Chapter 6 Radionuclide imaging and therapy

6.1 Radionuclide imaging

Learning objectives:

→ Explain how radioactive tracers are chosen for use in medicine.

→ Explain what is meant by the effective half-life of a radioactive tracer.

→ Describe how a technetium generator works.

Properties of radioisotopes

Radioactive isotopes are used to diagnose medical problems by tracing their path through the relevant parts of the body (i.e., *in vivo*) or by taking a sample of fluid or tissue from the body (i.e., *in vitro*). The radioactive isotope in a suitable liquid solution is given to the patient orally or by injection. For example, sodium iodide solution containing a small quantity of the radioactive iodine isotope $^{131}_{53}\mathrm{I}$ may be given for kidney tests.

The activity of a radioactive isotope in the body decreases because the isotope decays and because the substance containing the isotope is lost from the body through natural processes.

The biological half-life T_b of a substance in the body is the time taken for half of that substance to be removed from the body.

The physical half-life T_p of a radioactive isotope is the time taken for the activity of the radioactive isotope to decrease to half its initial activity.

The effective half-life T_{eff} of a radioactive isotope in the body is the time taken for the activity of the radioactive isotope in the body to reduce to half its initial activity.

Because the effective decay constant is the sum of the decay constants for the physical and biological processes, using the decay constant equation $\lambda = \frac{\ln 2}{T_{½}}$ gives

$$\frac{1}{T_{eff}} = \frac{1}{T_b} + \frac{1}{T_p}$$

The radioactive isotope chosen for a particular diagnostic purpose needs to:

1 be a gamma emitter because:

- alpha radiation is easily absorbed by the body and therefore difficult to detect outside the body for *in vivo* tests and would cause unnecessary exposure to ionising radiation
- beta radiation would also be difficult to detect outside the body for *in vivo* tests and would therefore also cause unnecessary exposure.

2 have an **effective half-life** in the body that is:

- long enough to provide enough time to make the necessary measurements
- short enough to ensure its radioactivity does not remain in the body.

3 be identical to one of the chemical elements in the solution and decay to a stable isotope.

Producing radioisotopes

Most radioisotopes are produced by exposing stable isotopes to neutron radiation in a nuclear reactor or from a particle accelerator (in which a high-energy proton causes neutrons to be emitted from a suitable target). The exposed isotope becomes unstable and emits gamma radiation after beta emission.

The technetium isotope $^{99}_{43}\text{Tc}$ is used for many diagnostic purposes because it forms in a 'metastable' state called technetium-99m (symbol Tc-99m) which then decays with a short half-life of 6 hours by emitting γ radiation. It then decays by emitting β radiation with a much longer half-life.

In addition, it can be prepared on-site in a technetium generator from the decay of the molybdenum isotope $^{99}_{44}\text{Mo}$, which is a beta emitter with a half-life of 67 hours. When a technetium generator is used, a solution of sodium chloride is passed through an ion-exchange column containing ammonium molybdate that has been exposed to neutron radiation several days earlier to make a significant number of molybdenum nuclei unstable. After several days, sufficient Tc-99m nuclei that have formed exchange with chlorine ions when the solution is passed through the column. The molybdenum ions don't exchange, so the solution that emerges from the column contains Tc-99m ions and no molybdenum ions.

Link

See Topic 26.8 More about decay modes Figure 5 The metastable state of $^{99}_{43}\text{Tc}$, in Year 2 of the *AQA Physics* student book.

