

AS Physics – Revision Notes
Unit 3 – Medical Physics

X-Rays

1. X-Rays are high-energy EM waves, with λ considerably shorter than light.
2. To produce X-Rays:
 - a. A filament is heated by a low voltage transformer, causing electrons to ‘boil’ off the surface of the filament.
 - b. A high voltage transformer provides a voltage between the filament and the anode.
 - c. The electrons boiling off accelerate towards the anode.
 - d. As the electrons are accelerated enormously, they produce X-Rays when they hit the dense anode.
 - e. The typical efficiency of X-Ray production is about 1%.
 - f. The other 99% is heat, and so the anode is made of tungsten, which has a high melting point to absorb most of the heat, and it is rotating to spread out the heat around its surface.
 - g. The X-Rays are produced in all directions, so lead shielding is used to cut out the X-Rays not wanted.
3. When a high energy electrons are fired at a heavy atom (high Z number):
 - a. Electrons approaching the nucleus are slowed down, and their loss of energy results in the release of X-Rays (braking radiation).
 - b. Some electrons knock orbital electrons out of the inner shells, and in the process of being replaced, X-Rays will be produced (ionisation).
4. For a spectrum of X-Ray energies and intensities:
 - a. The continuous spectrum illustrates braking radiation – every wavelength is possible.
 - b. The peaks at specific wavelengths illustrate ionisation (the line spectrum)
 - c. The maximum energy of X-Rays is given by E_{\max} and λ_{\min} .
5. One electron-volt (1eV) is the energy gained when one electron is accelerated through a potential difference of 1V. Energy in joules = energy in eV \times charge on one electron.
6. As the tube voltage is increased:
 - a. E_{\max} increases and λ_{\min} decreases.
 - b. The peak intensity of the continuous spectrum moves to a higher energy.
 - c. The total intensity (area under the curve) increases – proportional to V_0^2 .
 - d. More ionisation peaks may appear on the spectrum.
7. An AC power supply will give a greater proportion of low energy radiation than a DC supply.
8. As the tube current is increased:
 - a. E_{\max} remains constant (V_0 is constant).
 - b. The shape of the spectrum is unchanged.
 - c. The total intensity increases – proportional to the tube current.
9. As the Z number of the target material increases:
 - a. E_{\max} remains constant (V_0 is constant).
 - b. The total intensity increases, as there is a greater probability of a collision.
 - c. The ionisation peaks are shifter to higher energies.
10. A filter (e.g. thin aluminium) is used to reduce the lower energy X-Rays so that less are absorbed by the skin and soft tissues.
11. The following terms are used:
 - a. Quality – the penetration of the X-Rays. This increases as V_0 increases.
 - b. Hardness – hard X-Rays have had the lower energy components removed (by filtering).
12. The quality of an X-Ray beam can be described by the half-value thickness (HVT). This is the thickness of material that is needed to reduce the intensity to half of its original value.
13. For diagnostic X-Rays, the tube voltage will be in the region of 30 kV (X-Ray energy of 30 keV), so that the absorption is proportional to the Z^3 of the body material.
14. Photographic emulsion is not very sensitive to X-Rays:
 - a. The film can be double coated with emulsion.
 - b. Intensifying screens can be used to convert X-Rays into visible light, which interacts better with the emulsion (but this decreases the resolution).
15. Artificial contrast mediums are used to study areas such as the digestive tract – i.e. radio-opaque barium is used.
16. The scattering of X-Rays in the body reduces both contrast and resolution of the image, so a lead grid is used to only allow normal X-Rays through.

17. The intensity of an EM wave is given as the power per unit area (Wm^{-2}), and this is shown by the inverse square law:

$$I_1 r_1^2 = I_2 r_2^2$$

18. Therapeutic X-Rays are used to destroy malignant cancer cells, and a high-energy beam in the range 0.5 to 5 MeV is used. This gives absorption independent of the Z number of the tissues, so all targeted tissue will be destroyed.
19. A therapeutic X-ray beam must be concentrated on the tumour:
- Several beams may be focused on the tumour from different directions.
 - The beam may be rotated.
 - The patient may be rotated (this is more likely, as the beam may be difficult to move).
20. For the production of therapeutic X-Rays:
- A linear accelerator may be used.
 - Radioactive sources may be alternatively used (e.g. ^{60}Co).
 - Very thick concrete walls surround all operating equipment.

