CHAPTER 20

# Radioactivity as a diagnostic tool

## *Radioactivity can be used as a diagnostic tool*

## 20.1 Radioactivity

- ***Outline properties of radioactive isotopes and their half lives that are used to obtain scans of organs***
- ***Identify that during decay of specific radioactive nuclei positrons are given off***

In order to understand how radioactivity can be used as a diagnostic tool, this chapter first examines briefly the nature and behaviour of radioactivity.

**Definition**

**Radioactivity** is the spontaneous release of energy or energetic particles from unstable nuclei. Naturally, there are three types of radioactivity (radioactive decay): alpha ($\alpha$), beta ($\beta$) and gamma ($\gamma$). $\alpha$ and $\beta$ are particles while $\gamma$ is an electromagnetic radiation (EMR).

**Definition**

**Transmutation** is the phenomenon in which one element changes its identity to become another element.

**NOTE:** Transmutation can be either natural, through $\alpha$, $\beta$ or $\gamma$ decays, or artificial, for instance, through neutron or proton bombardment.

**Definition**

**Isotopes** refer to the same element with different numbers of neutrons; isotopes of the element that may undergo radioactive decay are referred to as radioisotopes.

Examples of radioisotopes


### Alpha ($\alpha$) radiation or decay

Alpha decay refers to an unstable nucleus breaking down to emit alpha radiation ($\alpha$). Alpha radiation (particles) are energetic helium nuclei, in other words, helium atoms without their two electrons, and are written as ${}^{4}_{2}\mathrm{He}$. An alpha particle has two protons and two neutrons and therefore is doubly positively charged.

#### What happens when alpha decay occurs?

For each alpha particle emitted, two neutrons and two protons (hence four nucleons) are lost. This reduces the mass number of

the radioisotope by four and the atomic number by two. This results in transmutation. A general equation for alpha decay can be written as:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He\ (\alpha)$$

transmutation

### Why does alpha decay occur?

As a general rule, unstable elements become more stable through the process of radioactive decay. When alpha decay occurs, the size of the nucleus reduces and becomes more stable. Hence one can conclude that alpha decay occurs for elements that are too 'big'; elements are considered too 'big' if their atomic number is equal to or greater than 83.

Some examples include:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He\ (\alpha)$$

$$^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He\ (\alpha)$$

**NOTE:** Both $^{238}_{92}U$ and $^{241}_{95}Am$ are elements beyond element 83, and therefore are too large to be stable.

## Beta (β) radiation or decay

There are two types of β decay: **$\beta^-$ decay** and **$\beta^+$ decay**.

$\beta^-$ decay occurs when an unstable nucleus breaks down to emit $\beta^-$ radiations (particles). $\beta^-$ particles are fast-moving electrons and have the symbol of $^{0}_{-1}e$. The $\beta^-$ particles are derived from the conversion of neutrons into protons inside the nucleus; electrons are the other product and are ejected from the nucleus whereas the protons stay within the nucleus: $^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$

### What happens when $\beta^-$ decay occurs?

For each $\beta^-$ particle emitted a neutron is converted into a proton, therefore the total number of nucleons, and hence the mass number of the radioisotope, should not change. However, because there is now an added proton, the atomic number increases by one. This again results in natural transmutation. A general equation for $\beta^-$ decay is:

$$^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + {}^{0}_{-1}e\ (\beta)$$

transmutation

### Why does $\beta^-$ decay occur?

Through $\beta^-$ decay, a neutron is converted into a proton and the element becomes more stable. Hence one can conclude that $\beta^-$ decay occurs when the atoms have too many neutrons compared to protons, or too few protons compared to neutrons. Generally, for small elements, the neutron–proton ratio should be about 1:1, whereas for larger elements such as uranium, the ratio can be as high as 1.5:1. It is wise to consult the periodic table to determine whether the number of neutrons in a particular atom is too many.

Some examples include:

$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e\ (\beta^-)$

$^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}e\ (\beta^-)$

$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e\ (\beta^-)$

**NOTE:** $^{14}_{6}C$, $^{90}_{38}Sr$ and $^{60}_{27}Co$ all have more neutrons than their stable isotope listed in the periodic table.

On the other hand, $\beta^+$ decay occurs when an unstable nucleus breaks down to emit $\beta^+$ radiations (particles). $\beta^+$ particles are anti-electrons or **positrons** and have the symbol of $^{0}_{+1}e$. Positrons are the anti-matter pair of electrons. Although they are fundamentally different from electrons, for the purpose of this module, they can be seen as electrons that carry a positive charge. The positrons in $\beta^+$ decay are derived from the conversion of protons into neutrons inside the nucleus: $^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e$

### What happens when $\beta^+$ decay occurs?

During a $\beta^+$ decay, the total number of nucleons, and hence the mass number of the radioisotope, remains unchanged. However, since there is a conversion from a proton into a neutron, the atomic number should decrease by one. A general equation for $\beta^+$ decay is:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e\ (\beta^+)$$

transmutation

### Why does $\beta^+$ decay occur?

In contrast to $\beta^-$ decay, $\beta^+$ decay occurs when the atoms have too few neutrons compared to protons, or too many protons compared to neutrons. Again, the periodic table should be consulted.

