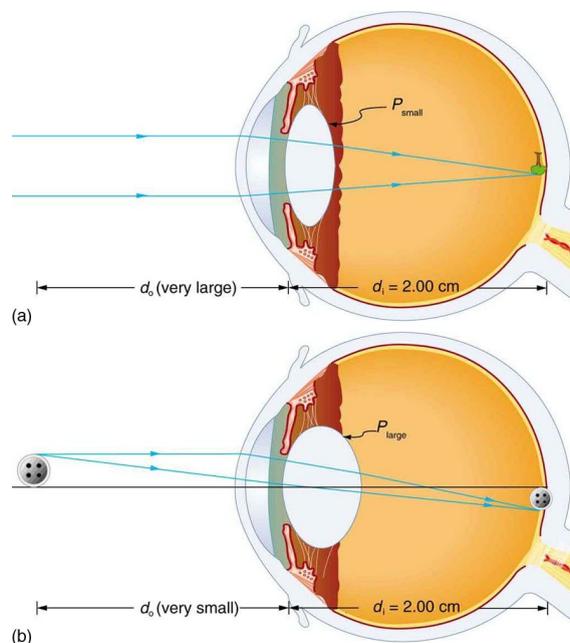

Image source: OpenStaxCollege, CC BY 4.0

3.10.1.2 - Defects of vision and their correction using lenses

Lenses **refract light in order to change its direction**, and there are two types of lenses:
- **Converging (convex)** - these are curved outwards on both sides and causes **parallel light rays to move closer together/converge at a point**. These lenses can form both **real images**, **which can be projected onto a screen** and **virtual images**, **which can't be projected onto a screen** because the light rays appear to be coming from another point in space. **Real** images are formed when the object is **further than the focal length**, while **virtual** images are formed when it is **closer than the focal length (f)**.
- **Diverging (concave)** - these are curved inwards on both sides and cause **parallel light rays to move apart/diverge**. Diverging lenses always form a **virtual image**.
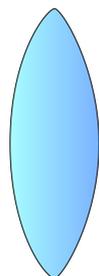
Image source: Durova, CC BY-SA 3.0
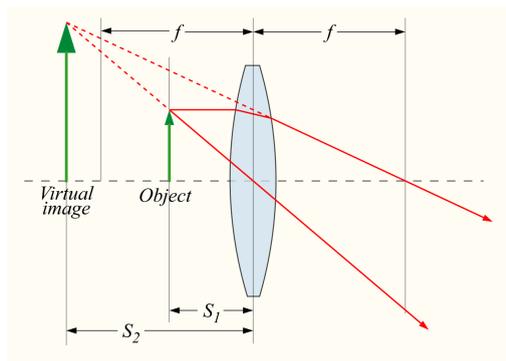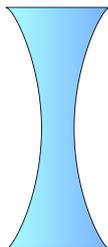
There are 3 main features associated with lenses that you need to be aware of:

➔ **Principal focus (F)** -
  In a **converging** lens: the point at which the light rays which are parallel to the **principal axis** (shown on diagram, perpendicular to the lens axis) are **focused.**
  In a **diverging** lens: the point from which the light rays **appear to come from.**
➔ **Focal length (f)** - the distance from the centre of the lens to the principal focus.
➔ **Power** - the measure of a **lens' ability to bend light**. In **converging** lenses this value is **positive** and in **diverging** lenses this value is **negative**. You can calculate the power of a lens by using the following formula:

$$Power = \frac{1}{f}$$ Where f is the focal length.
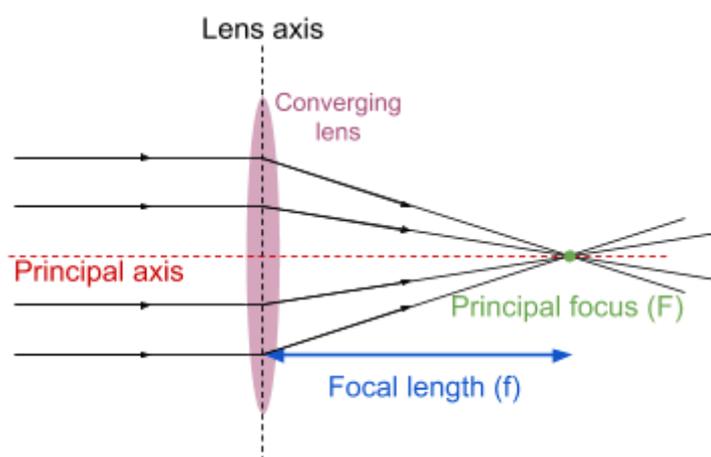
You can use **ray diagrams** in order to map where an image will appear after passing through a lens. To draw a ray diagram:

1. Draw **two lines from the same point of an object** (e.g the top), one which **passes through the centre of the lens** and is left unrefracted and one which moves **parallel to the principal axis** and passes through the principal focus.
2. If the image is **real**, it will from where the **two lines meet**. If it is **virtual**, it will appear where the **two lines appear to come from**, this can be found by drawing a dashed line backwards from both of the initial lines and finding the point they meet.
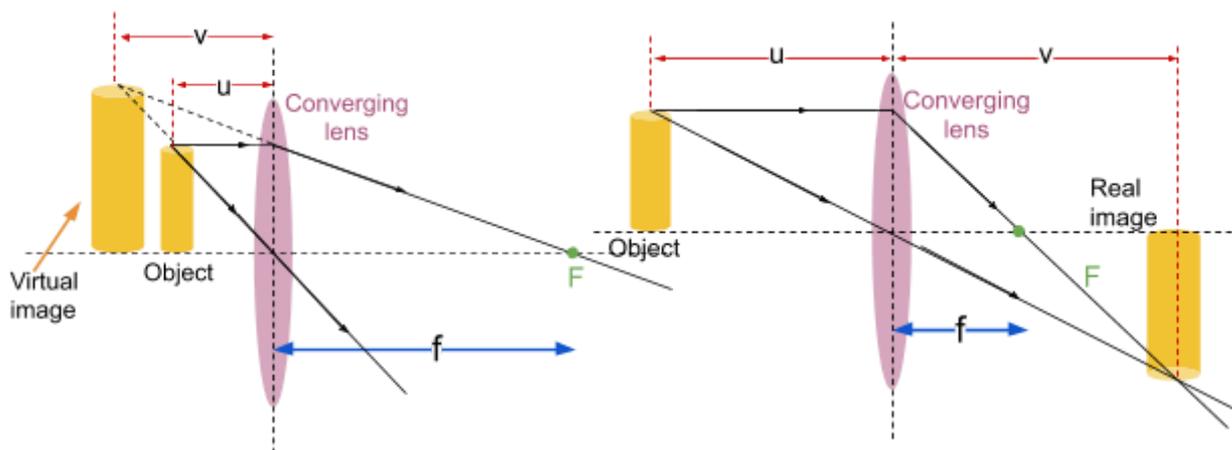
On the two diagrams on the previous page, the distances **u** and **v** can be used to find the **power** of the lens by using the following formula:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f} = power$$

Where **u** is the **distance between the object and the lens axis**, **v** is the **distance between the lens axis and the image** (positive if real, negative if virtual) and **f** is the focal length.

Using these values you can also measure the **magnification (m)** of the lens:

$$m = \frac{size\ of\ image}{size\ of\ object} = \frac{v}{u}$$

There are 3 possible defects of vision you must know about:

- **Myopia** (short-sightedness) - This is where the eye is **unable to focus on objects which are far away** because the image of distant objects is focused before the retina. This occurs when the eyeball is too long, or the combined power of lenses is too high, and the **far point is less than infinity**.
    - This can be corrected through the use of **diverging lenses** (**where focal length = - far point**)

- **Hypermetropia** (long-sightedness) - This is where the eye is **unable to focus on objects which are close to it** because their image is focused behind the retina. This occurs when the combined power of the lenses is too small, or when the flexibility of the lens is reduced and so accommodation is limited and the near point is further away than 25 cm.
    - This can be corrected through the use of **converging lenses**.

- **Astigmatism** - This occurs when the cornea is not spherical and so different planes of the cornea have different curvatures (and so different refracting powers) and will diffract light in different directions, therefore the **image is unevenly focused on the retina**.
  This can be corrected through the use of **cylindrical lenses**. The **prescription** given to treat astigmatism will include both the **power** of the lens (required to correct myopia/hypermetropia) and the **axis angle of the lens**, which is how curved the lens needs to be for correction.
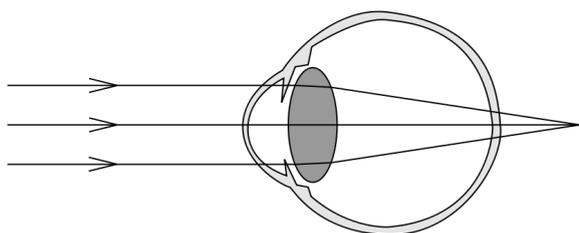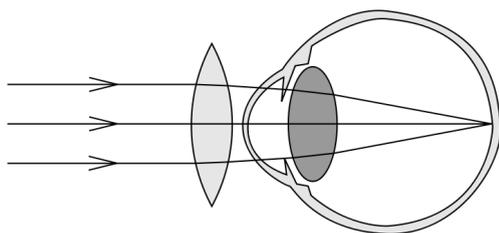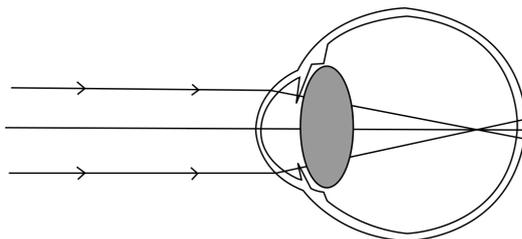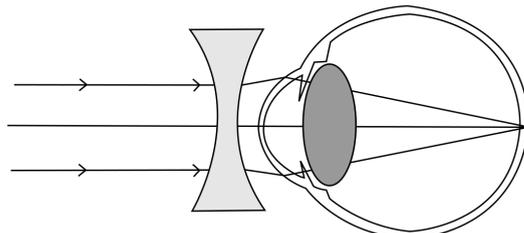
Hypermetropia

Image source: CryptWizard,CC SA 1.0

Myopia

Image source: CryptWizard,CC SA 1.0

Below are some example calculations:

A converging lens has a focal length of 5 cm, at what distance will this lens form an image which is 20 cm away?

For this question you will need the lens equation: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

u is the distance from the object to the lens, which is what you are trying to find.
v is the distance from the image to the lens, which is 20 cm and **f** is the focal length, which is 5 cm.

$\frac{1}{5} = \frac{1}{u} + \frac{1}{20}$ $\qquad$ $\frac{1}{u} = \frac{3}{20}$ $\qquad$ $u = \frac{20}{3}$ **cm**

A diverging lens with a focal length of 40 cm forms an image that is 20 cm tall and is 5 cm from the lens. What is the size of the object?

For this question you will need the lens equations: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$ and $m = \frac{v}{u}$

First, write down all the information you have been given:

f = 40 cm $\qquad$ v = **-5 cm** (as the lens is diverging so will form an image in front of the lens)

Find u using the first lens equation.

$\frac{1}{40} = \frac{1}{u} - \frac{1}{5}$ $\qquad$ $\frac{1}{u} = \frac{9}{40}$ $\qquad$ $u = \frac{40}{9}$ cm

Calculate magnification using the second formula.

