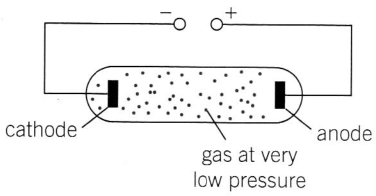
27 MEDICAL IMAGING
27.1 X-rays

Specification reference: 6.5.1

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → the basic structure of an X-ray tube; components – heater (cathode), anode, target metal and high voltage supply
- → production of X-ray photons from an X-ray tube.

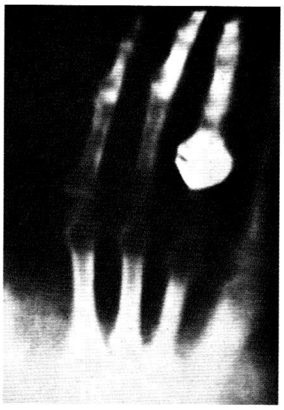


▲ **Figure 1** *A discharge tube containing gas at low pressure through which charge can flow*

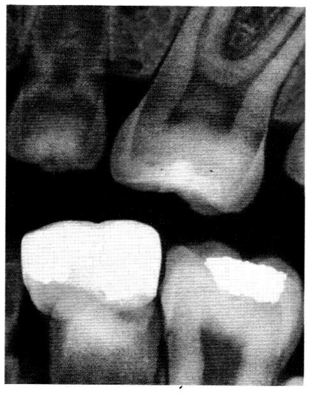
The first X-ray picture

Wilhelm Röntgen discovered **X-rays** in 1895. He was investigating the light emitted by gases in a discharge tube when a p.d. is applied between its two electrodes (Figure 1). When the gas in the tube was at extremely low pressure, the tube went dark, but he noticed that a fluorescent plate near his apparatus glowed. When he placed his hand between the tube and the plate, he could see shadows of the bones in his hand. The unknown rays from the tube were passing through soft tissue but were stopped by bone. We now call these rays X-rays.

Röntgen took the world's first X-ray picture (Figure 2). He did not know that intense X-rays are very harmful. Modern medical X-ray imaging uses low-intensity X-rays for very short exposure times, so is relatively safe, yet produces amazing images of structures within the body (Figure 3).



▲ **Figure 2** *The first recorded X-ray image shows the hand of Anna Bertha Röntgen, Wilhelm Röntgen's wife – note the ring on her finger*



▲ **Figure 3** *Modern X-ray images are sophisticated and have good contrast – this colour image shows a child's teeth with fillings*

The nature of X-rays

Experiments performed on the newly discovered X-rays showed that they could be polarised, were diffracted by atoms in crystals, and had extremely short wavelengths (range 10^{-8} to 10^{-13} m). They are electromagnetic waves and therefore travel through a vacuum at the speed of light.

X-ray photons have 10–10 000 times more energy than a photon of visible light, depending on their wavelength. X-rays are harmful to living cells and can kill them. It is this property of X-rays that is used in the treatment of cancer.

Synoptic link

X-rays are part of the electromagnetic spectrum, which you studied in Topic 11.6, Electromagnetic waves.

Production of X-rays

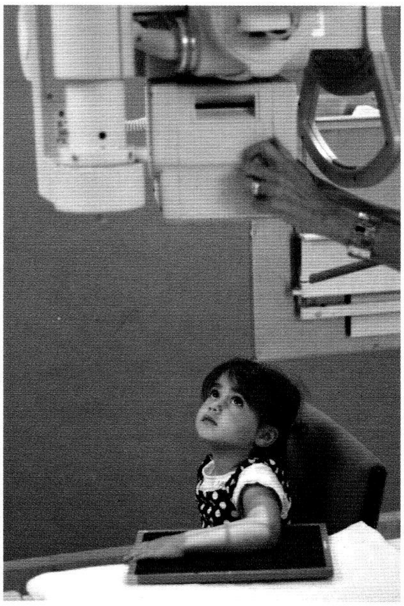
X-ray photons are produced when fast-moving electrons are decelerated by interaction with atoms of a metal such as tungsten. The kinetic energy of the electrons is transformed into X-ray photons.

Figure 4 shows a patient having a radiograph (X-ray image) taken. The X-ray machine is above the patient. It contains an **X-ray tube** that produces X-ray photons that pass through the patient to the detection plate below. Digital detection plates have replaced photographic plates, because the images can be stored and shared on computers and can be enhanced to detect subtle changes in tissues and bones.