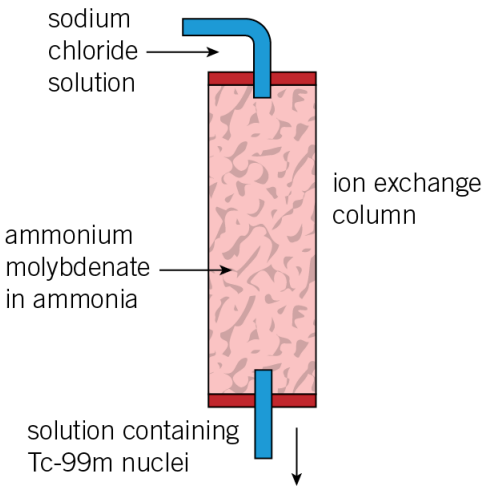

Figure 1 *A technetium generator*

Detectors of gamma radiation

The gamma camera

The gamma camera is designed to detect gamma radiation from sites in the body where a gamma-emitting isotope is located. For example, bone deposits in the joints can be located by using a phosphate tracer labelled with Tc-99m administered to the patient. The camera consists of a sodium iodide crystal behind a lead collimator with photomultiplier tubes behind the crystal, as shown in Figure 2. Only gamma photons parallel to the grid channels of the collimator can pass through the collimator. Each gamma photon that reaches the crystal causes a flash of light, which is detected by the adjacent photomultiplier. As a result, an electronic pulse is generated by the photomultiplier. The electronic pulses from the photomultipliers are used to produce an image consisting of many dots showing the location of the gamma-emitting isotope in the patient. The tubes and the crystal are contained by a thick lead shield to prevent background radiation from producing unwanted dots.

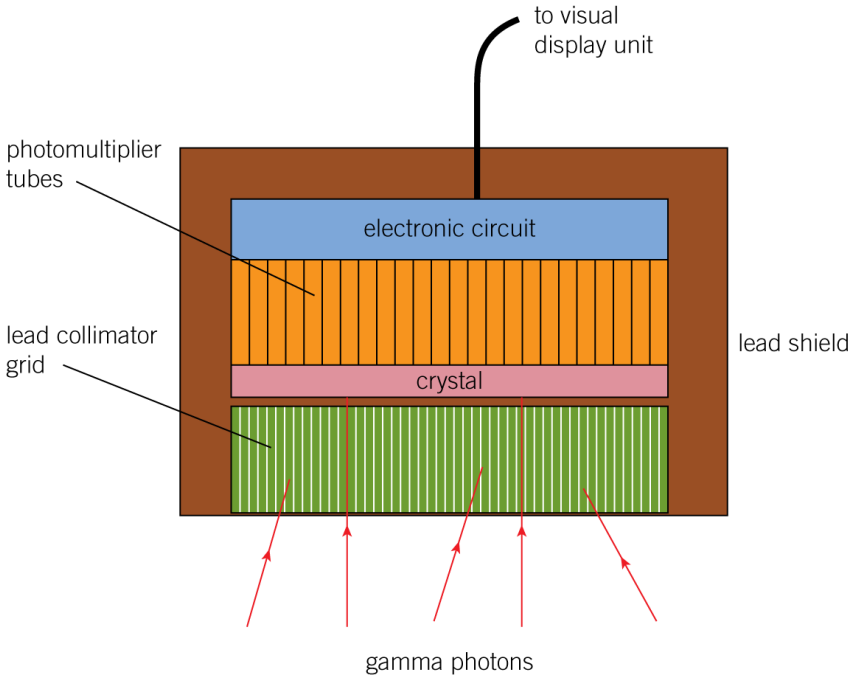

Figure 2 *The gamma camera*

The photomultiplier tube

Figure 3 shows the construction of a photomultiplier tube. When it is used to detect gamma radiation as in Figure 2, its photocathode faces a scintillation crystal. Each gamma (γ) photon incident on the crystal causes light photons to be emitted towards the photocathode inside the tube.

- The light photons reach the photocathode and cause it to emit electrons into the tube.
- The emitted electrons are attracted to dynodes (a type of electrode) along the tube, causing secondary emission of electrons at each dynode.
- As a result, the number of electrons reaching the anode is many times greater than without the dynodes. Typically, more than one million electrons reach the anode for each electron emitted by the photocathode.

The output pulse from the anode is proportional to the energy of the incident gamma photons. In addition, the photomultiplier used in this way is able to detect gamma photons at a much faster rate than a Geiger counter and is much more efficient than a Geiger counter.