$m = \frac{5}{40/9}$ $\qquad$ $m = \frac{9}{8}$

Divide the image size by magnification to find the object size.

Object size = $\frac{20}{9/8} = \frac{160}{9}$ **cm**

Bill is short-sighted, his far point is 100 cm and the distance between his lens and retina is 2 cm. What is the power of the lens which can correct his vision?

To solve this you must remember that **short-sightedness is corrected using diverging lenses** where the **focal length = - far point**, and use the equation $Power = \frac{1}{f}$

f = -100 cm = -1 m   You must change the units to **metres** to find the power in dioptres (D)

$power = \frac{1}{-1} =$ **-1 D**

Melinda is long-sighted, her near point is 2.5 m and the distance between her lens and retina is 2 cm. What is the power of the lens which can correct her vision?

To solve this you must remember that the **near point of a healthy eye is 25 cm**, and use the lens formula $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$.

First, you must calculate the power of Melinda's eye for an object at her near point, so **u** would be 2.5 m, while **v** is 2 cm.

$Power = \frac{1}{f} = \frac{1}{2.5} + \frac{1}{0.02}$ You must change the units to **metres** to find the power in dioptres (D)

$Power = 50.4\ D$

Next, you must calculate the power required to focus on an object at a normal near point of 25 cm, so **u** would be 25 cm, while **v** is still 2 cm.

$Power = \frac{1}{f} = \frac{1}{0.25} + \frac{1}{0.02}$ You must change the units to **metres** to find the power in dioptres (D)

$Power = 54\ D$

Therefore the refracting power of her eyes must increase by 3.6 D, as this is the **difference between the power of her eyes and the power needed to focus objects at 25 cm**. So the power of the lens required to correct her vision is **3.6 D**.

3.10.2 Physics of the ear

3.10.2.1 - Ear as a sound detection system

The ear is formed of 3 sections:
- **Outer ear** - formed of the **pinna** (ear flap) and the **external auditory canal.**
  The **pinna** collects sound, and is shaped so that sound from ahead is more easily detected, meaning the direction of a source source can be identified, and directs it down the **external auditory canal**, which leads to the **tympanic membrane** (ear drum). The **auditory canal** contains **wax glands**, which secrete a substance which helps protect the **tympanic membrane** and keep it flexible.
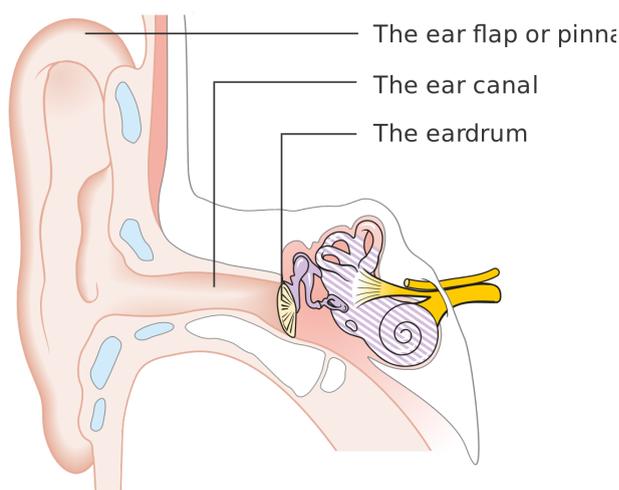

The ear flap or pinna
The ear canal
The eardrum

Image source: Cancer Research UK uploader,CC BY-SA 4.0

- **Middle ear** - formed of the **ossicles** (ear bones), **Eustachian tube, oval window** and **round window**. The **ossicles** are a group of three **connected** bones: the **malleus** (hammer), **incus** (anvil) and **stapes** (stirrup). The **malleus** is connected to the tympanic membrane, while the **stirrup** is connected to the oval window, and the ossicles act as a **lever** which **amplify the vibrations** from the tympanic membrane (by a factor of around 1.5), **transmit them to the inner ear** (through the oval window) and **reduce the amount of energy reflected** from the inner ear. The **Eustachian tube** is connected to the throat, allowing the middle ear to remain at **atmospheric pressure** (like the outer ear). The **oval window** has a **very small area** in comparison to the tympanic membrane, causing an increase of pressure variations of around a factor of 15. Along with the increased force created by the **ossicles** acting as a lever, the **pressure detected by the tympanic membrane is increased by around a factor of 20** by the time it reaches the **oval window**. The **round window** allows fluid in the inner ear to move by allowing the inner ear to have two flexible ends.
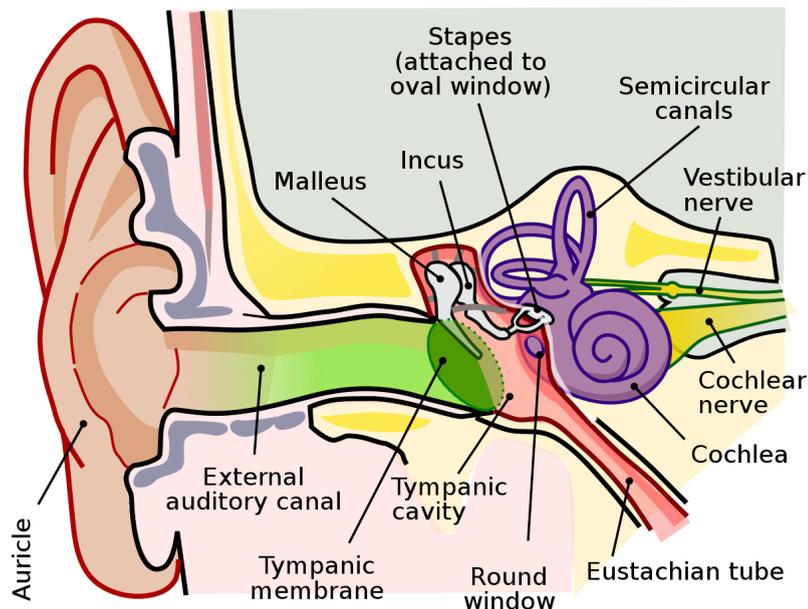
Green = outer ear, red = middle ear, purple = inner ear
Image source: Lars Chittka; Axel Brockmann,CC BY 2.5

- **Inner ear** - is **filled with fluid called perilymph** which allows the transmission of vibrations and is formed of the **cochlea**, the **auditory nerve** and **balance organs (semicircular canals)**. The **balance organs** detect orientation and changes in velocity. The **cochlea** is an organ in the shape of a **spiral** and is filled with a fluid called **endolymph**, which allows vibrations to pass through the entire length of the organ to the **basilar membrane**, which is covered in **hair cells** which **produce electrical signals when caused to vibrate at large amplitudes**. The vibrations of the oval window are transmitted through the cochlea as pressure waves, and cause the **basilar membrane** to vibrate. The basilar membrane has different regions with different natural frequencies, meaning a certain region will experience resonance (depending on the frequency of the vibrations) and vibrate at a large amplitude. **Hair cells** in this region will produce electrical signals which are passed along the **auditory nerve** to the brain to be interpreted. Hair cells that detect high frequency sounds are found close to the base of the cochlea, while those which detect low frequency sounds are found near the apex of the cochlea (the further point from the oval window).

As sound waves move through all three sections of the ear their amplitude will decrease, but their frequency is constant.
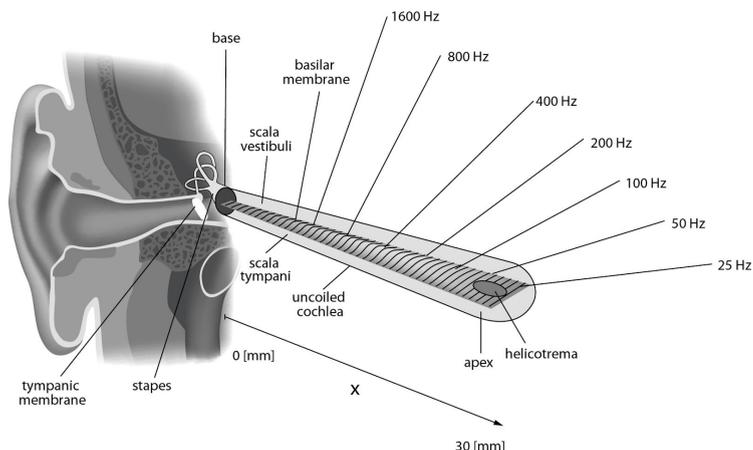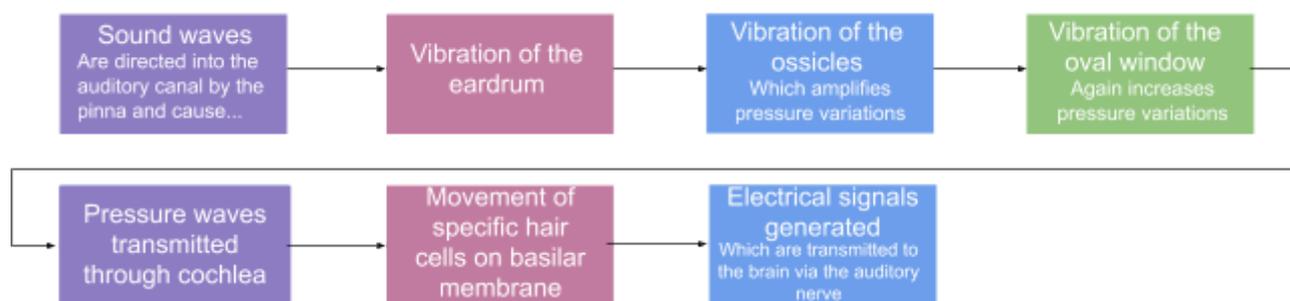
Image source: Kern A, Heid C, Steeb W-H, Stoop N, Stoop R,CC BY 2.5

Below is a diagram summarising the mechanism of hearing and all the steps involved:

3.10.2.2 - Sensitivity and frequency response

The **intensity (I)** of a sound is defined as the amount of energy arriving at the ear per second per unit area, or the power per unit area, and its unit is **Wm⁻²**.

$$I = \frac{P}{A}$$

Where I is the intensity, P is the power and A is the area.

Sound spreading out from a point source can be assumed to move **equally in all directions**, and so its intensity follows an inverse square law. To measure the intensity at a certain distance away from a source, you must use the **area of a sphere** with a **radius of the distance from the source**, as the area in the calculation. For example:

A source produces a sound of power 15 W, what intensity of this sound would be heard from 5 m away?

Find the area of a sphere with a radius of 5 m.
$4 \times \pi \times 5^2 = 100\,\pi$

Find intensity using $I = \frac{P}{A}$.
$I = \frac{15}{100\pi} = 0.05$ Wm⁻²

The **threshold of hearing** is the **minimum intensity of a sound that a human ear can detect**, and it is defined as **1 pWm⁻² at 1 kHz**. The frequency of a sound will affect its perceived loudness, which is why the threshold of hearing is defined as an intensity at a certain frequency, this is because our ears are naturally better at detecting certain frequencies than others.

The **threshold of pain** is the **maximum intensity of a sound that a human ear can detect** without extreme discomfort, and it is defined as **1 Wm⁻²**. This gives a **possible range of 10^{12} sound intensities** that can be detected by the human ear, however a sound at an intensity of 1 Wm⁻² is not perceived as 10^{12} times as loud, this is because the ear automatically decreases the amplification of high intensity sounds, therefore there is **not** a linear response between sound intensity and perceived loudness. For example, the crinkle of a wrapper in a cinema may be perceived as much louder than the same sound in a loud school canteen, this is because perceived loudness is proportional to the change in intensity over the initial intensity. The **change**

in loudness detected is actually proportional to the logarithm of intensity change, which is what allows the ear to have this huge range.