Some examples include:

$^{15}_{8}O \rightarrow {}^{15}_{7}N + {}^{0}_{+1}e\ (\beta^+)$

$^{18}_{9}F \rightarrow {}^{18}_{8}O + {}^{0}_{+1}e\ (\beta^+)$

**NOTE:** $^{15}_{8}O$ and $^{18}_{9}F$ all have fewer neutrons than their stable isotope in the periodic table.

## Gamma ($\gamma$) radiation or decay

Gamma radiation (ray) is the highest frequency EMR in the EMR spectrum. Gamma decay occurs when elements try to discharge excessive amounts of energy from the nucleus. The nucleus would have the excessive amounts of energy usually as a result of some kind of prior disturbance, such as having been bombarded by neutrons from an external source or having previously undergone alpha or beta decay. Gamma radiation is pure energy. By itself it does not cause transmutation. Nevertheless, through gamma decay, the element becomes more stable.

Some examples include:

(a) $^{60}_{27}Co \rightarrow {}^{60m}_{28}Ni + {}^{0}_{-1}e$

And immediately $^{60m}_{28}Ni \rightarrow {}^{60}_{28}Ni + \gamma$ (No transmutation)

$m$ = metastable/excited, indicating that the nucleus has excessive amounts of energy.

Overall equation $^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + \gamma$

(b) $^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc + {}^{0}_{-1}e$

After a while $^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma$ (No transmutation)

Note that for cobalt-60, because the gamma radiation occurs immediately after the beta decay, sometimes the two forms of radiation are said to occur together and cobalt-60 is described as a co-emitter of beta and gamma radiations. However, in the second example, the gamma decay for technetium-99 is a delayed process. Consequently, technetium-99m is described as pure gamma emitter and its parent isotope molybdenum-99 is described as a beta emitter. Nevertheless, the principle of the gamma decay is the same in both cases and in particular, gamma decay by itself does not cause transmutation.

The physical properties of alpha, beta and gamma radiation are summarised in Table 20.1.

**Table 20.1** Properties of the alpha, beta$^-$ and gamma radiation

| Name | Identity | Charge | Mass (u) | Energy | Ionisation power | Penetration power |
|---|---|---|---|---|---|---|
| **Alpha** | Helium nucleus $^{4}_{2}He$ | + 2 | 4.03 | Low | High | **Low**<br>■ Travels for 7 cm in air<br>■ Blocked by a layer of skin or a thin piece of paper |
| **Beta$^-$** | Fast-moving electron ($^{0}_{-1}e$) | –1 | $5.48 \times 10^{-4}$ (*approx.* $\frac{1}{1825}$) | Medium | Medium | **Medium**<br>■ Travels for 1 m in air<br>■ Blocked by a thin layer of metal sheet |
| **Gamma** | Highest frequency EMR ($\gamma$) | 0 | 0 | High | Low | **High**<br>■ Penetrates through thin metal sheets<br>■ Blocked by a thick lead sheet or a concrete wall |

## The radioactivity used in clinical medicine

The radiation used for medical imaging purposes is gamma, whether directly through pure gamma decay (e.g. technetium-99m) or via annihilation of matter and anti-matter pair in positron emission tomography (see later). Technetium-99m is the most commonly used radioisotope in nuclear medicine.

Gamma rays are penetrative enough to pass through the body to reach the detector. They cause the least amount of ionisation compared to both alpha and beta radiation when inside the body, and therefore are relatively safer for injection into the

patient. Furthermore, most gamma emitters, in particular, technetium-99m, have very short half-lives (see next section). They will not stay in the body for long after the injection, which further increases their safety for clinical uses.

# 20.2 Half-life

■ ***Outline properties of radioactive isotopes and their half lives that are used to obtain scans of organs***

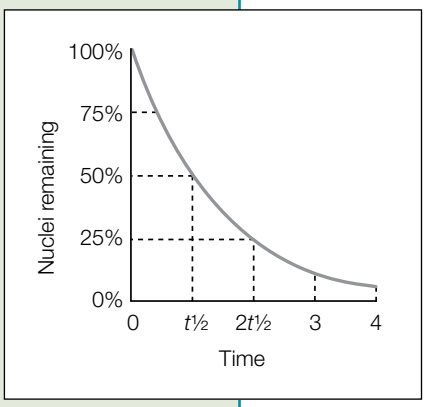



**Figure 20.1** Half-life of a radioisotope: the amount of the radioisotope decreases exponentially

**Definition**

**Half-life** is defined as the time needed for half the amount of a given radioisotope to decay or the time for the intensity of its radiation to decrease by a half

This can be represented using the graph shown in Figure 20.1.

As shown in the graph, after the first half-life has elapsed, the amount of radioisotope has dropped to 50% of the original amount. The amount then drops to 25% and 12.5% after two and three half-lives respectively, and so on. Also from this graph, any halving in values on the *y*-axis will correspond to a time elapse on the *x*-axis that equals to one half-life, and any time interval that is one half-life long on the *x*-axis will correspond to a reduction of the amount of the radioisotope by a half.

## Further example

### Example 1

Iodine-131 is a co-emitter of beta and gamma radiation and has a half-life of 8.0 days. A sample of iodine-131 has a mass of 6.4 g.

(a) Write a nuclear equation to describe the decay of iodine-131.

(b) Calculate the mass of iodine-131 remaining after 40 days.

(c) How long does it take for the mass of the iodine-131 to reach $2.5 \times 10^{-2}$ g?

**Solution**

(a) ${}^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e + \gamma$

(b) Forty days is equivalent to five half-lives. Therefore the amount of iodine-131 will be halved five times, hence:

Remaining mass

$$= 6.4 \times \left(\frac{1}{2}\right)^5$$

$$= 0.20\ g$$

(c) Let the number of half-lives needed be $n$:

$$6.4 \times \left(\frac{1}{2}\right)^n = 2.5 \times 10^{-2}$$

$$\left(\frac{1}{2}\right)^n = \frac{2.5 \times 10^{-2}}{6.4}$$

$$\left(\frac{1}{2}\right)^n = \frac{1}{256}$$

$$\left(\frac{1}{2}\right)^n = \frac{1}{2^8}$$

$$n = 8.0$$

Since each half-life is eight days, the time required will be eight lots of eight days, that is, 64 days.

