27.5 PET scans

Specification reference: 6.5.2

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → medical tracers: fluorine–18
- → positron emission tomography (PET)
- → diagnosis using PET scanning.

Fluorine-18

Fluorine-18 is a versatile radiopharmaceutical (medical tracer) used in positron emission tomography (PET). The isotope is a positron emitter with a half-life of about 110 minutes. A nucleus of fluorine-18 decays into a nucleus of oxygen-18, a positron, a neutrino, and a gamma photon.

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{+1}\mathrm{e} + \nu_e + \gamma$$

Fluorine-18 has to be made either on-site or in a specialist laboratory near the hospital with a particle accelerator. In one method, high-speed protons collide with oxygen-18 nuclei and produce fluorine-18 nuclei and neutrons. Non-radioactive oxygen-18 is easy to find – about 20% of natural oxygen is this isotope. A single collision is shown by the nuclear transformation equation

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

▲ **Figure 1** *A particle accelerator facility in Russia where medical tracers for PET scanners are produced*

Diagnosis using PET scans

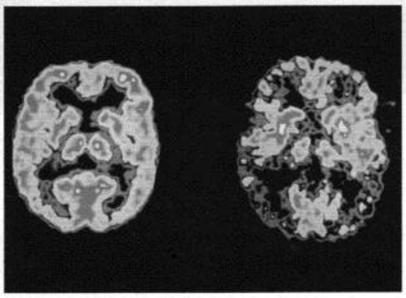
Just as in CAT scans, a PET scan produces slices through the body that can be used to construct a detailed three-dimensional image, but gamma radiation is used instead of X-rays.

Most PET scanners use a medical tracer called fluorodeoxyglucose (FDG), which is similar to naturally occurring glucose but is tagged with a radioactive fluorine-18 atom in place of one oxygen atom. The advantage of using FDG is that our bodies treat it like normal glucose. When FDG is injected into the patient it accumulates in tissues with a high rate of respiration. The activity from the FDG in the body is monitored using gamma detectors.

Another medical tracer used for PET scanning is carbon monoxide made using the carbon-11 isotope. This isotope emits a positron and has a half-life of about 20 minutes. Carbon monoxide is very good at clinging onto haemoglobin molecules in the red blood cells, so it can be transported through the body and the concentrations of carbon monoxide can be monitored in a PET scan.

The PET scanner

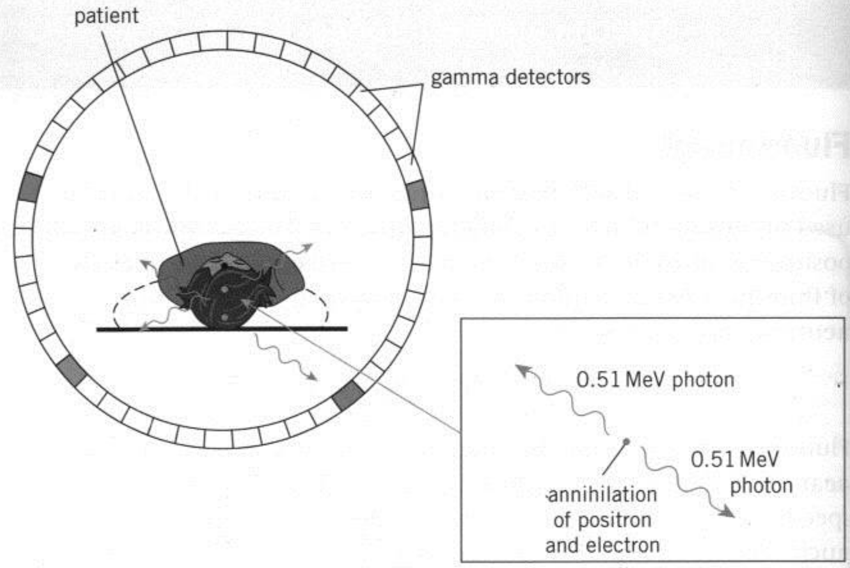
Figure 2 shows the principles of a PET scanner. The patient lies on a horizontal table and is surrounded by a ring of gamma detectors. Each detector consists of a photomultiplier tube and a sodium iodide scintillator, and produces a voltage pulse or signal for every gamma photon incident at its scintillator. The detectors are all connected to a high-speed computer.



▲ **Figure 3** *PET scans can diagnose abnormal activity in the brain, such as in this comparison between the activity (red and yellow) in a normal brain (the scan on the left) and the brain of a person with Alzheimer's disease (the scan on the right)*

Summary questions

1. Name the medical tracer (radiopharmaceutical) that contains fluorine-18 nuclei. *(1 mark)*
2. Describe one method used to produce fluorine-18 nuclei. *(1 mark)*
3. Describe the construction and function of a gamma detector used in PET scanners. *(2 marks)*
4. Annihilation of a positron and an electron produces two gamma photons. Calculate the time difference between the arrival times of these photons if one of them travels 5.00 cm further than the other. Comment on your answer. *(3 marks)*
5. A patient is injected with FDG. A typical PET scan takes about 20 minutes. Calculate the percentage drop in the original activity of FDG by the time the scan finishes. *(3 marks)*



▲ **Figure 2** *A patient surrounded by a ring of gamma detectors*

The patient is injected with FDG. The PET scanner detects the gamma photons emitted when the positrons from decaying fluorine-18 nuclei annihilate with electrons inside the patient. Note that the gamma photons detected for the PET scan come from the annihilation of the positrons, not the gamma photons emitted by the decaying fluorine-18 nuclei. On average, a positron travels about 1 mm from its emission point before it annihilates an electron.