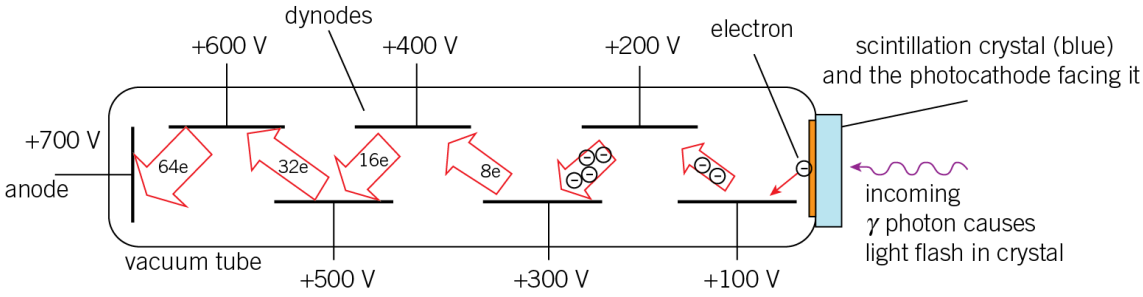

Figure 3 *The photomultiplier tube*

The PET scanner

Antimatter in the form of positrons is used to scan different parts of the body including the brain and the heart. Before the scan is carried out, the patient is given a drink of water containing a tiny amount of a positron-emitting isotope such as the fluorine isotope $^{18}_{9}F$.

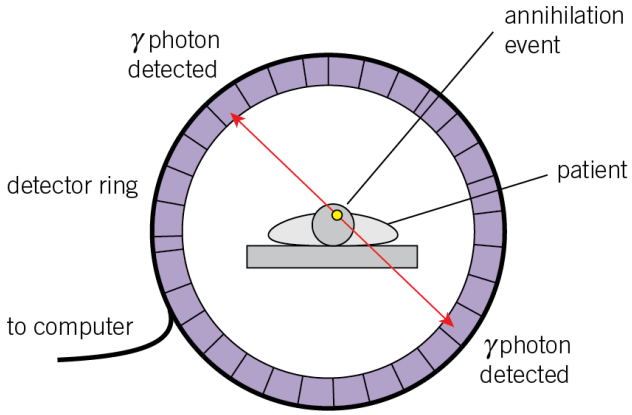

Figure 4 *A PET scanner*

- Each positron travels less than a millimetre in the patient before it meets an electron and they annihilate each other to produce two gamma photons travelling in opposite directions.
- A ring of detectors connected to a computer registers a positron emission when opposite detectors detect a gamma photon at the same time. Such an emission must be midway between the two detectors because the gamma photons travel at the same speed in opposite directions and are created at the same time.
- The computer is programmed to map out the location of the positron-emitting isotope in the body. More information about the use of the fluorine isotope $^{18}_{9}F$ is given in Table 1.

Table 1 *Examples of diagnostic radioisotopes*

Isotope	Physical half-life	Gamma energies / MeV	Example of use	Notes
Iodine $^{131}_{53}I$	8.1 days	β^-: 0.61	Thyroid activity	Sodium iodide solution given orally enters the bloodstream and is collected by the thyroid gland. The count rate is measured and compared with an identical solution prepared at the same time.
Indium $^{111}_{49}In$	67 hours	0.25, 0.17	White blood cell scans to detect infection	A sample of blood from the patient is tagged with In-111 and injected into the patient. The patient is scanned with a gamma camera.
Technetium $^{99}_{43}Tc^m$ (also called Tc-99m)	6 hours	0.14	Blood flow through the brain (or heart)	No more than 0.5 ml of sodium pertechnetate solution containing Tc-99m is injected into the blood stream. Two detectors either side of the head detect the sample passing though the brain a few seconds later. The detector traces (activity versus time graphs) are compared with each other and with normal traces.
Fluorine $^{18}_{9}F$	110 minutes	e^+: 0.64	PET scans	A small volume of fluorodeoxyglucose tagged with F-18 is injected into the patient. A PET scanner is used as in Figure 3 to detect gamma rays due to positron–electron annihilation. See Topic 1.2, Stable and unstable nuclei, in Year 1 of the *AQA Physics* student book.
Sodium $^{24}_{11}Na$	15 hours	1.37 2.75	Blood plasma volume	A small volume v of solution containing Na-24 of known activity A_0 is injected into a blood vessel. If the activity A of an equal volume of a blood sample is measured 30 hours later, the plasma volume $V = \left(\frac{A_0}{4A}\right)v$