A **logarithmic scale** is therefore used to compare sound intensities because of the ear's logarithmic response and because of the huge range of possible intensity levels. You can measure the **relative intensity level of a sound in comparison to the threshold of hearing** by using the following formula:

$$Relative\ intensity\ level\ =\ 10\ log_{10}\frac{I}{I_0}$$

Where I is the intensity level and I_0 is the threshold of hearing (1 pWm^{-2}).

The unit used for the **relative intensity level** as compared to the threshold of hearing is the **decibel (dB)**. By using the formula above, you can see that an increase in 10 dB is equal to the sound intensity increasing by a factor of 10, while an increase in 20 dB is equal to the sound intensity increasing by a factor of 100.

$$10\ dB\ =\ 10\ log_{10} x \quad\quad 1 = log_{10} x \quad\quad x = 10^1 \quad\quad (where\ x = \frac{I}{I_0}\ )$$
$$20\ dB\ =\ 10\ log_{10} x \quad\quad 2 = log_{10} x \quad\quad x = 10^2$$

Relative intensity level (dB)	Intensity (Wm^{-2})	Example/effect
0	1×10^{-12}	Threshold of hearing at 1 kHz
20	1×10^{-10}	Whisper at 1 m distance
40	1×10^{-8}	Average home
60	1×10^{-6}	Normal conversation
80	1×10^{-4}	Loud radio, classroom lecture
100	1×10^{-2}	Noisy factory, siren at 30 m; damage from 8 h per day exposure
120	1	Loud rock concert, pneumatic chipper at 2 m; threshold of pain
140	1×10^2	Jet airplane at 30 m; severe pain, damage in seconds

Table source: OpenStax College, CC BY 4.0, Table is modified (some rows excluded and titles changed)

Image source: Federal aviation administration,CC0 1.0
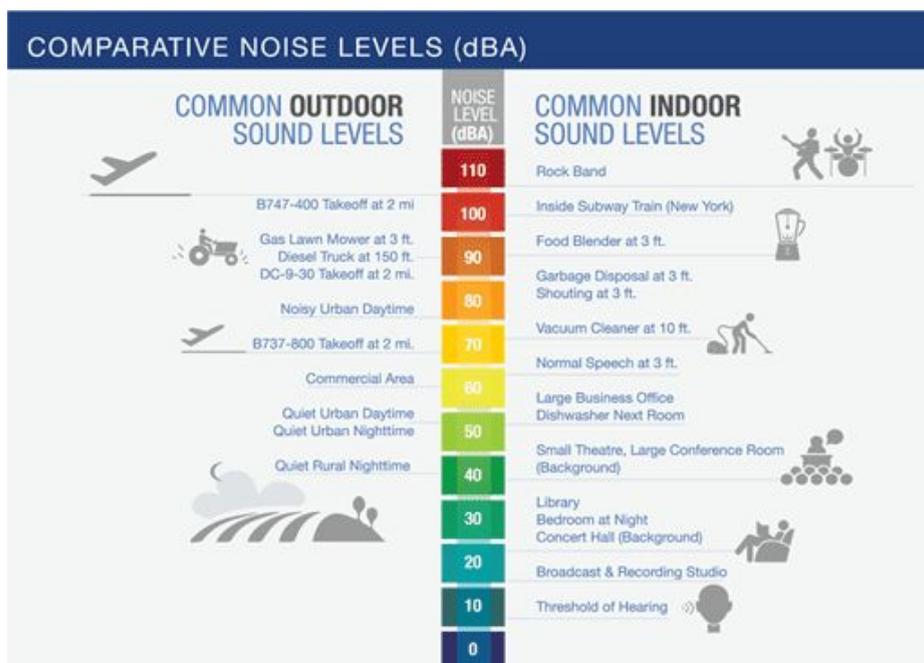
It is important to note that the **relative intensity level is not a measure of loudness**, as perceived loudness is subjective, for example a sound at 50 dB may seem louder to some than to other people hearing the exact same sound, this is due to the variations of sensitivity of different people's ears.

The **sensitivity of our hearing depends on the frequency of the sound detected**, the human ear is most sensitive at detecting sounds from 2 kHz to 5 kHz, being **most sensitive at 3 kHz**, and as the frequency increases above or decreases below this range, the sensitivity decreases. This can be illustrated by **equal loudness curves (also known as audiograms)**, which showcase the required relative intensity level to detect a sound at a number of frequencies and **vary from person to person**.
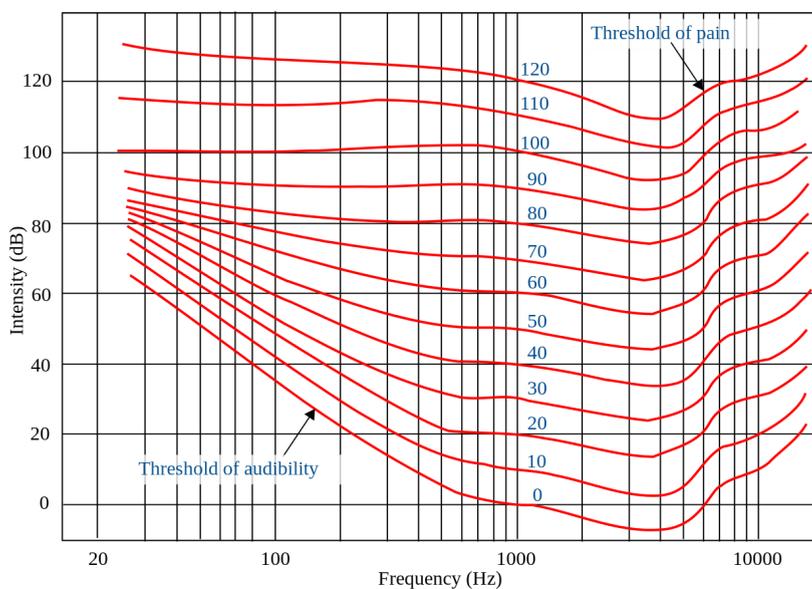

Image source: Oarih,CC BY-SA 3.0

In order to produce an equal loudness curve the **loudness of a standard sound is compared to the loudness of a second sound**; this is done by **adjusting the intensity of the second sound until it is the exact same perceived loudness as the standard sound**. Therefore equal loudness curves demonstrate the **sound intensity required for each frequency to have the same perceived loudness**. A **logarithmic scale** is used due to the huge range of possible frequencies.

Because the perceived loudness of a sound (for humans) is dependent on its frequency, **sound level meters are fitted a filter called the A weighting filter in order to be able to mimic human ear's response to different frequencies of sound**. The sound intensity level measured by a sound level metre is given the unit **dBA**, and this scale is used in environmental noise monitoring and hearing tests.

The graph below shows the effect of different types of weighting filter on the measured intensity level, you only need to be aware of the effect caused by an A weighting filter (red line).
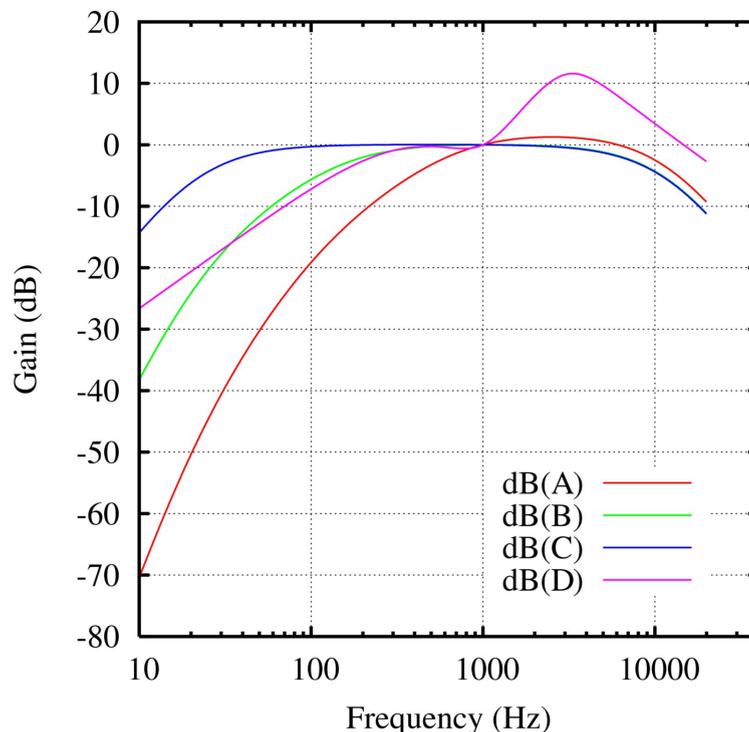
Image source: Omegatron, CC BY-SA 3.0

3.10.2.3 - Defects of hearing

Hearing loss is where you hearing has become less sensitive and needs to experience higher intensity sound waves in order to have the same perceived loudness.
Hearing loss can be caused by **deterioration with age** or by **injury** caused by exposure to very loud noise over time e.g. from working in a noisy factory. The degree of hearing loss is not uniform for all frequencies:

- When caused by **deterioration with age**, the **higher frequencies are affected more than lower frequencies.**
- When caused by being **exposed to a certain frequency** of sound over time, **the frequency of that sound or sounds will be affected the most.**
- When exposed to **excessive noise**, frequencies around **4 kHz will be affected the most**.

Equal loudness curves can be used to **detect the cause of hearing loss**. When hearing has **deteriorated with age** an equal loudness curve will be **higher at all frequencies**, but most noticeable higher at the higher frequencies, but will follow the same general shape as the equal loudness curve of a person with healthy hearing. However, when hearing has been caused by an **injury** the equal loudness curve will have a **peak at a range of the most affected frequencies**, which are the frequencies of sound which caused the hearing loss.
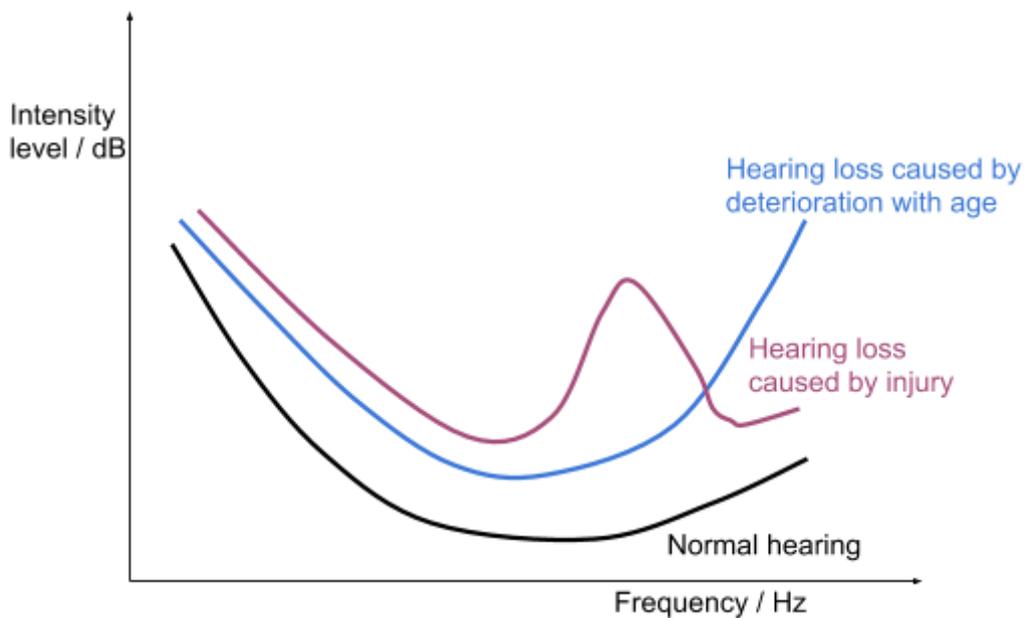
3.10.3 Biological measurement