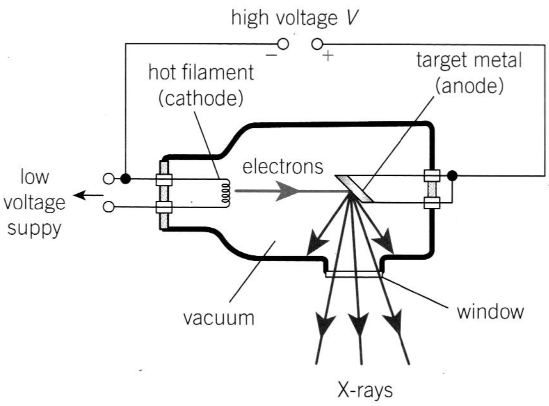
An X-ray tube (Figure 5) consists of an evacuated tube containing two electrodes. The tube is evacuated so that electrons pass through the tube without interacting with gas atoms. An external power supply is used to create a large p.d. (typically 30–100 kV) between these electrodes. The cathode (negative) is a heater, which produces electrons by **thermionic emission**. These electrons are accelerated towards the anode (positive). The anode is made from a metal, known as the **target metal**, such as tungsten, that has a high melting point.

X-ray photons are produced when the electrons are decelerated by hitting the anode. The energy output of X-rays is less than 1% of the kinetic energy of the incident electrons. The remainder of the energy is transformed into thermal energy of the anode. In many X-ray tubes, oil is circulated to cool the anode, or the anode is rotated to spread the heat over a large surface area.

The anode is shaped so that the X-rays are emitted in the desired direction through a window. The X-ray tube is lined with lead to shield the radiographer from any X-rays emitted in other directions.



▲ **Figure 4** *The X-ray tube is housed inside the machine above the young patient*



▲ **Figure 5** *An X-ray tube*

The shortest wavelength

An electron accelerated through a potential difference V gains kinetic energy eV, where e is the elementary charge. Since one electron releases one X-ray photon, from the principle of conservation of energy, the maximum energy of a photon from an X-ray tube must equal the maximum kinetic energy of a single electron.

maximum energy of X-ray photon = maximum kinetic energy of electron

The energy of a photon is equal to the Planck constant h × frequency f, and maximum frequency of the emitted X-rays f is the speed c divided by the minimum wavelength λ, so

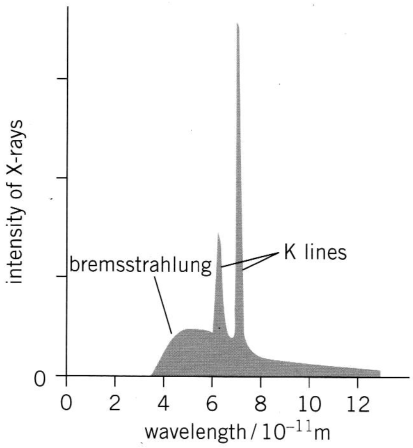
$$hf = eV$$

$$\frac{hc}{\lambda} = eV \qquad \text{therefore} \qquad \lambda = \frac{hc}{eV}$$

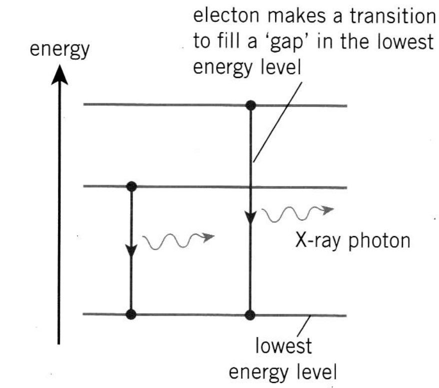
The wavelength from an X-ray tube is inversely proportional to the accelerating potential difference. Increasing the tube current just increases the intensity of the X-rays.

Synoptic link

One electron is responsible for producing one photon – this one-to-one mechanism is similar to that described in Topic 13.2, The photoelectric effect.



▲ **Figure 6** *A typical X-ray spectrum for molybdenum*



▲ **Figure 7** *How K-lines are produced by transitions between electron energy levels*

Characteristic spectrum

Figure 6 shows a typical X-ray spectrum, a graph of the intensity of the X-rays from an X-ray tube against wavelength for a particular supply voltage. The target metal used is molybdenum.

The range of decelerations of the electrons inside the X-ray tube produces the broad background of bremsstrahlung. 'Bremsstrahlung' means 'braking radiation' in German. The narrow, intense lines are referred to as the K-lines, and are characteristic of the target metal. The bombarding electrons can remove electrons in the metal atoms close to the nuclei. So the gaps created in the lower energy levels of the metal atoms are quickly filled by electrons dropping from higher energy levels. These transitions release photons of specific energies and therefore wavelengths (Figure 7).

1. Use Figure 6 to estimate the accelerating p.d. for the X-ray tube.
2. Estimate the difference between the two energy levels responsible for the most intense K-line in the X-ray spectrum of molybdenum.
3. Suggest how the shape of the graph would change when the accelerating p.d. is increased.