Comparison of radioisotope imaging with other imaging techniques

PET scans and gamma scans require suitable radioactive substances to be introduced into the organ or body structure under investigation. The substances are chosen so the radiation from them when they are in the body can be detected outside the body and their half-life is such that their activity decreases as rapidly as possible after the scanning procedure is completed. In comparison, X-ray images and images from CT, MR, and ultrasound scans are obtained by sending radiation into the body to be scattered and/or absorbed then detected outside the body. See Topic 5.3 Image enhancement for a comparison of CT, MR, and ultrasound scanners.

Some further points in comparing imaging techniques are listed below.

1 **Safety:** MRI scans and ultrasound scans use non-ionising radiation and therefore do not harm body tissues whereas X-rays and the radiation from radioactive isotopes do. Specialist facilities that use ionising radiation for imaging need handling and storage facilities for radioactive isotopes and lead shielding to protect people where X-ray machines and CT scanners are used.

2 **Image resolution:** CT scans and MRI scans give better resolution than ultrasound scans. However, although their resolution is less, PET scans and gamma scans show where the radioisotope used is distributed in the part of the body under investigation. For example, the gamma camera is used to investigate bone deposits in joints and the PET scanner is used to locate cancers that preferentially absorb the radioisotope used.

3 **Convenience:** Because of safety issues and costs, ultrasound scanners are more widely used and are usually quicker than ionising radiation scans and MRI scans when detailed resolution is not essential. In addition, patients may need to travel long distances to reach hospitals where CT, MRI, and PET scanners are located as such facilities are often not available in local hospitals.

Summary questions

1 a i Explain what is meant by the term 'biological half-life'.

ii A radioactive isotope has a physical half-life of 8.0 hours and a biological half-life of 24 hours. Calculate the effective half-life of this isotope in the body.

2 The technetium isotope $^{99}_{43}\mathrm{Tc}^{m}$ is metastable and has a half-life of 6.0 hours.

a Explain what is meant by a metastable isotope.

b The isotope is prepared in a technetium generator from the decay of the molybdenum isotope $^{99}_{44}\mathrm{Mo}$, which is a beta emitter with a half-life of 67 hours. Explain why it is necessary for the half-life of the molybdenum to be significantly longer than that of the technetium isotope.

3 a With the aid of a diagram, describe the principal features of a gamma camera.

b The radioactive isotope indium $^{111}_{49}\mathrm{In}$ is used to scan the body for white blood cells. It has a half-life of 67 hours and decays through electron capture to the cadmium isotope $^{111}_{48}\mathrm{Cd}$, which is stable. The radioactive isotope indium $^{110}_{49}\mathrm{In}$ has a half-life of 65 minutes and decays through positron emission and emission of γ radiation to form the radioactive cadmium isotope $^{109}_{48}\mathrm{Cd}$. This isotope has a half-life of 330 days through electron capture and emission of γ radiation. Explain why $^{110}_{49}\mathrm{In}$ in place of $^{111}_{49}\mathrm{In}$ is not suitable for use in scanning.

4 a State the main differences between a PET scanner and a CT X-ray scanner.

b The fluorine isotope $^{18}_{9}\mathrm{F}$ emits positrons and has a half-life of 110 minutes. Describe how the decay of a $^{18}_{9}\mathrm{F}$ nucleus produces γ radiation and how the detection of the radiation is used to locate the position of the nucleus.

6.2 Radiation therapy

Learning objectives:

→ Describe how X-rays are used for therapy.