3.10.3.1 - Simple ECG machines and the normal ECG waveform

The heart is a large muscle that acts as a double pump, which moves blood through the lungs and around the entire body. The two sides of the heart (right and left) each have a chamber called an **atrium and a ventricle separated by a valve**. In order to move blood from the atria to the ventricles, the atria **contract**, then once all the blood enters the ventricles, the ventricles will **contract** causing blood to be pumped away from the heart.
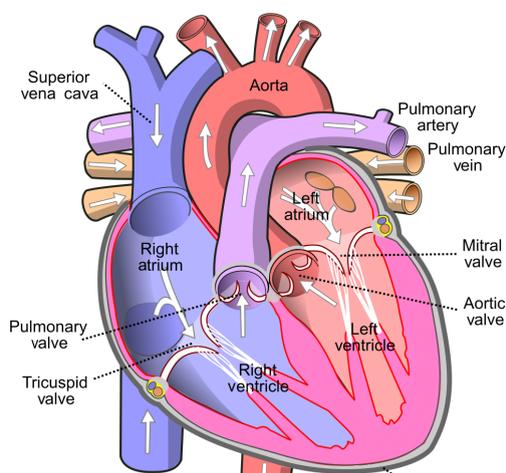
Image source: Wapcaplet,CC BY-SA 3.0, Image is cropped

The contractions of the atria and ventricles are controlled by **electrical signals** produced by the heart in the **sino atrial(S-A) node**, which firstly move across the atria, then after a **short delay** of the signal in the **atrioventricular(A-V) node**, the signal moves across the ventricles causing them to contract. These electrical signals can be measured using an **electrocardiograph**, which forms an **ECG (electrocardiogram)**, which shows the **change in potential difference over time**.

Image source: Rasel Hossain Md,CC BY-SA 4.0, Some information is removed from the diagram

When muscles in the heart are in their **relaxed state** they are **polarised,** when the muscles experience a potential they become **depolarised** and so will **contract**, and slowly become repolarised. This occurs due to the change in ion imbalances in the cells.
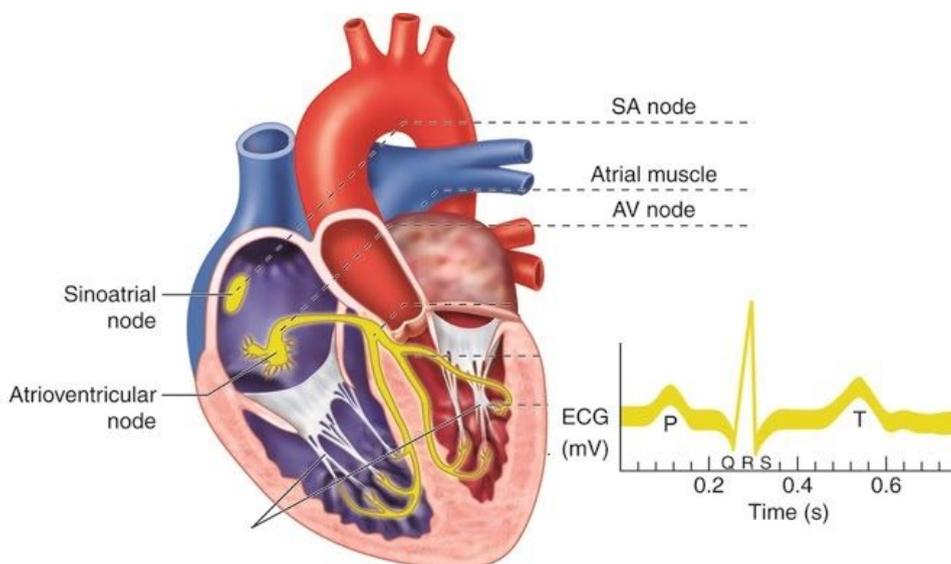
In order to produce an ECG, **several** electrodes are connected to a patient's body where arteries are close to the surface, as this is where the largest values of potential difference can be measured. And the change in potential difference is measured over time. Several steps are taken to ensure the **best possible connection of electrodes:**

- The **electrodes are attached to the patient firmly** (usually using tape) to reduce the effect of noise on the reading.
- **Dead skin cells and hair are removed** from the connection site through the use of **abrasive paper** (e.g. sandpaper), this is so that contact resistance is decreased.
- A **conducting gel** is used between the electrodes and the skin to remove air so that electrical contact is improved.

Electrical noise (unwanted detection of potential difference) must be reduced in order to produce the most accurate ECG possible, this is done by:

- Making sure the **patient is relaxed** and stays still because electrical signals produced by muscle movements can be detected.
- **Shielding the electrocardiograph** and any leads connected to it from any sources of alternating current (e.g. mains electricity) as this may produce unwanted signals.
- **Electrodes** are made out of a **material which does not react** with chemicals produced by the skin so no unwanted signals are produced.
- As mentioned above, **electrodes are attached firmly to the patient**, to reduce the movement of the electrodes and the production of any signals through electrostatic effects.

The signal detected by the electrodes must be **amplified**, which means reducing noise is vital as the noise will also be amplified. The amplifier must:

- Be **High-gain** - so that the tiny signals detected at the skin are significantly amplified.
- Be **Low noise** - so that the reading is not affected.
- Have a **high input resistance** - to minimise the distortion of the signal received.

An ECG waveform is formed of 3 distinct waves:

1. **P wave** - this is when the **electrical signal is first produced** in the **sino atrial(S-A) node** and **causes the atria to contract (depolarisation).**
2. **QRS wave** - this occurs around **0.2 s later** and this is where the **electrical signal leaves the atrioventricular(A-V) node** and **causes the ventricles to contract (depolarisation)** (The relaxation/repolarisation of this atria also occurs here but cannot be detected as it is masked by the large spike caused by the contraction of the ventricles).
3. **T wave** - this occurs around **0.2 s later** again and is where the **ventricles relax/are repolarised in preparation for a second heartbeat**.

The following diagram displays the described wave types:
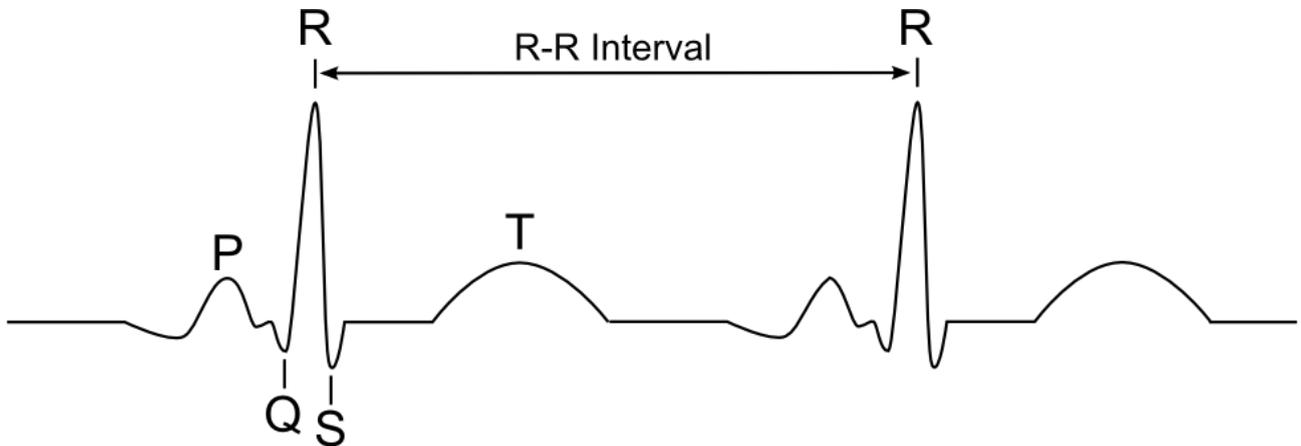
Image source: Tedburke,CC BY-SA 4.0

By measuring the distance labelled R-R interval, you can find the **period** of the waveform and use this to find the **pulse rate per minute**:

$$Pulse\ rate\ per\ minute = \frac{60}{period\ in\ seconds}$$

By measuring the height of the peak of the waveform from the flat part of the trace, you can find the **amplitude** of **potential difference detected at the skin** which is around **1 mV**.

If the person connected to the electrocardiograph began to exercise, their pulse rate would increase therefore the period of the ECG waveform would decrease and the length of the flat part of the trace would decrease.

3.10.4 Non-ionising imaging

3.10.4.1 - Ultrasound imaging

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 used 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** (the reverse is also true), this is known as the **piezoelectric effect** and it is used to produce ultrasound waves.
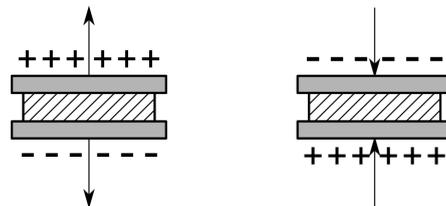
A transducer, containing piezoelectric material is used to transmit and detect ultrasound waves, this is because:

- 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 produce pulses of ultrasound waves that are 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 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)	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

Table source: OpenStax College,CC BY 4.0, Table is modified (some rows excluded)

You can calculate the proportion of the incident ultrasound signal that is reflected when it moves between two 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 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 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, decreasing their amplitude. The **degree of attenuation is increased as the acoustic impedance of the material the ultrasound is travelling through increases**. Therefore reflected ultrasound waves which have travelled further in the body must be amplified more to reduce loss of data, this is done by a **swept-gain amplifier** attached to the time-base of the oscilloscope displaying the reflected waves.

There are two types of ultrasound scans which can be used for medical imaging:
- **A-scan (Amplitude scan)** -
    1. **Short pulse** ultrasound waves are transmitted into the body, at the **same time** as the pulse is first emitted by the transducer the electron beam on a cathode ray oscilloscope (CRO) begins to move across the screen.
    2. The pulse travels inside the body until it reaches a **boundary between two mediums** where some of the pulse is reflected back towards the transducer.

3. The reflected ultrasound will cause an **p.d to be generated** in the transducer (due to deformation of a piezoelectric material), which can be displayed on a CRO by the **vertical displacement** of the electron beam for the duration of the received signal.

4. The beam then moves back to the equilibrium position until another signal is received.

Because the electron beam on the CRO begins moving as the ultrasound is emitted, the **horizontal displacement** between the vertical displacement due to the reflected signal signifies the amount of **time taken for the ultrasound to travel through the body, to the boundary and back**. This information along with the speed of ultrasound in the body can be used to assess the **depth** of the structure on which the ultrasound was reflected.