Summary questions

1. State a typical value for the wavelength of X-rays. *(1 mark)*
2. Use the wavelength from question 1 to calculate:
   - **a** the frequency of the X-rays; *(2 marks)*
   - **b** the energy of a single X-ray photon. *(2 marks)*
3. An X-ray tube is connected to a 65 kV supply. Calculate:
   - **a** the kinetic energy of an electron at the anode; *(2 marks)*
   - **b** the maximum energy of an X-ray photon. *(1 mark)*
4. The tube current in an X-ray tube is 21 mA. Calculate the number of electrons hitting the anode per second. *(2 marks)*
5. The X-ray tube in question 4 has an efficiency of 0.60%. Estimate the number of X-ray photons emitted from the tube per second. *(2 marks)*
6. Calculate the shortest wavelength of X-rays from an X-ray tube operating at 100 kV. Explain your answer. *(4 marks)*

27.2 Interaction of X-rays with matter

Specification reference: 6.5.1

Absorption of X-rays

Figure 1 shows a digital X-ray image of a patient's leg. Clearly, bones absorb more X-ray photons than do soft tissues and muscles. X-ray photons interact with the atoms of the material they pass through. The photons can be scattered or absorbed by the atoms, and this reduces the intensity of the X-rays. The term **attenuation** is used to describe the decrease in the **intensity** of an electromagnetic radiation as it passes through matter. So you can say that bone attenuates X-rays more than soft tissues.

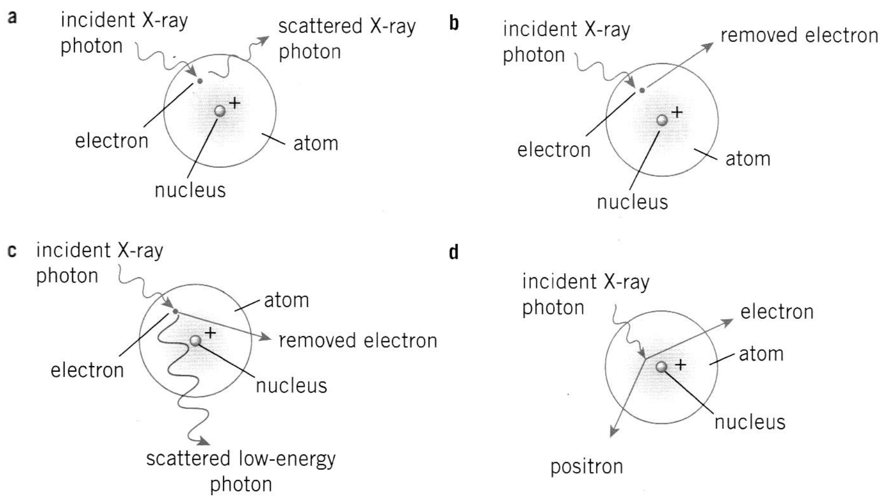
Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → attenuation of X-rays
- → X-ray attenuation mechanisms: simple scatter, photoelectric effect, Compton effect, and pair production
- → $I = I_0 e^{-\mu x}$
- → X-ray imaging with contrast media.

Attenuation mechanisms

The intensity of a parallel (collimated) beam of X-rays will decrease as it passes through matter. There are four attenuation mechanisms by which X-ray photons interact with atoms (Figure 2). Each mechanism reduces the intensity of the collimated beam in the original direction of travel.



▲ **Figure 2** *Attenuation mechanisms: (a) simple scatter – the X-ray photon is scattered elastically by an electron; (b) photoelectric effect – the X-ray photon disappears and removes an electron from the atom; (c) Compton scattering – the X-ray photon is scattered by an electron, its energy is reduced, and the electron is ejected from the atom; (d) pair production – the X-ray photon disappears to produce an electron–positron pair*

Synoptic link

Intensity is defined as the radiant power per unit cross-sectional area and has SI unit W m^{-2}. See Topic 11.5, Intensity.

▲ **Figure 1** *You can easily identify the outline of the fibreglass cast around the leg and of course the broken bone in this X-ray image*

Simple scatter

This mechanism is important for X-ray photons with energy in the range 1–20 keV. The X-ray photon interacts with an electron in the atom, but has less energy than the energy required to remove the electron, so the X-ray photon simply bounces off (is scattered) without any change to its energy. The X-ray machines used in hospitals use p.d.s greater than 20 kV, so this type of mechanism is insignificant for hospital radiography.

Synoptic links

You will recognise the value of 1.02 MeV from Topic 26.1, Einstein's mass–energy equation. It is the minimum energy required for a photon to create an electron–positron pair.

X-rays interact with matter as photons. You have already seen this in Topic 13.2, The photoelectric effect.

Photoelectric effect

This mechanism is significant for X-ray photons with energy less than 100 keV. The X-ray photon is absorbed by one of the electrons in the atom. The electron uses this energy to escape from the atom. Attenuation of X-rays by this type of mechanism is dominant when an X-ray image is taken, because hospital X-ray machines typically use 30–100 kV supplies.