Ultrasonics

1. Ultrasonics is the use of sound waves above the human threshold (20 kHz). These are used for diagnostic medicine (and also for therapeutic in some cases, e.g. smashing kidney stones), and will be in the range 1 to 15 MHz.
2. The acoustic impedance (Z) of a material is given by:
- $$Z = c\rho$$
3. The ratio of reflected intensity to incident intensity (R) on the boundary of two materials will be:
- $$R = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$
4. A boundary between air and another substance will cause practically all of the ultrasound to be reflected, and so any air in the body during an ultrasound scan will effectively act as a block for the transmission of ultrasound.
5. An ultrasound transducer uses piezoelectric crystals. These are made of a non-conducting material (usually quartz) that will alter its charge distribution when squeezed, setting up a potential difference across the crystal:
- To transmit, a pulse of electricity across the crystal causes it to vibrate and send out a pulse of ultrasound at its precise resonant frequency.
 - To receive, the reflected ultrasound will cause the crystal to vibrate, and induce a current.
6. During an ultrasound scan, the transducer must be placed on a layer of jelly on the skin, with acoustic impedance closely matching that of the skin, as this will ensure that the ultrasound will get through the skin and into the body.
7. An ultrasound A-scan will have the following components in its circuit:
- Transducer – transmits and receives the ultrasound.
 - Transmitter – generates a short pulse of ultrasound into the body via the transducer.
 - Receiver – detects the returning echoes from the body interfaces, and sends a signal to the Y-plates of the oscilloscope, proportional to the echo strength.
 - Swept Gain Generator – progressively increases the gain of the receiver amplifier, to take into account the absorption of ultrasound in the body that makes the later signals weaker.
 - Time Base – controls the movement of the time across the oscilloscope.
 - Rate Generator – synchronises the whole process, simultaneously triggering the transmitter, swept gain generator and time base.
 - Oscilloscope – this displays the data as a CRT image. Expert analysis is needed to relate this to the physical parameters.
8. An ultrasound B-scan works on the same principles as the A-scan, but the Y-plates of the oscilloscope are not altered, and instead the brightness of the spot is altered, and so an actual picture of the body can be built up (this is the most commonly used).
9. Ultrasound is considered to be safe, and is therefore much better for the patient than X-Rays.

Nuclear Medicine

1. In diagnostic studies, a radioactive substance is injected into the body along with other substances to target a specific organ:
- The tracer is the radioisotope to be detected.
 - The tracee is the solution containing the tracer.

2. A tracer must have the following features:
 - a. The half-life must fit in with the scale of the investigation.
 - b. It must be a gamma emitter, as this can be detected and is less harmful to the body.
 - c. It must be non-toxic.
3. Iodine tracers can be produced as the by-products of nuclear fission:
 - a. ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{92}^{236}\text{U} \rightarrow {}_{53}^{138}\text{I} + {}_{39}^{95}\text{Y} + 3{}_0^1\text{n}$.
 - b. The ${}^{138}\text{I}$ is straightforward to be removed using chemical techniques.
 - c. From this, the ${}^{138}\text{I}$ will decay into more useful isotopes.
 - d. This is extremely dangerous however, as the spent fuel rods are extremely radioactive, making the process costly and hazardous.
4. An alternative method is to place stable isotopes of iodine in the control rods, where they will be bombarded with neutrons and converted into unstable isotopes. There are fewer risks this way.
5. A metastable isotope is one that is in a state of stability that it shouldn't be in. It will decay into a stable state by rearranging the nucleus, and therefore emitting just gamma radiation.
6. Technetium-99m is one of the most widely used tracer:
 - a. ${}^{99\text{m}}\text{Tc}$ has a half-life of 6 hours, and so is produced on site from molybdenum-99.
 - b. ${}_{42}^{99}\text{Mo} \rightarrow {}_{43}^{99\text{m}}\text{Tc} + {}_{-1}^0\text{e}$.
 - c. As the ${}^{99}\text{Mo}$ decays, the ${}^{99\text{m}}\text{Tc}$ builds up in the generator. This is washed out in daily elutions with a saline solution.
 - d. The ${}^{99}\text{Mo}$ has a half-life of 60 days, and so a fresh technetium generator is delivered to the hospital every week.
 - e. Most investigations will be scheduled shortly after delivery, as there will be the most ${}^{99\text{m}}\text{Tc}$ at this time.
7. There are three different types of half-life:
 - a. Radioactive half-life (T_r) – the time taken for half of a sample to radioactively decay.
 - b. Biological half-life (T_b) – the time taken for half of a sample to be biologically removed from the body.
 - c. Effective half-life (T_e) – the actual half-life as a combination of the radioactive and biological half-lives. This is given by:

$$\frac{1}{T_e} = \frac{1}{T_r} + \frac{1}{T_b}$$
8. A gamma camera has the following components:
 - a. Collimator – a lead grid that only allows radiation normal to the grid to pass through.
 - b. Scintillation crystal – converts gamma radiation into visible light. This is 1 to 2 cm thick to ensure an efficient conversion rate, but this compromises the transmitted accuracy.
 - c. Photomultiplier tubes – amplifies light from the crystals. Light will hit a photoelectric emitting plate, which releases an electron that can be accelerated across a high voltage to give a pulse of electricity.
 - d. Display electronics – early equipment used an oscilloscope to display the results, but modern equipment produces clear, colour-coded displays of the study area. An averaging process will be used, to allow for the randomness of radioactive emissions.
9. Dilution analysis can be used to determine the quantity of blood in the body:
 - a. The tracer used will be tritiated water – i.e. water containing ${}^3\text{H}$ (half-life 12 years).
 - b. A known volume of tracer is introduced to the body, with activity around 10^4 Bq.
 - c. An identical volume is retained as a standard.
 - d. Eight hours later, a sample of blood is isolated from the body, and centrifuged.
 - e. The activity of the plasma of same volume as the standard is now measured and compared with that of the standard.
 - f. The proportion of activity measured will give rise to the total volume of blood.
10. A similar method is used to find the volume of red blood cells:
 - a. The tracer used will be ${}^{53}\text{Cr}$ (half-life 27.8 days).
 - b. The tracer is introduced to a sample of the patient's blood.
 - c. After 30 minutes this is re-introduced into the blood stream; a standard sample is retained.
 - d. After 15 minutes, another blood sample is obtained.
 - e. This is compared to the activity of the standard to calculate the quantity of red blood cells.