This type of scan is very useful when the surface that needs to be imaged lies across a particular line through the body, however it is not useful for complex structures.
This type of scan is used to measure distances in the eye and the bi-parietal diameter of a foetus, in order to measure its development.
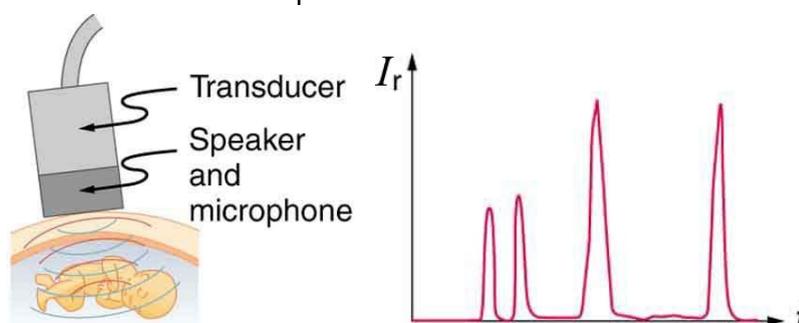

Image source: OpenStax College,CC BY 4.0, Images are cropped

- **B-scan (Brightness scan)** -
  Forms an image by **moving the ultrasound beam across the patient**, this is done because reflected signals can only be received if the **transducer is normal to the reflected beam**, which isn't always the case due to the different shapes of surfaces inside the body.
  In this type of scan the **amplitude of the reflected signal is used to determine the brightness** of a spot on an oscilloscope. Information about the position of the transducer is monitored in order to determine where the spot should be placed on the screen, and so a 2D image of a section of the body can be formed.

  This type of scan is used to find the midline structure of the brain in a foetus in order to know in which region an A-scan can be used to measure bi-parietal diameter, it is also used to determine the position of the placenta so that it can be determined whether a baby will have a safe delivery or if it will need to be delivered by caesarean section. It is also used in order to perform genetic testing on a foetus by imaging the position of the placenta and foetus accurately.
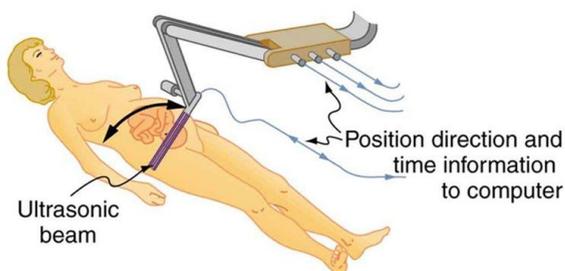
The **advantages** of ultrasound imaging are:
- It is a **non-invasive** procedure, and produces **no known hazards** to a patient or the operator, unlike x-rays which cause exposure to radiation.
- It is very good at imaging soft tissues, and produces a **real-time image** allowing movement to be observed (e.g movement of a heart valve).
- It is relatively **cheap** and very **portable.**
- It is a quick procedure (around 15 minutes), and produces no discomfort.

The **disadvantages** of ultrasound imaging are:
- You **cannot** view regions of the body **behind bone** (e.g the brain) or **behind the lungs** because almost all of the ultrasound will be reflected before entering that region.
- The **resolution** is **relatively poor** in comparison to x-rays, and so fine details cannot be seen.
- In order to produce high quality images the **operator must be skillful** and **experienced**
- Solid masses can be imaged but **no specific details are revealed** through the use of an ultrasound.

3.10.4.2 - Fibre optics and endoscopy

Optical fibres are flexible, thin tubes of plastic or glass through which light can travel with very little loss of intensity due to total internal reflection.
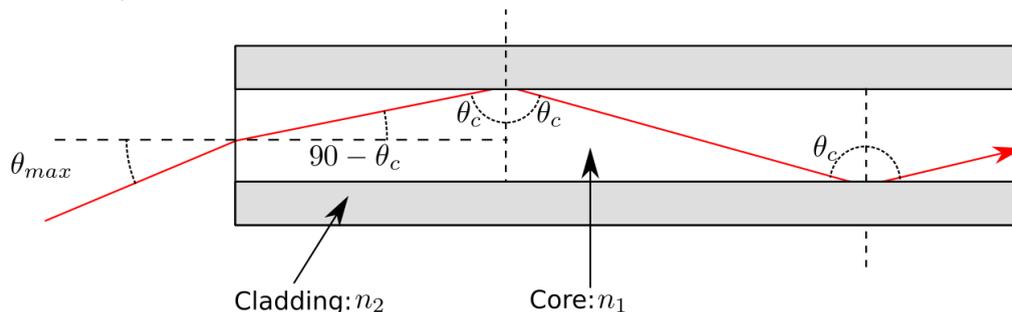
Total internal reflection can occur when the **angle of incidence of the light is greater than the critical angle** and the incident refractive index is greater than the refractive index of the material at

the boundary. Therefore optical fibres have an **optically dense core** surrounded by cladding with a lower optical density allowing TIR to occur, this **cladding** also **protects the core from damage** and prevents **signal degradation** through **light escaping the core**.

Many optical fibres can be used to form a bundle and there are two types of bundle which can be formed:

- **Coherent bundle** - All of the **relative positions of all optical fibres are kept the same** along the entire bundle, therefore an image from one end of the bundle can be clearly seen at the other end (shown on the diagram below).
- **Incoherent bundle** - Individual fibres are **arranged randomly**, therefore an image an image from one end of the fibre can't be viewed at the other end. These types of bundles are **much cheaper** to make and so are **used to transmit light to hard to reach areas**.

The resolution of the image formed by a coherent bundle of fibres depends on the size of the fibres and the distance between them, if the fibres have a **small diameter** and are packed tightly, **more detail** can be seen than if the fibres were larger, however thin fibres are more expensive to produce. Also images can be **magnified** if the **diameter of the fibres gradually increases** along the bundle.
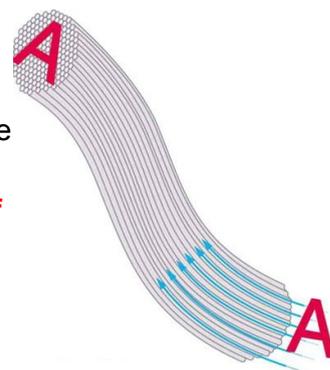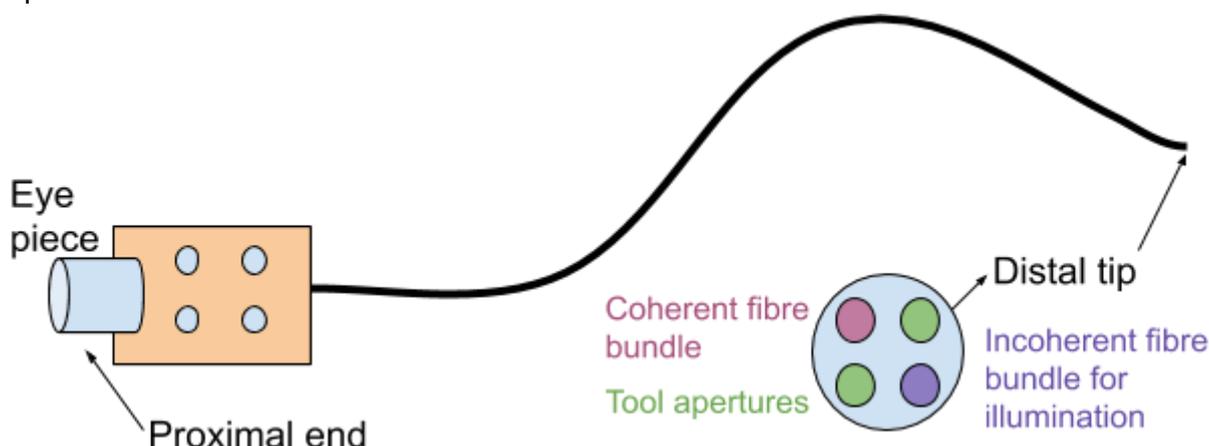
Image source (Right): OpenStax College,CC BY 4.0, Image is cropped

Endoscopes are instruments made for viewing inside the body, and they are formed of an **incoherent bundle** of fibres which **transmit light** to the location so that it can be viewed and a **coherent bundle with an objective lens** (at the distal tip) which **carries back an image** to the eye-piece.

An endoscope may contain other channels such as a **water channel** to clear the lens and a **CO_2 channel** to make room for the endoscope in the body. The tool apertures in the endoscope are used when performing **key-hole surgery**, which is where surgical instruments are passed through the endoscope (or through additional incisions in the body) in order to **perform surgery without the need of making a large incision** to see the area being operated on. Key-hole surgery is **minimally invasive**, meaning the **risk of infection is greatly reduced** and **recovery times are much quicker** making procedures cheaper for hospitals and less distressing for a patient.

Endoscopes are often used in diagnosis in order to **examine internal regions of the body**, and can be used to **look for tumours** and **take biopsies** for examination without the need for open surgery.
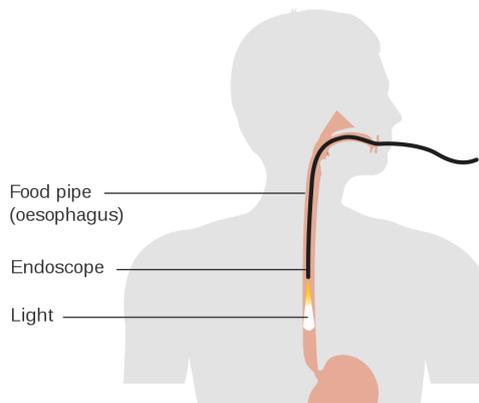

Image source: Cancer Research UK,CC BY-SA 4.0, Image is cropped

3.10.4.3 - Magnetic resonance (MR) scanner

A **magnetic resonance scanner** uses a **superconducting magnet**, which is cooled using **liquid helium**, in order to produce a **uniform magnetic field** in which a patient must lie to form an image.

The uniform magnetic field which is generated affects protons (hydrogen nuclei) in the body as they have a quantum property called **spin**, which makes them behave like very small magnets. Initially, all the protons are positioned **randomly**, however in the presence of the magnetic field, the protons become **aligned parallel to the magnetic field lines**. Spinning protons experience **precession**, which is a slight wobbling motion and as they become aligned parallel to the magnetic field they also **precess about the magnetic field lines**.