### Example 2

A sample of Ag-108 has an activity level of $6.4 \times 10^4$ Bq. This activity level drops to $2.0 \times 10^3$ Bq after 12 minutes. Calculate the half-life of Ag-108.

**NOTE:** Bq stands for becquerel, the SI unit used to measure the activity of a radioisotope.

#### Solution

Let the number of half-lives needed be $n$:

$$6.4 \times 10^4 \times \left(\frac{1}{2}\right)^n = 2.0 \times 10^3$$

$$\left(\frac{1}{2}\right)^n = \frac{2.0 \times 10^3}{6.4 \times 10^4}$$

$$\left(\frac{1}{2}\right)^n = \frac{1}{32}$$

$$\left(\frac{1}{2}\right)^n = \frac{1}{2^5}$$

$$n = 5.0$$

This means five half-lives have elapsed in 12 minutes, hence one half-life will equal to 12 divide by 5, hence 2.4 minutes.

## The significance of half-lives

The length of the half-life of a radioisotope is significant for its use in clinical medicine and radioisotopes with shorter half-lives are preferred clinically. Any radioisotopes can potentially do harm to the body due to their energy and ability to ionise, which can cause destruction of the cellular structures, in particular the DNA materials. They have the potential to induce secondary cancer and may affect pregnancies. A shorter half-life means that the injected radioisotope will disappear from the body soon after the scan is completed, hence minimising harm. The dose of the radioisotope used should be kept to a minimum. Importantly, radioisotope scans are contraindicated in pregnancies.

# 20.3 Radioactivity as a diagnostic tool: nuclear medicine

## ■ *Describe how radioactive isotopes may be metabolised by the body to bind or accumulate in the target organ*

The general principle for using radioisotopes to acquire images of a body organ is similar across all sub-types of radioisotope scans. These scanning methods belong to a branch of medicine called **nuclear medicine** and are performed in the hospital within the department of nuclear medicine by doctors who specialise in this area. The operating principle may be simplified and summarised as follows.

### Introducing a radioisotope into the body

Introducing a radioisotope into the body is usually done by injecting the radioisotope into the bloodstream through a vein. The radioisotope injected can be in the state of free elements, but is more commonly injected after being attached to natural biological molecules that the body recognises. These biological molecules attached to a radioisotope are termed **radiopharmaceuticals**. The reason for the use of radiopharmaceuticals is to avoid the radioisotope being recognised by the body as a foreign substance, as well as aiding the transportation in the bloodstream and the accumulation of the radioisotope in the target organ. Different types of biological molecules are used to target different organs since the body will naturally distribute and accumulate organ-specific molecules in the target organs.

Iodine-123 is one of a few radioisotopes that can be injected as free elements. This is because the body is able to transport free iodine and selectively accumulate it in the thyroid gland. Technetium-99m, the most commonly used radioisotope, cannot be injected into the bloodstream as free atoms because the body will recognise them as foreign and will not transport them. Technetium-99m therefore must be attached to natural biological molecules, the nature of which depends on the body organ targeted.

### Circulation and accumulation of the radioisotope

The radioisotope circulates through the body, whether as free elements or bound to other molecules and, given adequate time, will eventually accumulate in the target organ. The amount of accumulation of the radioisotope is determined by the metabolic activity of the target organ, in other words, how quickly the target organ is processing the nutrients supplied in the blood.

### Detection of the radiation

While the radioisotope is in the organ, it will continue to emit radiation (gamma rays), which can be detected using a detector outside the body. The detected radiation then generates electrical signals and the signals are fed into a computer to form images of the organ.

Such a detector is known as a **gamma camera** (also known as an Anger camera), which is a modified version of a scintillation counter. A photograph of a gamma camera used in a hospital is shown in Figure 20.2 and a schematic drawing of a gamma camera is shown in Figure 20.3.

The side of the gamma camera facing the patient is made of a layer of scintillation crystal, such as sodium iodide, which is able to give a flash of light every time a beam of gamma ray strikes it. This light then reaches the photomultiplier tubes directly

**Figure 20.2** A gamma camera used in a hospital

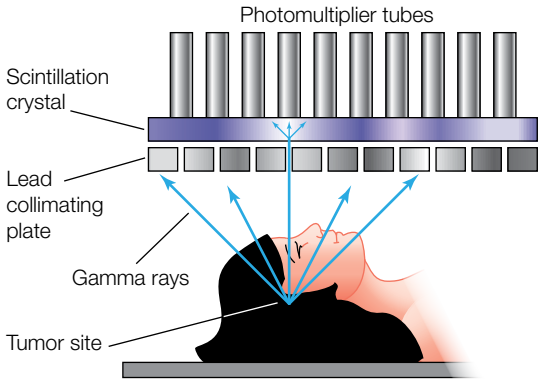



**Figure 20.3** A schematic drawing of a gamma camera

behind the crystal. The photomultiplier tubes convert the light into electrical signals via the photoelectric effect. The electrical signals are then fed into the computer system to produce the images of the scanned organ.

When a lot of radioisotopes are accumulated in the organ (or one part of the organ), the organ emits more gamma rays, which in turn results in stronger electrical signals produced and subsequently 'hot' spots are displayed (brighter or dark depending on the type of the scan). When fewer radioisotopes accumulate, then the organ or a part of the organ display 'cold' spots. Based on this information, diagnosis of a particular disease can be made. Some examples are given in the next section.