→ Describe how radioactive isotopes are used for internal therapy.

Ionising radiation

Ionising radiation is used in medicine for therapy as well as for diagnosis. For diagnosis, the radiation intensity must be as low as possible because of the health risk of ionising radiation. Higher intensities are needed for therapy, but the radiation must not damage healthy tissue. The type of radiation used depends on the disorder and its location in the body and may be either:

- X-rays from an X-ray tube or from a particle accelerator such as a linear electron accelerator
- alpha, beta, or gamma radiation from a suitable radioactive isotope
- a particle beam from a particle accelerator.

Ionising radiation therapy kills cells by damaging their DNA, either directly or by creating charged particles called free radicals within the cells that damage the DNA. Cancer cells whose DNA is damaged beyond repair stop dividing, or die. When the damaged cells die, they are broken down and eliminated from the body by natural processes.

X-ray therapy

A collimated beam of high-energy X-rays directed at the body will damage or destroy cells along its path. However, conventional X-ray tubes have a single anode and don't operate above about 300 kV, because their insulation breaks down at such high potential differences. So the X-rays from them are not penetrating enough to reach tumours deep inside the body. Therefore, conventional X-ray therapy is limited to treatment of disorders near the body surface. Gamma radiation from a suitable radioactive isotope such as cobalt-60 is used to treat deeper disorders, but such sources need to be shielded with thick lead because they radiate in all directions and can't be switched off.

Electron accelerators designed for medical therapy can generate X-ray beams with energies up to 25 MeV, which are capable of destroying deep tumours. An electron accelerator is a linear accelerator that accelerates electrons from a heated filament onto a tungsten target. The electrons are emitted from a heated filament in a metal tube called a waveguide and are accelerated towards a positive anode that has a hole through which some electrons pass to enter the waveguide tube. The electrons that enter the waveguide are accelerated along it by pulses of microwaves. A bending magnet is used to deflect the electrons onto a metal target, which stops the electrons, causing them to emit X-rays in the process. A lead block with a narrow hole drilled through it is placed in the path of the X-rays so that a narrow beam of X-rays emerges from the hole. The beam is directed at the affected region of the patient.

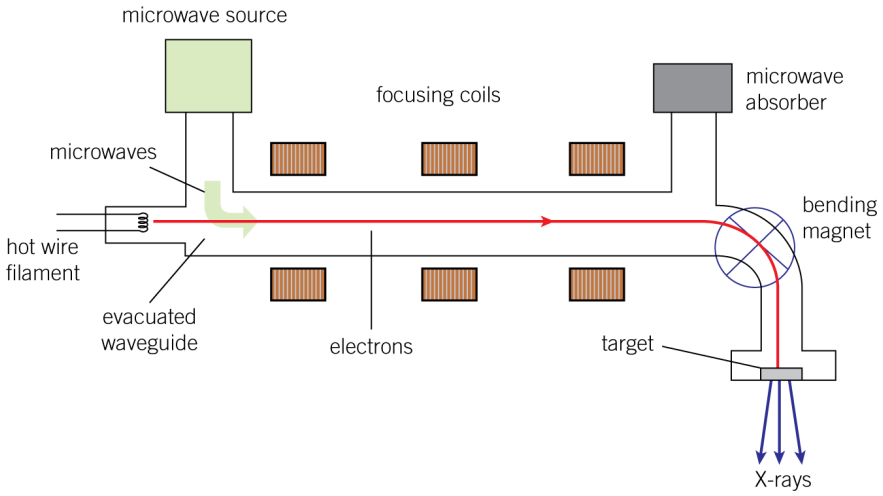

Figure 1 *A medical linear accelerator*

The maximum energy of the X-ray photons in the beam is equal to kinetic energy of the electrons when they reach the target. The electrons can reach kinetic energies up to 25 MeV depending on the length of the waveguide. So the maximum energy of the X-ray photons from an accelerator can be as much as 25 MeV.