Smaller electromagnets are used alongside the main electromagnet in order to form a **gradient of magnetic field strength** across the patient's body by **overlapping magnetic fields**, these smaller electromagnets are known as **gradient coils**. As different areas are experiencing different magnetic field strengths **protons will have different precession frequencies** (the angular frequency at which the precess/wobble), and so will **absorb different frequencies of radiation**.
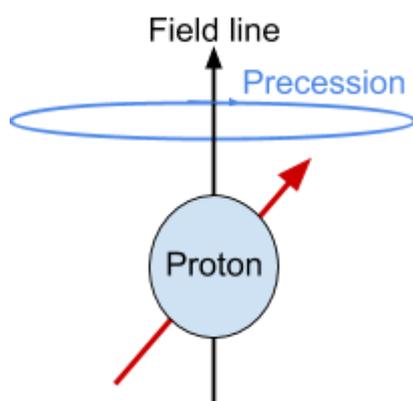
Radio frequency coils are used to produce **pulses of radio waves (radio frequency (RF) pulses)** at different frequencies, which causes protons with the same precession frequency as the

frequency of the radio waves to become **excited**, and to **change their spin state** (their alignment). This occurs in **small successive regions** of the body, as **protons in different regions of the body have different precession frequencies due to the gradient of the field**. When the protons **de-excite** they will emit EM radiation in the form of **radio frequency signals at their precession frequency**, these signals are detected and c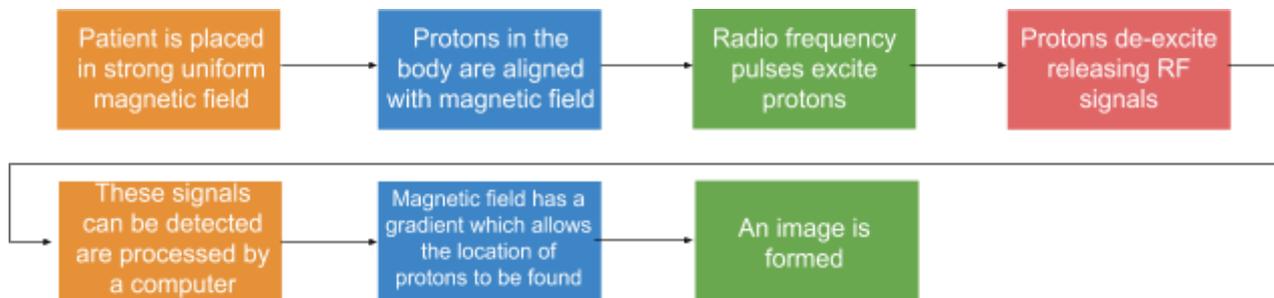an be processed by a computer to form an image as the position of the protons can be calculated from the frequency of the signal they emit.

RF radiation at two different frequencies

Protons in different parts of the body emit different frequencies of RF radiation depending on their location as they have different precession frequencies
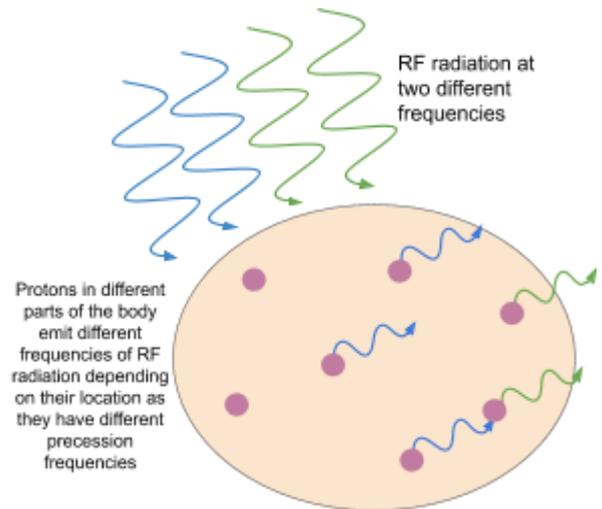
This process can be used to image a 2D cross-section or to build up a 3D image from multiple cross-sections. The process is briefly outlined in the diagram below:

Patient is placed in strong uniform magnetic field → Protons in the body are aligned with magnetic field → Radio frequency pulses excite protons → Protons de-excite releasing RF signals → These signals can be detected are processed by a computer → Magnetic field has a gradient which allows the location of protons to be found → An image is formed

The **contrast in the image can be adjusted** by changing the time between pulses of radio waves, for example tissues formed of **large molecules are best imaged using pulses with a very short time between them**. The image to the right shows the effect of changing the contrast on the image formed.

T1 Weighted   T2 Weighted   Pb Weighted
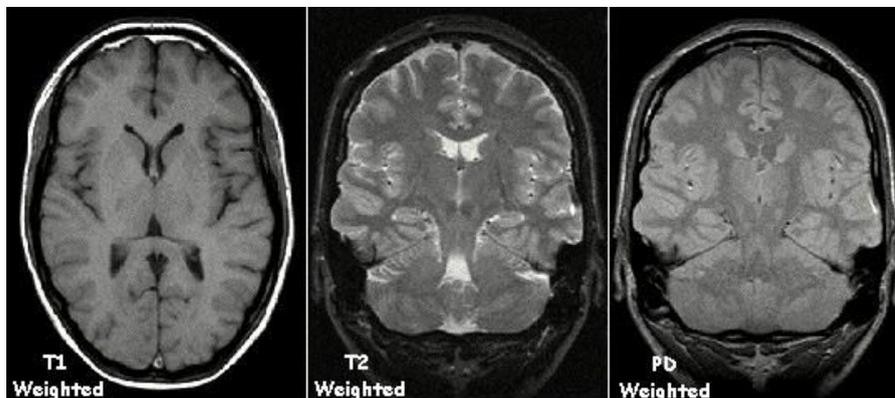
The **advantages** of magnetic resonance imaging are:
- It is a **non-invasive** procedure, and produces **no known hazards** to a patient or the operator, unlike x-rays which cause exposure to radiation.
- **Very high quality images of tissues** can be obtained, even if they are behind air or bone (e.g the brain).
- The **contrast can be adjusted** so that **different regions can be examined in more depth**
- Imaging can be **real-time** and so can movement in the body can be observed.

The **disadvantages** of magnetic resonance imaging are:
- It is **very expensive.**
- **Imaging of bones is poor .**
- Scanners are quite **noisy** and **take a fairly long time**, which causes some **discomfort** for the patient. Also some patients may feel **claustrophobic** while in the scanner.
- This type of imaging **cannot** be used on anyone with **metallic implants** in their body as they could cause real harm.

3.10.5 X-ray imaging

3.10.5.1 - The physics of diagnostic X-rays

Thermionic emission is used in the production of X-rays and this is where a metal is heated until the free electrons on its surface gain enough energy and are 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 will **decelerate and will 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, therefore they are known to form a **characteristic spectrum** of X-ray radiation, which are **line spectra** as only **photons at specific energies** can be emitted.
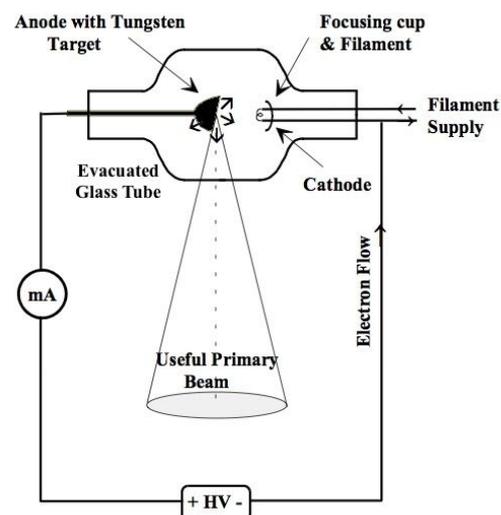
The **maximum X-ray photon energy** produced by the above method is equal to the **product of the charge on the electron**

and the accelerating voltage as this is the value of the kinetic energy of the electrons as they hit the target.

$$Maximum\ photon\ energy\ =\ eV_a$$

Where e is the charge on an electron, and V_a is the accelerating voltage.

If you **combine** both the **continuous spectrum** formed by the bremsstrahlung and the **characteristic spectrum**, you can see the **energy spectrum** of the X-rays produced. As you can see the line spectra is **superimposed** on the continuous bremsstrahlung spectrum.

As the **accelerating voltage is increased**, the **total intensity** of emitted X-ray photons **increases**, the **peak photon energy increases**, the **minimum wavelength decreases** and **more characteristic lines may appear** (as electrons have higher energies). The **intensity is approximately equal to the accelerating voltage squared**.
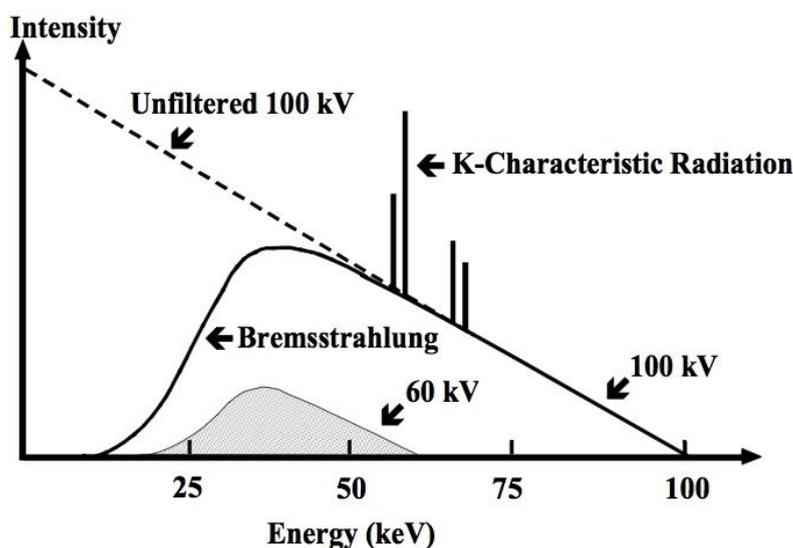
In practice, only around **1% of the electron's kinetic energy is converted into X-ray photons**, most of the energy actually increases the internal energy of the metal target, increasing its temperature. Because of this, the metal target must be made with a metal which is a very **good thermal conductor** and has a **high specific heat capacity and melting point**. **Tungsten** is often used as the metal target because it fulfils the above criteria and its nuclei has a large mass leading to an increased probability of X-ray emission when high-energy electrons collides with it.
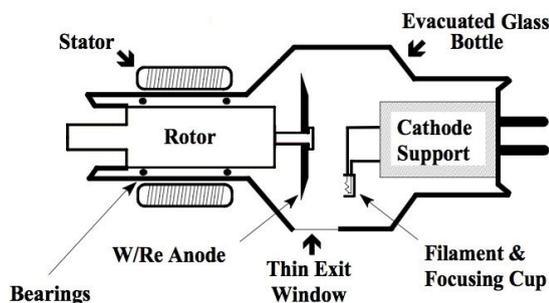
To prevent overheating, the **metal target/anode is also rotated at high speeds** (around 3000 revolutions per minute) so that the electron beam heats different areas of the target. The metal

target has a **bevelled edge**(as seen in the diagram) which allows the **electrons to be focused on to be large area**, while the **source area of the X-rays remains small** (so a sharper image can be produced). **Due to this rotation the target can absorb higher quantities of heat** before melting and so **higher values of anode voltage and current can be used** meaning larger X-ray outputs can occur.

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** and 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 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 through the following ways:

1. Putting **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) as 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.
● **Exposure time**.

Generally, the larger the exposure time, the higher the resolution of the final image, however it can be reduced 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** as they are unlikely to reach 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.
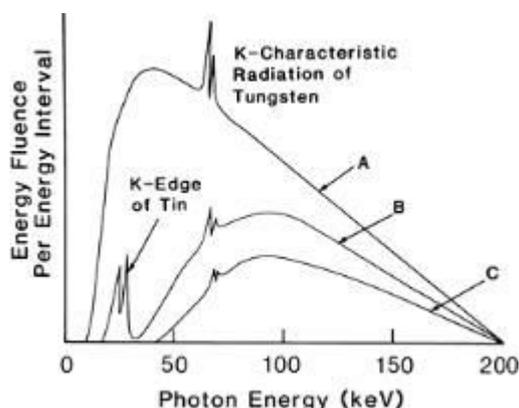
The image on the left shows the effect of 3 different types of filter on the intensity of radiation:
- A - Aluminium
- B - Aluminium and tim
- C - Aluminium, tin and copper

Finally, dose can also be decreased by making the patient wear a **lead-lined apron** to protect the parts of their body, which are not being imaged, from radiation.