## The uses of radioisotope scans

- ***Perform an investigation to compare an image of a bone scan with an X-ray image***
- ***Gather and process secondary information to compare a scanned image of at least one healthy body part or organ with a scanned image of its diseased counterpart***

**FIRST-HAND AND SECONDARY SOURCE INVESTIGATION**

**PFAs**

H3

**PHYSICS SKILLS**

H12.3A, B, C, D
H12.4C
H14.1A, B, E, G, H

Radioisotope scans are extensively used in clinical medicine for diagnostic purposes. Because they focus on the metabolic activity or functional level of an organ, they may detect or diagnose problems that other imaging methods are unable to provide. However, because the gamma rays may be diffracted and absorbed by the body tissues as they travel towards the camera, the resolution of the images formed is usually poor. Furthermore, because the radioisotope does not get distributed entirely throughout the organ, some detail of the organ may not be shown. As a consequence, radioisotope scans do not provide detailed information about the structure of the organ.

There are vast numbers of radioisotope scans and some are more complicated than others. A few common ones are discussed here.

### Thyroid scan

To perform a thyroid scan, iodine-123 is administered orally. Iodine-123 circulates through the bloodstream to accumulate only in the thyroid gland.

**NOTE:** The thyroid gland uses the accumulated iodine to make thyroid hormone, an important hormone that controls the rate of the body's metabolism.

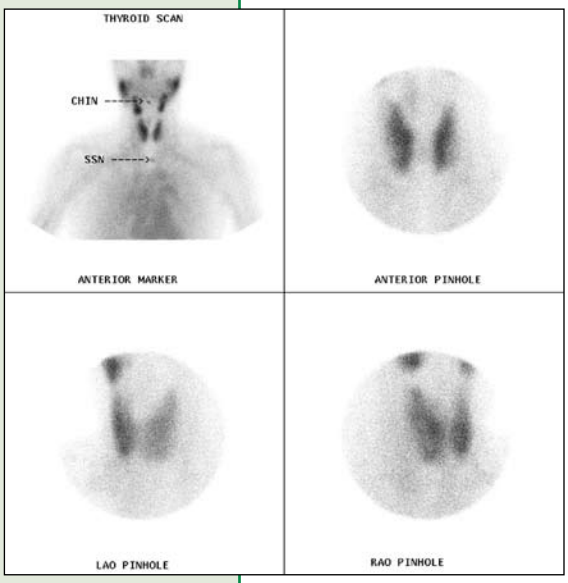



**Figure 20.4 (a)** A normal thyroid scan

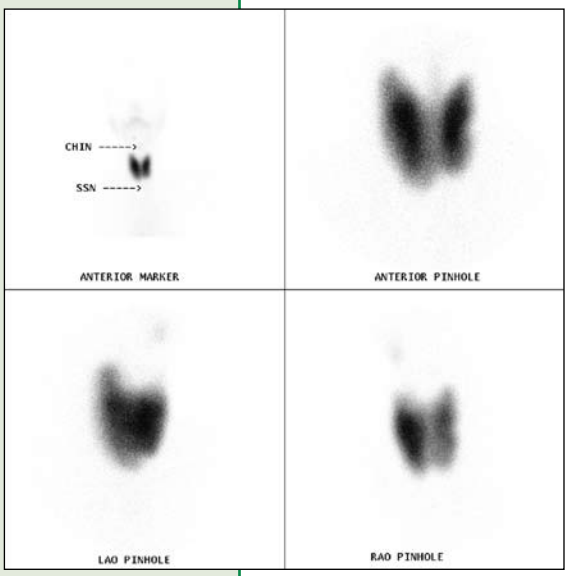



**Figure 20.4 (b)** Hyperthyroidism—the thyroid gland is illuminated more than (a)

This radioisotope, when accumulated in the gland, continues to emit gamma rays, which are detected by a gamma camera placed just in front of the neck (where the gland is situated). A normal thyroid scan should look like the one in Figure 20.4.

Whenever the thyroid is overly active, it will take up more iodine than normal. This is known medically as hyperthyroidism. Accumulation of iodine-123 in the gland leads to more gamma rays being detected by the gamma camera. Consequently, the thyroid gland will appear 'hot' on the scan images. Depending on the pattern of the distribution of the 'hot' spots, different diseases maybe diagnosed. For example, uniform increase in uptake may indicate Graves' disease, an autoimmune disease where the thyroid gland is stimulated inappropriately. A patchy increase in uptake may indicate multinodular goitre, an excessive growth of the thyroid gland.

When the thyroid gland is underactive (known as hypothyroidism), it will take up less iodine-123, therefore less radiation will be emitted. Consequently, the images of the gland will show 'cold' spots. Again this can indicate diseases such as thyroiditis (inflammation of the thyroid gland) or even thyroid cancer, where cancerous tissues have replaced normal thyroid tissues and the gland no longer takes up iodine to make thyroid hormone.

The thyroid scan is the investigation of choice when a patient is suspected clinically to have either hyper- or hypothyroidism. The scan and some simple blood tests are usually adequate in establishing a diagnosis. A thyroid scan is also useful to determine the functional state of a thyroid lump: a lump that is 'hot' is much less likely to be malignant compared to a lump that is 'cold'.

## Bone scan

To perform a bone scan, technetium-99m labelled polyphosphate molecules (e.g. oxidronate) are injected intravenously. These molecules circulate in the bloodstream and finally accumulate in the skeletal system after two to four hours.