Compton scattering

This mechanism is significant for X-ray photons with energy in the range 0.5–5.0 MeV. The incoming X-ray photon interacts with an electron within the atom. The electron is ejected from the atom, but the X-ray photon does not disappear completely – instead it is scattered with reduced energy. In the interaction, both energy and momentum are conserved. (Yes, photons do have momentum, but this concept is not covered at A Level.)

Pair production

This mechanism only occurs when X-ray photons have energy equal to or greater than 1.02 MeV. An X-ray photon interacts with the nucleus of the atom. It disappears and the electromagnetic energy of the photon is used to create an electron and its antiparticle, a positron.

Attenuation coefficients

You have already seen that X-ray photons interact with matter and this interaction reduces the intensity of a collimated beam of X-rays in the original direction of travel. The transmitted intensity of X-rays depends on the energy of the photons and on the thickness and type of the substance. For a given substance and energy of photons, the intensity falls exponentially with thickness of substance. The transmitted intensity I is given by the equation

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

where I_0 is the initial intensity before any absorption, x is the thickness of the substance, and μ is the **attenuation coefficient** or the **absorption coefficient** of the substance. Bone is a better absorber of X-rays than muscle, so bone has a larger value of μ than muscle. The SI unit of the attenuation coefficient is m^{-1}, but you can use cm^{-1} and mm^{-1}.

Worked example: Absorption by bone

A collimated beam of X-rays from a 100 kV supply is incident on bone. The initial intensity of the beam is $18\,W\,m^{-2}$. The attenuation coefficient of bone is $0.60\,cm^{-1}$. Calculate the intensity of the beam after it has passed through 7.0 mm of bone.

Step 1: Write down all the quantities given. It is important to have the values of μ and x in consistent units (here cm^{-1} and cm, respectively).

$$I_0 = 18\,W\,m^{-2},\ \mu = 0.60\,cm^{-1},\ x = 0.70\,cm$$

Step 2: Substitute the values into the exponential decay equation and calculate the transmitted intensity I.

$$I = I_0 e^{-\mu x} = 18 \times e^{-(0.60 \times 0.70)} = 12\,W\ (2\ s.f.)$$

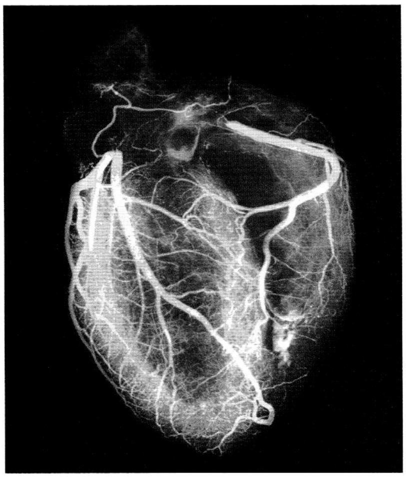
Contrast medium

Soft tissues have low absorption coefficients, so a contrast medium is used to improve the visibility of their internal structures in X-ray images. The two most common are iodine and barium compounds, both of which are relatively harmless to humans.

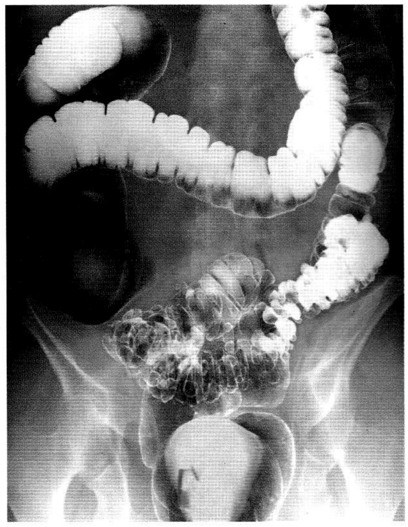
Barium and iodine are elements with large atomic number Z. For X-ray imaging, the predominant interaction mechanism is the photoelectric effect, for which the attenuation coefficient is proportional to the cube of the atomic number ($\mu \propto Z^3$). The average atomic number for soft tissues is about 7. This means that iodine ($Z = 53$) and barium ($Z = 56$) are about 430 times and 510 times more absorbent than soft tissues, respectively.

Iodine is used as a contrast medium in liquids, for example, to view blood flow. An organic compound of iodine is injected into blood vessels so that doctors can diagnose blockages in the blood vessels and the structure of organs such as the heart from the X-ray image (Figure 3).

Barium sulfate is often used to image digestive systems. It is given to a patient in the form of a white liquid mixture (a 'barium meal'), which the patient swallows before an X-ray image is taken. Figure 4 shows an X-ray image of the intestine of a patient who has had a barium meal. The pale regions are where the barium has accumulated.