3.10.5.2 - Image detection and enhancement

When exposed to X-ray radiation, photographic film only absorbs around 0.1% of the X-ray energy, meaning that for a clear image the **exposure time must be long**, however this will increase the **radiation dose** and **increase the chance of blurring** due to the patient moving.

X-rays can detected digitally by using a **flat panel (FTP) detector**, which uses a **scintillator**, which is **a material that emits light photons when struck by high energy photons** (such as X-rays). The **energy of the light photons emitted by the scintillator is proportional to the energy of the X-rays photons it absorbs**. **Photodiodes** are bound to a scintillator material (e.g caesium iodide), so that when the material emits light photons, the photodiodes can easily absorb them and convert them to electronic charge. **Each photodiode acts as a single pixel**, and the number of them that are present determines the **resolution** of the FTP. The charge on each photodiode is found through **electronic scanning** and the use of **thin-film transistors**, converted to digital signals and sent to an **image processor** which forms a **digital image**.
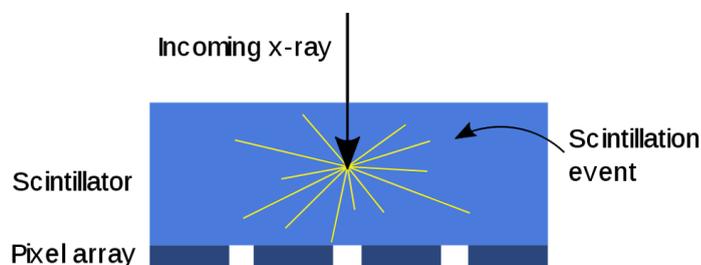
The **advantages** of using an FTP detector over using photographic film are:
- FTP detectors are **more sensitive** than film so a much **lower exposure time** is required to produce the same quality image, so patients receive a **lower dose of radiation.**
- FTP detectors are **much faster** at forming X-ray images as they don't need to be processed or developed like film.

- The digital X-rays formed by FTP detectors can be stored for further use easily, accessed from a device such as a phone or tablet and **can be sent to professionals for evaluation instantly.**
- FTP detectors form images with a **higher resolution** and with **less distortion** in comparison to photographic film.
- FTP detectors are relatively **small** and **light-weight**, meaning they can be **easily transported** around a hospital and positioned around a patient.

To obtain a **clear X-ray image**, the **difference between the proton number of the material being examined and its surrounding should be large**. If this is not the case, the **contrast can be enhanced** by **placing a contrast medium in the area being examined**, which is made up of a material with a high proton number. For example, **barium meal** is used as a contrast medium:

1. The patient swallows the barium meal.
2. It will pass into their gastrointestinal tract, and allow the tract to be seen clearly against surrounding tissue.

Contrast media are known as being **X-ray opaque** as they will absorb more X-ray radiation than its surroundings, and so will appear opaque white on an X-ray image.

To **reduce the exposure time required for photographic detection**, an **intensifying screen** can be used:

- The intensifying screen is formed of **crystals which fluoresce when exposed to X-ray radiation**, this happens because the **screen atoms absorb X-ray photons and their electrons become excited**, and then de-excite emitting visible light photons.
- The film is usually placed between two intensifying screens and in close contact to them, this is so that as much light as possible is captured by the film to produce a **sharp image.**
- As **film is more sensitive to visible light than to X-rays**, the exposure time is reduced meaning a lower radiation dose is received by a patient.
-
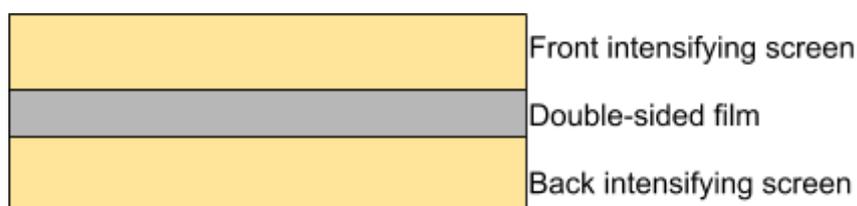
To **form moving X-ray images** to for example, view the movement of an organ, you can use **fluoroscopic image intensification**, which is where a **fluorescent screen** is used instead of film:

- The X-ray photons will hit the fluorescent screen and emit light which can be viewed, however the **output of light from the screen will be very low** so an **image intensifier** must be used along with the screen.
- As light photons are emitted by the fluorescent screen, they will hit a **photocathode**, which will **release electrons** into a vacuum tube, where they are **accelerated by a potential difference**, increasing their kinetic energy.
- The electrons are **focused using electrodes** in order to **preserve their relative positions** and will now collide with a fluorescent viewing screen, and as their kinetic energy has been

increased, the brightness of the screen is much higher than the light emitted by the initial screen.
- The focusing electrodes also **decrease the size of the image** in order to further increase its brightness, so **lower intensity X-rays can be used** to reduce the dose received by the patient.
- The image formed can be viewed directly or recorded for further evaluation.

The side of the fluorescent viewing screen closest to the photocathode is covered in a thin layer of **aluminium**, which **allows electrons to pass through but prevents the light produced at the viewing screen to move back to the photocathode**. This method of imaging gives a **relatively high dose of radiation** as a constant beam of X-ray radiation is used.
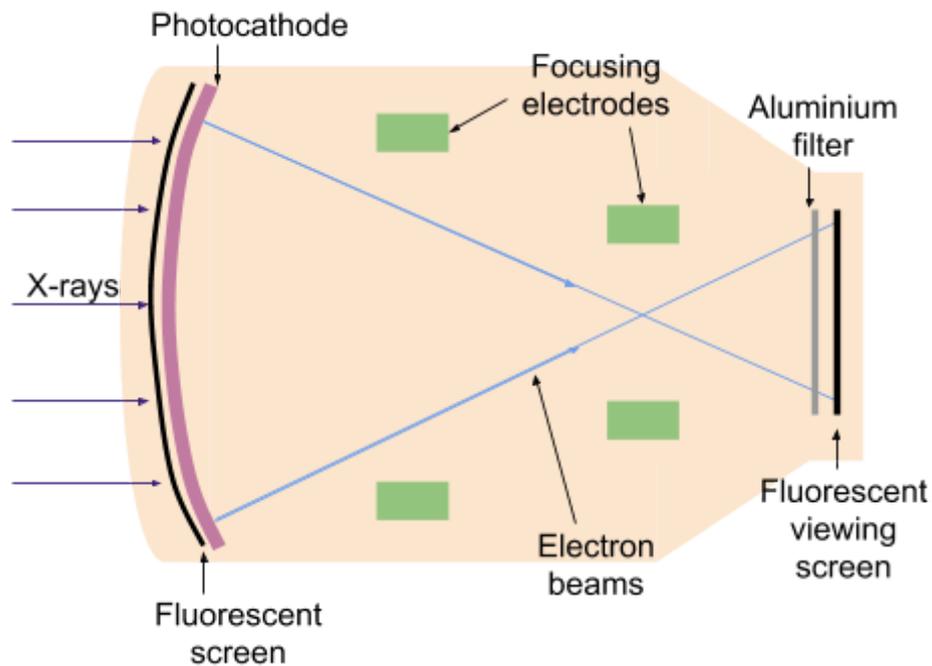
3.10.5.3 - Absorption of X-rays

As X-rays pass through a substance they will interact with it, causing the intensity of the beam to be reduced as it moves through, this is called **attenuation** and is caused by X-rays being absorbed and scattered. The amount of **attenuation depends on the thickness, density and proton number of the material** being passed through, as well as the **energy of the photons**.

The intensity of a **narrow**, **monoenergetic** beam of **X-rays decreases exponentially due to attenuation**, and therefore you can calculate the **intensity of an X-ray beam (I)** by using the following equation:

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

Where I_0 is the initial intensity, x is the thickness of the material, and μ is the material's linear attenuation coefficient.
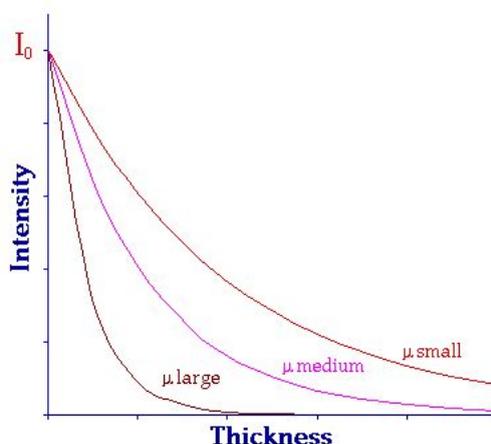
A material's **linear attenuation coefficient (μ)** is a measure of how easily a beam of X-rays (for example) can pass through it, and **describes the rate of energy loss per unit thickness**. This value **depends on the density** of the material, as a **higher density material will absorb more energy as there are more atoms for the photons to encounter**.

The **mass attenuation coefficient (μₘ)** describes how the **rate of energy loss per unit mass**. This value is only dependent on the material and not its density, for example water will have the same mass attenuation coefficient as a liquid, solid and a gas, whereas the linear attenuation coefficient would vary. This value can be calculated using the following equation:

$$\mu_m = \frac{\mu}{\rho}$$

Where ρ is the material's density and μ is the material's linear attenuation coefficient.

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.

The fact the **attenuation is dependent on the density** of a material is particularly important when viewing X-ray images of materials (e.g tissues) which have very similar proton numbers because **the degree of attenuation allows the materials to be differentiated**.

3.10.5.4 - CT scanner

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 **detector directly opposite the source of the beam will register its intensity**.
3. The recorded intensities are sent to a **computer, which processes them and forms an image** of the cross-section.
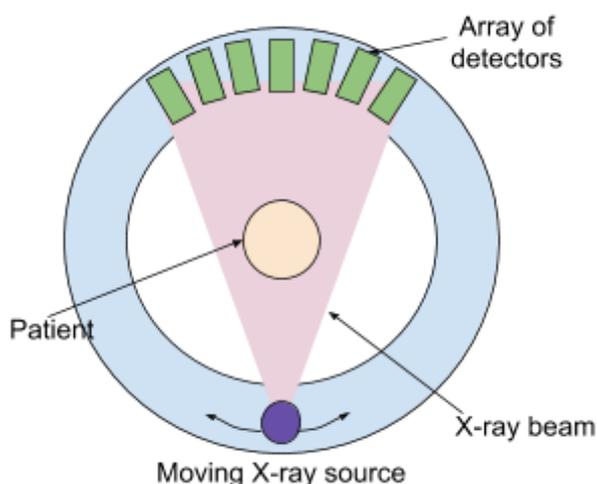
The **advantages** of a CT scanner are:
- Can produce very **high quality images of complicated bone fractures, and organs** (e.g brain).
- It is completely **non-invasive.**
- CT scanners produce a **higher quality image than ultrasound imaging.**
- An image of a **full cross-sectional** area is formed.

The **disadvantages** of a CT scanner are:
- 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.

3.10.6 Radionuclide imaging and therapy

3.10.6.1 - Imaging techniques

Gamma emitting radioisotopes can be used as **tracers** to investigate specific regions of the body and how they are functioning. These radioisotopes can be **bound to substances** which are used in certain parts of the body, and the **path** the radioisotope will take through the body, will **depend on this substance**. The gamma radiation emitted by these tracers can be detected by a **gamma camera** to produce an **image of inside the patient**.