**NOTE:** Bones take up phosphate ions as a part of their mineralisation process.

Normal bones have a very low level of metabolism, therefore only a small amount of technetium-99m labelled polyphosphate molecules should accumulate in them. However, when parts of a bone increase their metabolic rate, an increased uptake (accumulation) is expected. Therefore more radiation is emitted and these parts will be seen as 'hot' spots. The bone (or parts of it) can become more metabolically active for many reasons: these include fractures, infections (osteomyelitis), or tumour deposits (both primary and metastatic, where cancer has spread from a distant organ).

A bone scan is very sensitive in picking up occult fractures (fractures that are not seen on a plain X-ray film), as shown in Figure 20.5. They are also good for diagnosing osteomyelitis and assessing the degree of spread of a primary cancer, which provides important information about a patient's prognosis.

Bone scans, just like many other radioisotope scans, are extremely sensitive and may sometimes give false positive findings, for example, a hot spot may simply be due to a bruise and hence not be significant. Also, like many other radioisotope scans, bone scans only demonstrate whether the organ (bone) is overly, normally or underactive. The interpretation of the images and hence the final diagnosis can only be made after collating the clinical history as well as findings from other investigations.

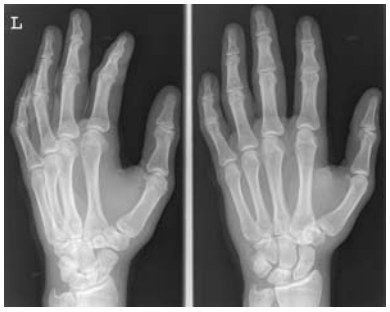
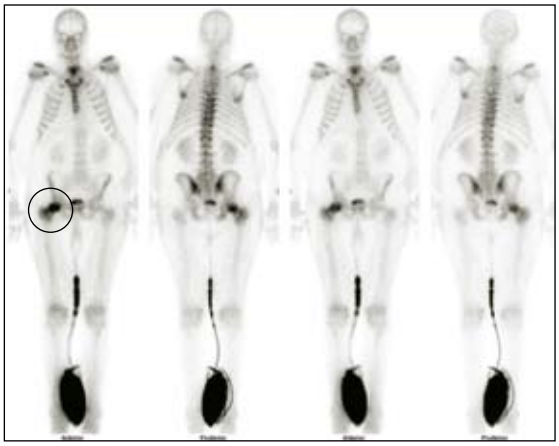



**Figure 20.5 (a)** A plain X-ray film of a hand, where a fracture cannot be seen

**Figure 20.5 (b)** A bone scan of the same hand, showing a 'hot' spot in one of the hand bones indicating a fracture in that bone

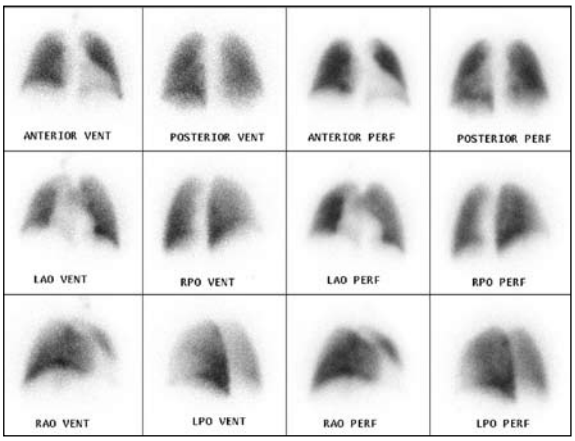
A normal whole body scan



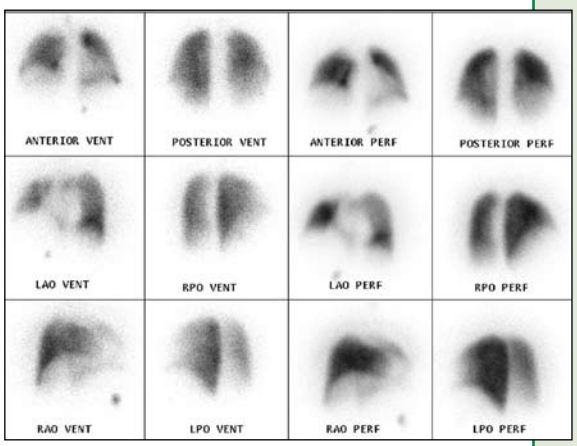
A whole body bone scan showing metastatic cancer in the right hip (circle)

## Ventilation and perfusion scan

A ventilation and perfusion scan is used to evaluate lung function. To perform the scan, albumin molecules (a protein found in the blood), labelled with technetium-99m, are injected intravenously so that they will circulate through the lungs, hence perfusion. At the same time, aerosols of a radioactive gas such as krypton-81m are inhaled by the patient into the lungs, hence ventilation. The perfusion component of the scan studies the blood circulation through the lungs, whereas the ventilation component studies the air movement in and out of the lungs.




A normal ventilation and perfusion scan




An abnormal ventilation and perfusion scan—note the missmatch between the anterior ventilation and anterior perfusion

For normal lungs, areas that are ventilated are matched with areas that are perfused. If an area of the lung has normal perfusion but poor ventilation, this may indicate an obstruction of the airway, such as by a tumour or more commonly by a foreign body such as an inhaled peanut in young children. On the other hand, images showing an area that has normal ventilation but impaired perfusion may indicate a blood clot in the arteries that supply that section of the lung. This is known as pulmonary embolism, which may present clinically with chest pain or breathlessness—even death. Once again, the results of the ventilation and perfusion scan need to be interpreted based on clinical suspicion and the results of other investigations.