▲ **Figure 3** *An X-ray image (angiogram) of a healthy heart, obtained by injecting iodine into the circulatory system so that the blood vessels show up clearly*



▲ **Figure 4** *A coloured X-ray image of a patient's intestine after a barium meal – notice how the outline of the intestine is easy to identify against the surrounding soft tissues*

Therapeutic use

X-rays are also used for therapy rather than imaging. Specialised X-ray machines, called linacs (linear accelerators), are used to create high-energy X-ray photons. These photons are used to kill off cancerous cells. They do so by the mechanisms of Compton scattering and pair production.

Summary questions

1. Name the attenuation mechanisms in which an electron inside an atom is involved. *(1 mark)*
2. Explain why simple scattering is not an important mechanism when X-ray images are taken in a hospital. *(2 marks)*
3. The attenuation coefficient of muscle is 0.21 cm^{-1} for X-ray photons of energy 100 keV. Convert this attenuation coefficient into m^{-1}. *(1 mark)*
4. Use the information in question 3 to calculate the percentage of intensity of X-rays transmitted for muscle of thickness 0.80 cm. *(3 marks)*
5. Calculate the minimum wavelength of an X-ray photon responsible for pair production. *(3 marks)*
6. Use the information given in question 3 to calculate the thickness of muscle that will reduce the transmitted intensity of X-rays by half. *(3 marks)*

27.3 CAT scans

Specification reference: 6.5.1

Learning outcomes

Demonstrate knowledge, understanding, and application of:

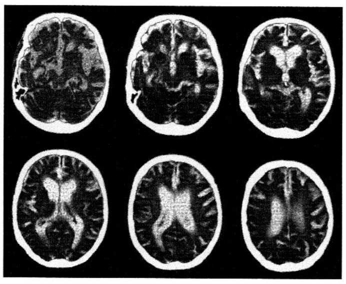
→ computerised axial tomography (CAT) scanning and the necessary components

→ the advantages of a CAT scan over an X-ray image.

Three-dimensional imaging

A conventional X-ray image provides a quick and cheap way to examine patients' internal structures. X-rays pass through the patient, and the intensity of the transmitted X-rays is recorded as a two-dimensional image on an electronic plate. Overlapping bones and tissues cannot be differentiated, and without the use of a contrast medium, different soft tissues are difficult to distinguish.

Figure 1 shows cross-sectional images of a head from a computerised axial tomography (CAT) scanner. A CAT scanner records a large number of X-ray images from different angles and assembles them into a three-dimensional image with the help of sophisticated software.

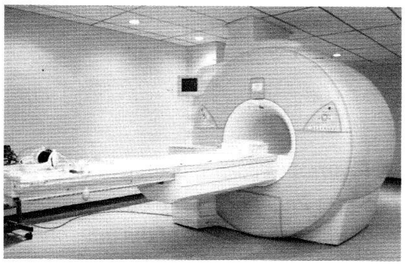


▲ **Figure 1** *A CAT scan yielded these virtual slices through the head of a patient with Alzheimer's disease – you can see the growing cavities (white) in the brain (brown)*

The scanning process and the analysis of electrical signals from detectors is controlled by a computer (and so the term 'computerised'). The term 'axial' refers to the images taken in the axial plane, cross-sections through the patient. Finally, 'tomography' is made up of two Greek words, 'tomos' meaning slice and 'graphein' meaning to record.

Computerised axial tomography

In a modern CAT scanner (Figure 2), the patient lies on their back on a horizontal examination table that can slide in and out of a large vertical ring or gantry. The gantry houses an X-ray tube on one side and an array of electronic X-ray detectors on the opposite side. The X-ray tube and the detectors opposite it rotate around within the gantry.



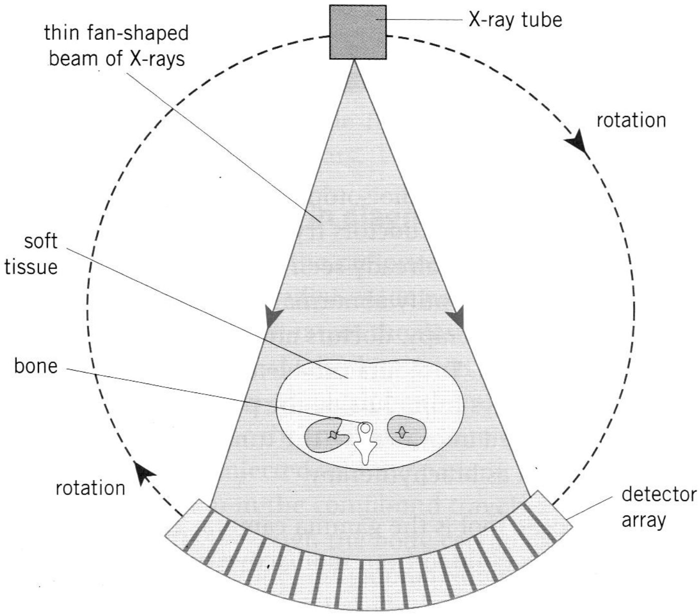
▲ **Figure 2** *A modern CAT scanner*

The X-ray tube produces a fan-shaped beam of X-rays that is typically only 1–10 mm thick. The thin beam irradiates a thin slice of the patient, and the X-rays are attenuated by different amounts by different tissues. The intensity of the transmitted X-rays is recorded by the detectors, which send electrical signals to a computer (Figure 3).