You need to know about the following tracers:
1. **Technetium-99m** - this is a **pure gamma emitter** with a physical half life of **6 hours**, which is short enough to limit exposure but long enough for tests to be carried out and it can be **easily prepared on site.**
2. **Iodine-131** - this emits both **beta and gamma radiation** which is not ideal, however the emission of beta radiation (which is potentially hazardous) is outweighed by the fact that **iodine is naturally absorbed by the thyroid**, so it can be used to investigate the thyroid. Iodine-131 has a physical half-life of **8 days**.
3. **Indium-111** - this is a **pure gamma emitter** with a physical half life of **2.8 days** and is used to **label antibodies and blood cells in order to detect infections**. It is quite expensive but far more suitable for this type of labelling.

Below is a table detailing some of the most important information (including energy of the gamma radiation emitted) you must know about the above radioisotopes:

Radioisotope	Radiation emitted	Physical half-life	Energy of gamma radiation emitted	Use
Technetium-99m	Gamma	6 hours	140 keV	General as it's easily combined with many radiopharmaceuticals
Iodine-131	Beta and gamma	8 days	360 keV	Investigating thyroid
Indium-111	Gamma	2.8 days	170 or 250 keV	Labelling antibodies and blood cells

Because Technetium-99m has such a short physical half-life, it cannot be transported to a hospital, however it can be produced on site using a **Molybdenum-Technetium generator**:
- Molybdenum has a much longer half-life of **66 hours**, meaning it can be **transported to hospitals much more easily**, and as it decays to technetium, it can be used to generate technetium when it is required.
- The molybdenum is combined with **aluminum oxide** and then it will decay into technetium, which does not bond strongly with aluminum oxide, so the **technitium can be isolated by washing it out**
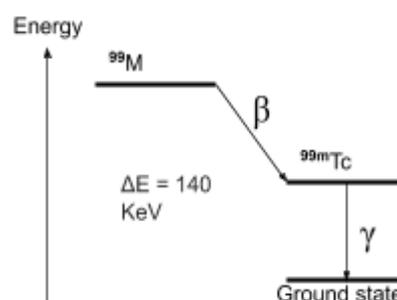
with a saline solution, which can then be injected into patients.

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** 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 now be absorbed and broken down, **releasing positrons** which will collide with electrons present in the body, causing them to become **annihilated**.
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 will 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.
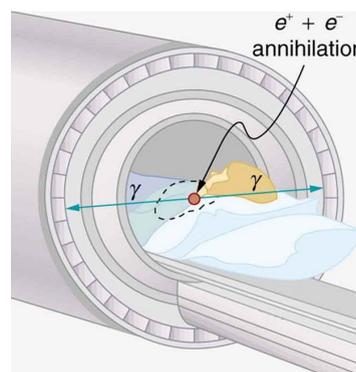
Image source (right): OpenStax College, CC BY 4.0

The **advantages** of PET scanners are:

● The **metabolic activity** of a region can be measured.
● **Tumours can be detected** and information about **whether they are spreading or malignant can be found**.
● **Brain activity** can be easily investigated as the gamma rays produced inside the brain will easily pass through the skull.

The **disadvantages** of PET scanners are:

● **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.

3.10.6.2 - Half-life

The body will process and **metabolise** the substances that radionuclides are attached to, meaning that the **rate of decay of radionuclides** within the body depends on two processes:

● The usual **physical decay process** -
represented by the radionucleide's **physical half-life (T_P)**, which is defined as the **time taken for the number of nuclei to halve.**
● The **rate of excretion** of the substance by biological means -
represented by **biological half-life (T_B)**, which is defined as the **time taken for half of a sample of material to be excreted by biological means.**

You can combine the above values for physical and biological half-life, to get a value for **effective half-life (T_E)**, which is the **time taken for the rate of decay of the initial sample within the body to halve**.

$$\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_P}$$

The effective half-life will always be less than physical half-life as the decay of the radionuclide is aided by biological means within the body.

3.10.6.3 - Gamma camera

A **gamma camera** is a device used to detect gamma rays and form a 2D image, however if multiple are used (like in a PET scanner) a 3D image can be formed.

A gamma camera uses a **photomultiplier tube**, which is an **evacuated tube** containing a **photocathode** and electrodes called **dynodes**, which are at increasingly higher positive potentials along the tube. When light is incident on the photocathode, electrons are released, **accelerated** towards the first dynode and **collide with it releasing more electrons** in a process called **secondary emission**. This repeats and the number of electrons initially released is increased by a considerable amount. Once the electrons reach the end of the photomultiplier tube, they will reach the anode causing an **electrical signal to be output**.
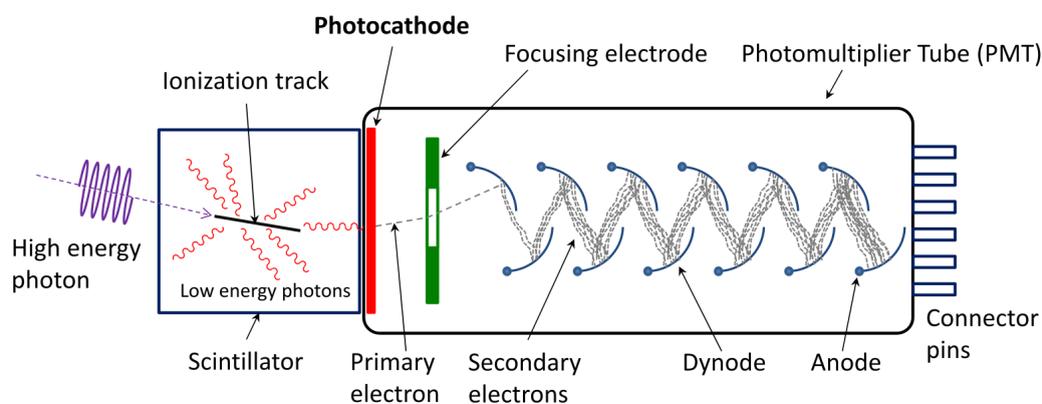

Image source: Qwerty123uiop,CC BY-SA 3.0

In order to be detected by a gamma camera, gamma photons first enter the camera through a **lead collimator**, which **only allows photons parallel to it to pass** through, while other photons are absorbed by its lead walls (this allows for a **sharper image** to be formed). Next, the photons collide with a **scintillator** (a material with emits light photons when struck by high energy photons), causing **visible light photons** to be released. These visible light photons are detected by the photomultiplier tubes, which convert them into **electrical signals**, which are collected and output to a **computer**, which can process them and form an image.
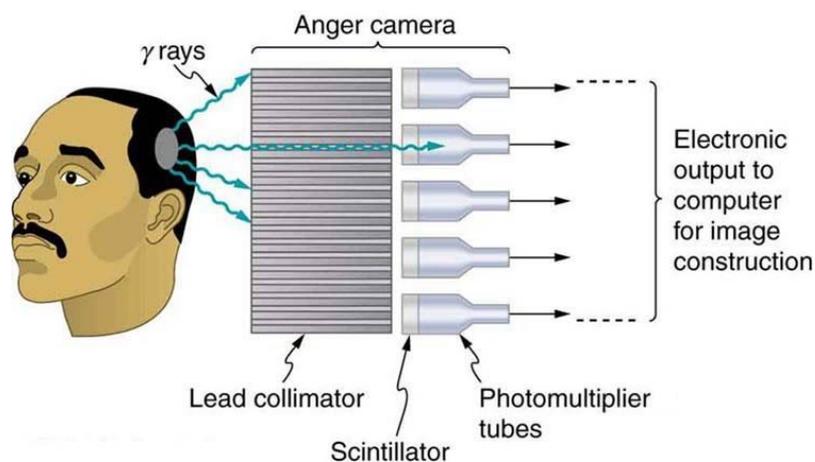
Image source: OpenStax College, CC BY 4.0

3.10.6.4 - Use of high-energy X-rays

High-energy X-rays are used in **radiotherapy** to **kill or contain malignant (cancerous) tumours**. As X-rays are a form of **ionising radiation**, they will damage any cells they come into contact with, including any healthy cells, therefore exposure to healthy cells is limited through the following methods:

- Scans are used to accurately locate tumours to be treated.
- The correct energy X-rays must be chosen to maximise harm to the tumour, but minimise harm to healthy tissue.
- Shielding may be used to protect healthy tissues from the X-rays
- The X-ray beam is made narrow and passed through a collimator to make the photons parallel.
- Multiple beams of radiation can be used, which overlap on the tumour meaning it experiences the most damage.
- A rotating beam can be used, which has the tumour at its centre of rotation, therefore limiting the exposure of healthy cells.
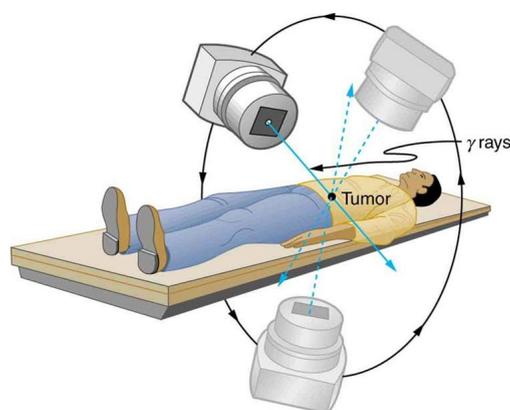

Image source: OpenStax College, CC BY 4.0

3.10.6.5 - Use of radioactive implants

Radioactive implants which emit **beta radiation** are also used to treat tumours. These implants are placed **next to or inside of a tumour,** and as beta radiation is emitted, cells at or very close to the implant site will be killed, because it is ionising. Healthy cells further from the site are not

damaged because the beta radiation will **lose most of its energy** (and be absorbed) before reaching these cells.

These implants must have relatively long half-lives in order to be able to treat a tumour effectively, for example **Iridium-192**, which has a half-life of 74 days is often used. They are able to deliver **higher doses of radiation to smaller areas** than external radiation therapy, with minimal risk to surrounding tissue.

3.10.6.6 - Imaging comparisons

You will need to be able to **compare** all the different types of imaging described, below is a table briefly comparing ultrasound, magnetic resonance, X-rays, CT scans, and PET scans:

	Ultrasound	MR	X-ray	CT	PET
Image resolution	Can't be used to image bones. Resolution of soft tissue is poor in comparison to X-rays and MR.	Imaging of bones is poor, however very high quality images of tissues are formed.	Imaging of bones is excellent, while imaging of soft tissue is good, though contrast may need to be increased.	Imaging of complex bone fractures and organs is excellent, though contrast between materials of similar densities is low.	Can form 3D images or cross-sections, which detail metabolic activity and function of regions.
Convenience	Very quick, cheap and portable.	Extremely expensive and large. Images take up to an hour to form.	Quick and relatively portable.	Quite expensive but takes a relatively short time.	Requires a large amount of preparation, so takes a long time and is relatively expensive.
Safety issues	No known side effects	No known side effects	Uses ionising radiation, which causes damage to cells, and can lead to the development of cancer.	Patients are exposed to a larger dose of ionising radiation than from a conventional X-ray.	Uses ionising radiation, which causes damage to cells, and can lead to the development of cancer.
Other	Comfortable for a patient.	Cannot be used with patients with any metallic implants. Can cause discomfort for a patient.	Can be processed very quickly when using digital detectors.	Can cause discomfort for a patient.	Can cause discomfort for a patient.