### Myocardial perfusion scan

A myocardial perfusion scan is performed by injecting a compound known as sestamibi, which forms a complex with technetium-99m. The compound circulates to accumulate in the heart muscle and the amount of accumulation depends on both the volume of the heart muscle and the level of blood supply of the heart muscle. Images of the heart muscles are taken when the patient is exercising and resting.

A myocardial perfusion scan is valuable in diagnosing heart problems as the cause of chest pain. The scan is able to differentiate between angina (when the heart muscles are temporarily deprived of blood supply) and myocardial infarction (when the heart muscles have been deprived of blood supply for a prolonged period of time and are now dead).

### Comparing medical images

When comparing medical images, a list of the properties of the images for comparison should be made first. These include the overall appearance, resolution, colour, contrast and range of tissues and pathologies shown. Comparing multiple images obtained from various sources will increase the reliability of the comparison. Medical images may be obtained from the Internet, textbooks, journals and medical imaging facilities (such as the hospital). All information obtained may be recorded in a table format and a summary should be made.

## 20.4 Positron emission tomography

Positron emission tomography (PET) is a special type of radioisotope scan that uses positrons emitted from the radioisotopes to form images of the target organ.

### The positron emitters

As described already, positrons are emitted from radioisotopes that have too many protons compared to neutrons or too few neutrons compared to protons. Oxygen-15 and fluorine-18 are common examples. In general, positron emitters have very short half-lives, in the order of a few seconds to minutes (see Table 20.2), therefore most of the positron emitters used for PET need to be artificially manufactured on site where the PET scan is performed. Since all positron emitters have fewer neutrons compared to their stable isotopes, they cannot be produced by neutron bombardment, which would only add more neutrons to the stable isotope. Consequently, positron emitting radioisotopes must be produced using a particle accelerator.

**Table 20.2** Half-lives of positron emitters

| Radioisotope | Half-life (minutes) |
|---|---|
| Carbon-11 | 20.4 |
| Oxygen-15 | 2.04 |
| Fluorine-18 | 110 |

**NOTE:** Particle accelerators are devices that are designed to use electric fields and/or magnetic fields to accelerate charged particles to very high speeds before smashing the particles against a target. Such smashing leads to transmutation. For more detail, see Chapter 17.

The particle accelerator accelerates protons to a high speed to enable them to overcome the electrostatic repulsion force when they are smashed into the (positive) nucleus of the target atoms to cause transmutation.

Fluorine-18 is the most commonly used positron emitting radioisotope and is produced via proton bombardment (accelerated using a particle accelerator, e.g. a cyclotron) of oxygen-18 enriched water:

$$^{18}_{8}O + {}^{1}_{1}p \rightarrow {}^{18}_{9}F + {}^{1}_{0}n$$

Fluorine-18 is recovered as an aqueous solution of fluoride-18 ($H_2O/^{18}F^-$) and can be extracted by ion-exchange chromatography. Oxygen-15 can be produced by bombarding nitrogen-14 with accelerated protons:

$$^{14}_{7}N + {}^{1}_{1}P \rightarrow {}^{15}_{8}O.$$

## The operating principle of a PET scan

20.5

- ***Discuss the interaction of electrons and positrons resulting in the production of gamma rays***
- ***Describe how the positron emission tomography (PET) technique is used for diagnosis***

To perform a PET scan, the positron emitting radioisotope is first attached to a biological molecule, similar to the radioisotope scans described before. Again, this compound is now called a radiopharmaceutical. Fluorine-18 is the most commonly used positron emitter and glucose molecules are used for attachment. Fluorine-18 attaches to the glucose molecules to form 2-fluoro-2-dioxy-D-glucose (FDG) molecules, which are then injected into the patient intravenously. The molecules circulate in the bloodstream and are concentrated in the target organ, for instance, the brain. The patient lies on a table and is positioned so that the target organ is inside a gantry, which contains many sets of modified gamma cameras. This is shown in Figure 20.6

While inside the organ, FDG molecules continue to emit positrons. The positrons will only travel for a few millimetres before they encounter the very abundant electrons. This encounter between a matter and anti-matter pair will result in the total annihilation of the mass of the positrons and the electrons. The annihilated masses are converted into energy in the form of paired gamma rays, governed by the equation $E = mc^2$. The pair of gamma rays travel away from each other perpendicular to the initial direction of the motion of the positron and electron. This is shown in Figure 20.7 (overleaf).

The gamma cameras mounted on the gantry will detect the pairs of gamma rays and the signals are fed to the computer to reconstruct the images of the section of the target organ that is placed inside the gantry, hence the term tomography. The patient is then moved slowly through the gantry so that images of the other sections of the organ can be produced.