Each time the X-ray tube and detectors make a 360° rotation, a two-dimensional image or 'slice' is acquired. By the time the X-ray tube has made one complete revolution, the table has moved about 1 cm through the ring. In the next revolution, the X-ray beam irradiates the next slice through the patient's body. So the X-ray beam follows a spiral path during the 10–30 minute scan.

The radiographer can view each two-dimensional slice through the patient. In addition, the slices can be manipulated by sophisticated software to produce a three-dimensional image of the patient. This three-dimensional image can be rotated and zoomed on a display.

The technology of CAT scanners is still developing. The CAT scanners described above have X-ray detectors that rotate with the X-ray tube, but there are CAT scanners with a complete stationary ring of X-ray detectors but still with a rotating X-ray tube.



▲ **Figure 3** *The X-ray tube and the detectors rotate around the patient*

Advantages and disadvantages

A single traditional X-ray scan is quicker and cheaper than a CAT scan. However, CAT scans can be used to create a three-dimensional image of the patient that helps doctors to assess the shape, size, and position of disorders such as tumours. CAT scans can distinguish between soft tissues of similar attenuation coefficients.

X-rays are ionising radiation and as such are harmful. Some CAT scans can be quite prolonged and so expose the patients to a radiation dose equivalent to several years of background radiation, much more than a simple X-ray.

Patients have to remain very still during the scanning process, because any movement blurs the slice. Remaining still can be quite tricky for some patients, especially for the very young.

Summary questions

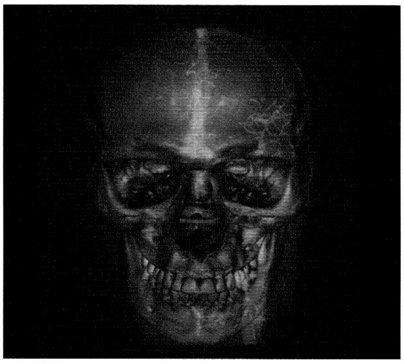
1 Name the main components of a CAT scanner. *(2 marks)*

2 State one advantage and one disadvantage of a CAT scan over an X-ray image. *(2 marks)*

3 Suggest why a thin beam of X-rays is necessary in a CAT scanner. *(1 mark)*

4 Explain what is meant by a 'slice' in CAT scanning. *(1 mark)*

5 Suggest how the CAT image of the blood flow in the head shown in Figure 4 may have been obtained. *(2 marks)*



▲ **Figure 4** *Blood supply to the head of a 38-year-old man – the left carotid artery (on the right of this image) is highlighted*

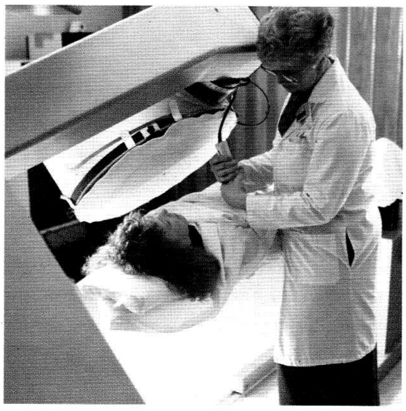
27.4 The gamma camera

Specification reference: 6.5.2

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → medical tracers technetium-99m and fluorine-18
- → the gamma camera and its components, formation of gamma camera images
- → diagnosis using the gamma camera.



▲ **Figure 1** *A modern gamma camera in use on a patient*

Diagnosis and therapy

In medicine, radioactive isotopes (radioisotopes) are used in both diagnosis and therapy. In diagnosis, doctors try to find out what is wrong with the patient. You have already seen how a CAT scanner can be used as a diagnostic tool to identify abnormalities inside a patient without surgery. In radiation therapy, doctors attempt to cure the patient using ionising radiation. Tumours can be targeted by gamma radiation or high-energy X-rays from outside the patient or by using a radioactive source implanted in or next to the tumour inside the patient, a technique known as brachytherapy.

Another valuable diagnostic tool is the gamma camera. This is a detector of gamma photons emitted from radioactive nuclei injected into the patient.

Choosing the right radioisotopes heading and weight

Radioisotopes used for medical imaging have to be placed inside the patient and their radiation detected from the outside. This makes gamma-emitting sources ideal because gamma photons are the least ionising and can penetrate through the patient to be detected externally. Alpha and beta sources cause more ionisation. They are dangerous and are not used for imaging techniques.