Electron accelerators can be switched on and off as required, enabling exposure times to be carefully controlled. In addition, they don't contain highly radioactive sources and therefore don't emit ionising radiation when they are not in use. Also, extensive shielding is not required around the source of radiation (i.e., the target) as with a gamma source (although shielding is required to ensure X-rays don't escape from the treatment room).

Gamma therapy

A narrow beam of gamma radiation can be used to destroy a deep tumour in the body. The beam is directed at the tumour from different directions, either by moving the patient or moving the source. This movement ensures that the healthy tissue surrounding the tumour is less exposed to the beam than the tumour is.

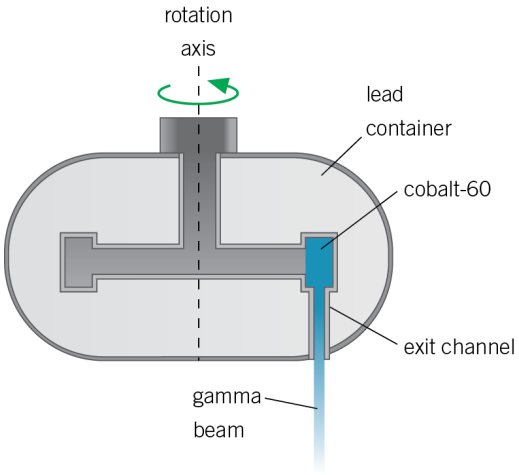

Figure 2 *Gamma treatment*

Figure 2 shows how a narrow beam of gamma radiation is produced from a cobalt-60 source. The source emits gamma photons of energy about 1 MeV and is on a rotating arm in a thick lead container. The source is rotated to the inner end of the exit channel when it is to be used. When it is out of use, the source is rotated away from the exit channel so it is completely surrounded by lead.

QUESTION: Describe how the beam of radiation is narrowed.

Radioactive implants

Malignant cells in a tumour in the body can be destroyed by implanting a suitable radioactive isotope near the site of the tumour. When such implants were first used, needles containing no more than a few milligrams of radium Ra-226 were implanted in growths to irradiate the nearby tissue with gamma radiation. However, this isotope has a very long half-life of 1620 years and produces a wide range of gamma photon energies that can penetrate beyond the tumour and damage healthy tissue. Radium-226 treatment has now mostly been superseded by shorter-lived isotopes such as caesium-137, which has a half-life of 30 years and produces monoenergetic gamma photons and therefore has less effect beyond its intended range. Such sources are useful for treating tumours that can be reached without the need for surgery, because the isotope can be be easily inserted and removed.

Beta-emitting isotopes with very short half-lives of the order of days are used for permanent implants. For example:

- Yttrium $^{90}_{39}Y$ is a β^- emitter with a half-life of 64 hours. It can be implanted as pellets in the pituitary gland to reduce gland activity. It is also used in the treatment of liver cancer.
- Phosphorus $^{32}_{15}P$ is a β^- emitter with a half-life of 14.3 days. It is given intravenously to control excess red blood cells in bone marrow.
- Lutecium $^{177}_{71}Lu$ is a β^- emitter with a half-life of 6.7 days. It is given intravenously and attaches itself to particular cancer cells. It is used in the treatment of thyroid cancer and other disorders, including tumours in the neuroendocrine system, which regulates hormones in various organs. $^{177}_{71}Lu$ also has the advantage of emitting low-energy gamma photons, which can be used to image the effect on the tumour.

Summary questions

1 **a** Calculate the wavelength of X-rays from an electron accelerator operating at 4 MeV.

b A 12 mm lead plate is located in the path of a 4 MeV X-ray beam. The intensity of the beam after passing through the plate is 80% of the incident intensity. Calculate the percentage reduction of the beam intensity if the lead plate had been 60 mm thick.

2 State two reasons why X-rays from a 100 kV X-ray tube are less suitable for medical therapy of a small growth in the eye than X-rays from an electron accelerator.

3 Discuss the advantages of using X-rays from an electron accelerator, instead of gamma radiation from a radioactive source, for radiation therapy.