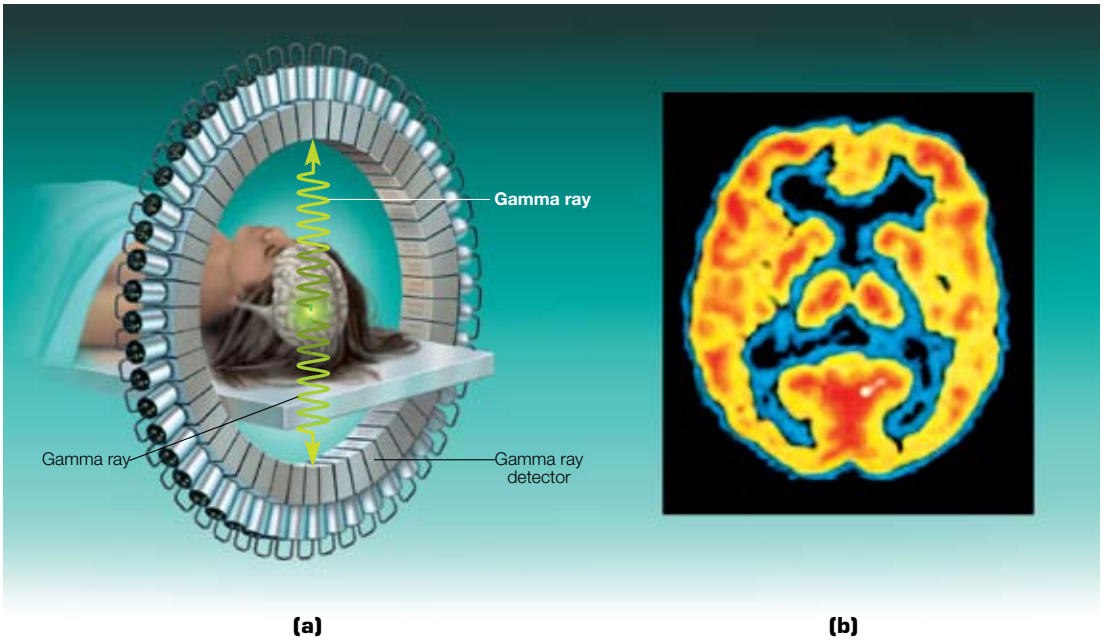



**Figure 20.6** **(a)** A patient undergoing a PET scan of the brain **(b)** The resulting image

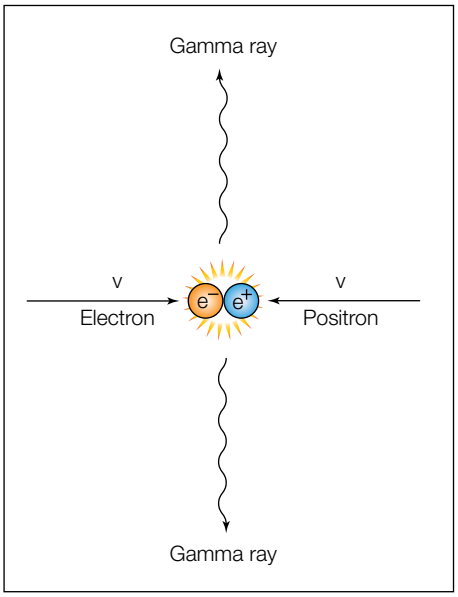



**Figure 20.7** The annihilation of the masses when a positron encounters an electron

In order to reconstruct the images, the position of each of the sources of gamma rays must first be located. This can be done by determining the time difference for each pair of gamma rays to arrive at the opposite gamma cameras, shown in Figure 20.6. Obviously, from an off-centre source, the gamma ray travelling towards the closer camera will take less time than the gamma ray travelling towards the further gamma camera. Because FDG molecules will be distributed through the entire organ, analysing the location of each of the FDG molecules will outline the structure of the organ.

**NOTE:** The accuracy of locating the radioisotopes is about 3 to 5 mm.

The second part to the image formation process is to determine the absolute intensity of the gamma rays produced. This can be done by knowing the intensity of the arriving gamma rays and the attenuation coefficients for gamma rays passing through tissues. The areas that are emitting more intense gamma rays are displayed as 'hot' spots, which reflect more accumulation of the radioisotope hence more metabolic activities. Areas that are emitting less intense gamma rays are displayed as 'cold' spots, corresponding to areas that are metabolically inactive.

A PET of a 'hot' spot in a brain can be done. Based on this information, as well as combing the clinical information and the results of other investigations, diagnosis of certain diseases can be made.

# Applications of PET scans

# 20.6

## Using PET scans to detect diseased organs

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H12.3 A, B, C, D
H12.4C

■ ***Gather and process secondary information to compare a scanned image of at least one healthy body part or organ with a scanned image of its diseased counterpart***

PET scans are expensive, mainly due to the cost of producing the positron emitting radioisotopes using a particle accelerator. Also, because the positron emitters have very short half-lives, they must be produced on site and this limits the availability of the PET scans.

Just like the simple radioisotope scans described before, PET scans focus on the functional status of the target organ but do not show the structure of the organ well.

### Using PET for brain pathologies

One of the common uses for PET scans is to diagnose brain diseases. FDG molecules are taken up well by the brain, and the pattern of the uptake depends on the state of the brain or the presence of a particular disease. A normal brain should have a uniform uptake of the molecules. For a diseased brain, say in a patient with epilepsy, during a seizure activity, the diseased part of the brain will be overly active (the seizure focus), hence this part will take up more FDG molecules, and will be shown as a 'hot' spot. After the seizure has ceased, this part of the brain is exhausted and is shut down, therefore the uptake of nutrients, in this case FDG molecules, will be reduced. A 'cold' spot will now be seen at the same part of the brain. Based on this, the seizure focus can be located accurately. Although a much cheaper test such as the electroencephalogram (EEG) may provide similar information, PET provides more precise and reliable information about the seizure focus and pattern of the seizure activity. Such information is essential if surgical resection of the affected part of the brain is to be considered for epilepsy that is resistant to drug treatment.

PET scans can also be used to diagnose multiple sclerosis, schizophrenia and Alzheimer's disease (a form of dementia). It is important to remember that PET scans are used to diagnose brain diseases where the brain structures may be normal and the disease arises from an abnormal functional state of the brain. Indeed, whether it is epilepsy, multiple sclerosis or Alzheimer's disease, there might be no change or just minimal change in the structure of the brain when evaluated using CT or even MRI. For this reason, PET scans are extremely useful as they can diagnose certain diseases that no other imaging method is able to.