Radioisotopes chosen for medical imaging must have a short half-life to ensure high activity from the source so that only a small amount is required to form the image. The other benefit is the patient is not subjected to a high dosage of radiation that continues long after the procedure.

Many of the radioisotopes used in medicine are produced artificially. Fluorine-18, for example, which is used in PET scans, has a short half-life and has to be produced on-site at the hospital using a particle accelerator. You will look in more detail at PET scanners in Topic 27.5, PET scans. Technetium-99m (Tc-99m) is an extremely versatile radioisotope that can be used to monitor the function of major organs such as the heart, liver, lungs, kidneys, and brain. The isotope is produced from the natural radioactive decay of molybdenum-99.

$$^{99}_{42}\text{Mo} \xrightarrow{67\,\text{h}} {}^{99\text{m}}_{43}\text{Tc} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$$

$$^{99\text{m}}_{43}\text{Tc} \xrightarrow{6.0\,\text{h}} {}^{99}_{43}\text{Tc} + \gamma$$

$$^{99}_{43}\text{Tc} \xrightarrow{210\,000\text{ years}} {}^{99}_{44}\text{Ru} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$$

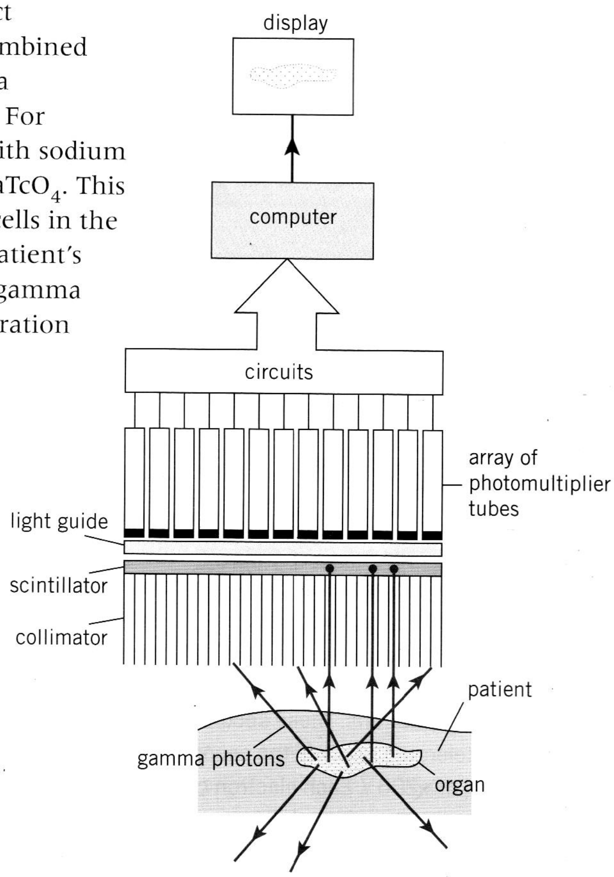
The Mo-99 isotope decays by beta-minus emission with a half-life of 67 hours. Tc-99m is a daughter nucleus in this decay, and it too is unstable (the 'm' means 'metastable', and refers to a nucleus that stays in a high-energy state, with more energy than the stable nucleus, for a longer period than expected). The Tc-99m isotope loses energy by emitting a gamma photon with energy of exactly 140 keV, with a half-life of about 6.0 hours. Stable Tc-99 remains, which has an extremely long half-life of 210 000 years.

Medical tracers used in diagnosis

In order to ensure that the radioisotope reaches the correct organ or tumour, the radioisotope has to be chemically combined with elements that will target the desired tissues to make a **radiopharmaceutical**, also known as a **medical tracer**. For example, technetium-99m can be chemically combined with sodium and oxygen to make the inorganic chemical compound $NaTcO_4$. This compound, once injected into the patient, will target the cells in the brain. The Tc-99m in the compound travels through the patient's body. Its progress through the body can be traced using a gamma camera as the Tc-99m emits gamma photons. The concentration of the radiopharmaceutical can be used to identify irregularities in the function of the body.

Use of the gamma camera

A gamma camera (Figure 2) detects the gamma photons emitted from the medical tracer (usually based on technetium-99m) injected into the patient, and an image is constructed indicating the concentration of the tracer within the patient's body.

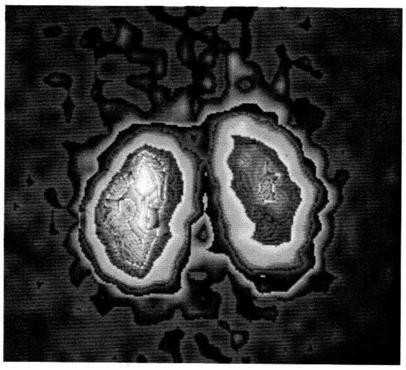


▲ **Figure 2** *The components of a gamma camera*

The gamma photons travel towards the **collimator**, a honeycomb of long, thin tubes made from lead. Any photons arriving at an angle to the axis of the tubes are absorbed by the tubes, so only those travelling along the axis of the tubes reach the **scintillator**.

The scintillator material is often sodium iodide. A single gamma photon striking the scintillator produces thousands of photons of visible light. Not all the gamma photons produce these tiny flashes, because the chance of a gamma photon interacting with the scintillator is about 1 in 10.

The photons of visible light travel through the light guide into the **photomultiplier tubes**. These tubes are arranged in a hexagonal pattern. A single photon of light entering a photomultiplier tube is converted into an electrical pulse (voltage). The outputs of all the photomultiplier tubes are connected to a computer. With the help of sophisticated software, the electrical signals from the tubes can be processed very quickly to locate the impacts of the gamma photons on the scintillator. These impact positions are used to construct a high-quality image that shows the concentrations of the medical tracer within the patient's body. The final image is displayed on a screen (Figure 3).



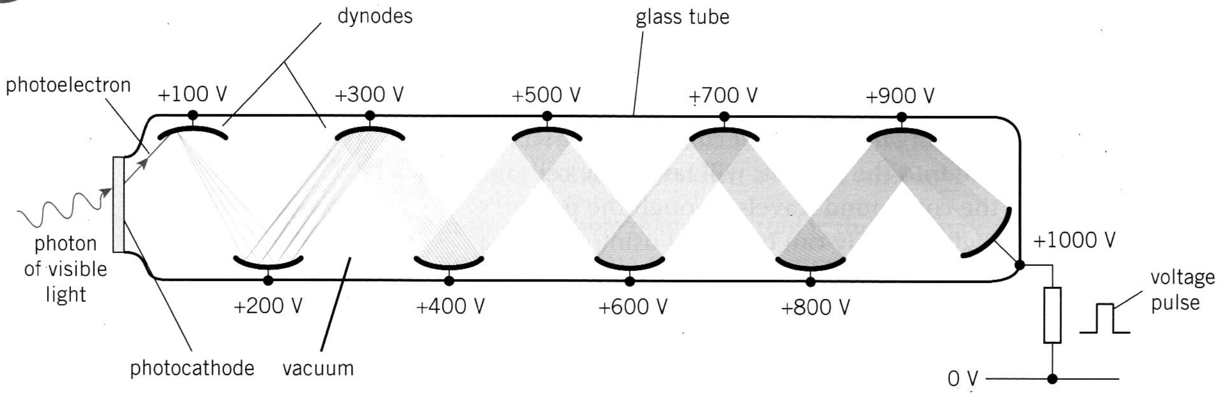
▲ **Figure 3** *A gamma camera image of a patient's kidneys, seen from the back – the kidney on the right is infected and less active than the normal one on the left, so it has taken up less Tc-99m*

Study tip

Use the term 'photons' to describe the operation of a gamma camera and not 'gamma rays' or 'visible light'.

A gamma camera differs from an X-ray imaging technique in one very important respect – it produces an image that shows the function and processes of the body rather than its anatomy.

Photomultipliers



▲ **Figure 4** *Photomultiplier tube*

Figure 4 shows the details of a simple photomultiplier tube. A single photon of visible light hitting the photocathode produces a photoelectron. This electron is accelerated to the first electrode (dynode), which is held at a potential of +100 V. The high-speed impact of this electron at the dynode produces an average of four secondary electrons. These secondary electrons are then accelerated towards the second dynode at a higher potential of +200 V. Each electron creates four secondary electrons on average as this process is repeated at successive dynodes, and the number of electrons grows exponentially. With ten dynodes, the number of electrons arriving at the anode from one photon can be as many as a million. The electrons collected at the anode pass through a resistor and produce a tiny voltage pulse.

1. State the function of a photocathode in a photomultiplier tube.
2. Show that a photomultiplier with ten dynodes produces about 10^6 electrons for every incident photon of visible light.
3. Calculate the total charge represented by 10^6 electrons.

Synoptic link

You first met photoelectrons in Topic 13.2, The photoelectric effect.

Summary questions

1. Name two radioisotopes used as medical tracers. *(1 mark)*
2. Suggest why a Tc-99m-based medical tracer has to be produced on-site in a hospital. *(1 mark)*
3. State the function of a photomultiplier tube. *(1 mark)*
4. State one advantage of a gamma scan over an X-ray scan. *(1 mark)*
5. Explain why the decay of Tc-99 within the patient is not a major concern during a gamma scan. *(2 marks)*
6. The typical initial activity of a Tc-99m-based medical tracer is about 500 MBq. Use the half-life from the text to calculate the initial number of Tc-99m nuclei. *(3 marks)*