A common query needs to be addressed: 'Why can't the glucose molecules be labelled with technetium-99m when scanning the brain, which would make the scanning process much simpler and cheaper?' The answer lies in the fact that glucose is a rather small molecule, too small to have the technetium-99m (or any other pure gamma emitters) added without distorting its structure and shape. This distortion means the molecule will no longer be taken up by the brain. Fluorine-18 is a small atom, therefore when attached it does not affect the structure of the glucose molecule. Consequently, in certain cases, where glucose molecules have to be used as the carrying molecules, fluorine-18 is attached and hence PET is the only available option.

### Using PET for detecting metastatic cancer

The other common use for PET scans is to detect the spread of cancer (metastasis). Metastases can sometimes be difficult to detect using other imaging methods, such as a CT scan, because they may be small and are embedded in the healthy tissues. However, the cancerous tissues often up-regulate their glucose transporters as a mechanism to increase their nutritional uptake to sustain their rapid growth, consequently, the uptake of FDG will be increased, which allows the cancer tissues to be displayed as 'hot' spots on PET images. Because treatment of cancer can be very different depending on the presence or absence of metastasis, the information provided by PET will guide the doctor to plan the best treatment for the patient.

High-grade (more advanced) cancers tend to take up more glucose molecules than low-grade cancers, and therefore will 'light' up more on PET images. This allows the doctors to assess the nature of a particular cancer without taking tissue samples. Once again, this information cannot be provided by scans that only reveal the anatomical structures.

### Using PET for research

PET can be used to study the brain activity during certain types of physical tasks such as speaking or undertaking a fine motor activity. Based on the area of the brain that increases the uptake of the FDG molecules when a particular task is performed, the researcher is able to determine the part of the brain that controls a specific activity or task. For example, when speaking, a part of the frontal lobe will 'light up' suggesting it is responsible for controlling speech. This increases the knowledge of the regional function of the brain. It also provides valuable information that guides doctors to predict the likely deficit and prognosis after a brain injury (such as a stroke).

Students are encouraged to source their own images and refer to page 376 for examples.

## 20.7 Evaluation of the uses of radioisotope scans

Radioisotope scans, including PET scans, are not useful for providing information about the anatomical structures of the body. They have very low resolution and do not show fine detail of the target organ. On the other hand, radioisotope scans are the only type of scans that enable the assessment of the functional status of the target organ. Based on this information, many diseases can be diagnosed, especially ones that do not show any structural abnormalities. Also, because radioisotope scans do not show structural details they are often used in conjunction with other imaging methods that do show anatomical structures well, including CTs or MRIs.

Furthermore, radioisotopes produce harmful ionising radiation, which can do damage to the body even if administered at low doses. Although in most cases the benefit gained from the results of the scans outweighs the associated risks, they should be used with care. The risk of developing a secondary cancer is small due to the low dose and the short half-life of the radioisotope used; however, the scans are generally contraindicated in pregnancies.

Lastly, radioisotope scans, especially PET scans, are expensive. PET scans also depend on particle accelerators for their function, therefore their availability is limited and the waiting list for PET scans is often long.

## CHAPTER REVISION QUESTIONS

1. Define 'radioactivity' and 'transmutation'.
2. (a) Determine whether the following elements are alpha emitters or beta (plus or minus) emitters.
   (i) Potassium-40
   (ii) Thorium-232
   (iii) Radium 226
   (iv) Iodine-131
   (v) Nitrogen-13
   (b) Write a nuclear equation to describe the decay of each of these elements.
3. Iron-59 undergoes gamma decay; write an equation to describe this reaction.
4. (a) When aluminum is bombarded with alpha particles, a highly unstable isotope of phosphorus is formed. Write a nuclear equation to describe this reaction.
   (b) This radioisotope or phosphorus then undergoes a decay to form phosphorus-30 and another product. Identify this product and write a nuclear reaction to describe this reaction.
5. Nitrogen-14 when bombarded with an alpha particle will give rise to oxygen-17 and one other element. Write a nuclear equation to describe this reaction.
6. A sample of radioactive $^{214}_{83}Bi$, which has a half-life of 19.9 minutes, has an activity of $5.84 \times 10^4$ Bq.
   (a) What will its activity be after 39.8 minutes?
   (b) What will its activity be after two hours?
7. Give two reasons for why technetium-99m is the most commonly used radioisotope in nuclear medicine for acquiring images of a diseased organ.
8. The following questions are about bone scans.
   (a) Why does technetium-99m have to be attached to polyphosphate molecules (oxidronate) when performing a bone scan?
   (b) Under what circumstances would bones increase the uptake of technetium-99m?
   (c) How is the radiation emitted by technetium-99m detected outside the body?
   (d) Give two examples of medical problems that can be shown by using a bone scan.
   (e) Give one example where bone scans can be more superior to plain X-ray films.
9. In general terms, what classes of thyroid pathologies are best diagnosed using a thyroid scan?
10. What happens when a positron is allowed to collide with an electron?
11. Explain in detail how PET can use fluorine-18 labelled glucose molecules to form images of the target organ.
12. Compared to CT scans, PET scans are superior in diagnosing brain pathologies such as epilepsy or Alzheimer's disease (a form of dementia). Why?
13. Why can PET scans detect metastatic cancer more accurately than other scanning methods, such as CTs?
14. What are some of the limitations of using radioisotope scans, in particular PET scans?


Answers to chapter revision questions