The annihilation of a positron and an electron produces two gamma photons travelling in opposite directions, so momentum is conserved (as mentioned in Topic 27.2, Interaction of X-rays with matter). The computer can determine the point of annihilation from the difference in the arrival times of these photons at the two diametrically opposite detectors and the speed of photons c ($3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$). The voltage signals from all the detectors are fed into the computer, which analyses and manipulates these signals to generate an image (scan) on a display screen in which different concentrations of the tracer show up as areas of different colours and brightness.

Advantages and disadvantages of PET

PET is a non-invasive technique (the patient is not subjected to the risks of surgery). PET scans are used to help diagnose different types of cancers, to help plan complex heart surgery, and to observe the function of the brain. It can help doctors identify the onset of certain disorders of the brain, such as Alzheimer's disease (Figure 3). PET scans are also being used to assess the effect of new medicines and drugs on organs.

One major disadvantage of PET is that the technique is very expensive because of the facilities required to produce the medical tracers. PET scanners are found only at larger hospitals, and only patients with complex health problems are recommended for PET scans.

27.6 Ultrasound

Specification reference: 6.5.3

Ultrasound scans

We can hear sound with frequencies in the range from about 20 Hz to 20 kHz. Ultrasound is simply longitudinal sound waves with frequency greater than 20 kHz, beyond the range of human hearing. Although ultrasound is inaudible to us, some animals such as bats and dolphins use ultrasound to communicate and hunt prey.

The benefits of using ultrasound to form images of the internal structures of the body are obvious. It is non-ionising and therefore harmless, it is non-invasive (no surgery is necessary, so no risk of infection), and it is quick.

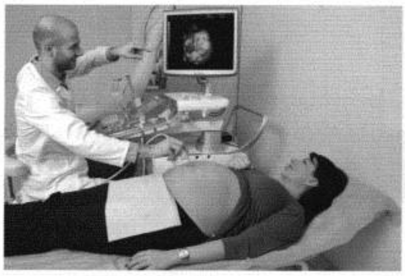
Ultrasound used for medical imaging has frequencies in the range of 1–15 MHz. Like audible sound, ultrasound can be refracted as it travels between substances, reflected at the boundary between two substances, and diffracted by small structures or apertures. The wavelength of ultrasound in the human body is less than 1 mm, so ultrasound can be used to identify features as small as a few millimetres.

An **ultrasound transducer** is a device used both to generate and to receive ultrasound. It changes electrical energy into sound and sound into electrical energy, by means of the **piezoelectric effect**.

Learning outcomes

Demonstrate knowledge, understanding, and application of:

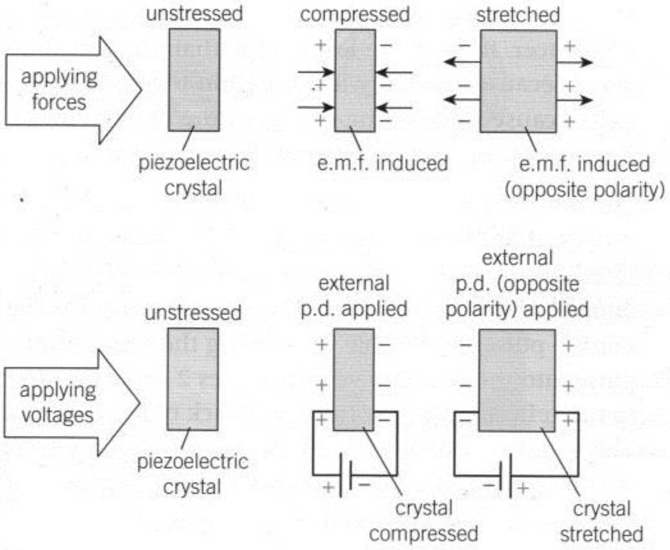
- → ultrasound frequency
- → the piezoelectric effect
- → ultrasound transducers
- → ultrasound A-scans and B-scans.



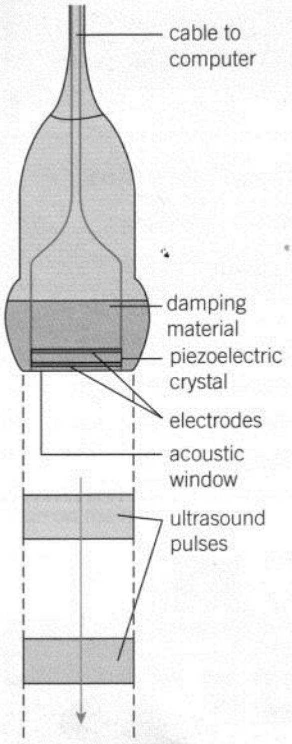
▲ **Figure 1** *An ultrasound transducer being used for a fetal scan (a B-scan – see later)*

The piezoelectric effect

Some crystals, such as quartz, produce an electromotive force (e.m.f.) when they are compressed, stretched, twisted, or distorted. This piezoelectric effect is a reversible process. In order words, when an external p.d. is applied across the opposite faces of the crystal, the electric field can either compress or stretch the crystal (Figure 2). The strain experienced by the crystal is no more than about 0.1%.



▲ **Figure 2** *Piezoelectric effect*



▲ **Figure 3** *An ultrasound transducer*

Ultrasound transducer

To generate ultrasound, a high-frequency (e.g. 5 MHz) alternating p.d. is applied across opposite faces of a crystal. This repeatedly compresses and expands the crystal. The frequency is chosen to be the same as the natural frequency of oscillation of the crystal. The result is that the crystal resonates, and produces an intense ultrasound signal.

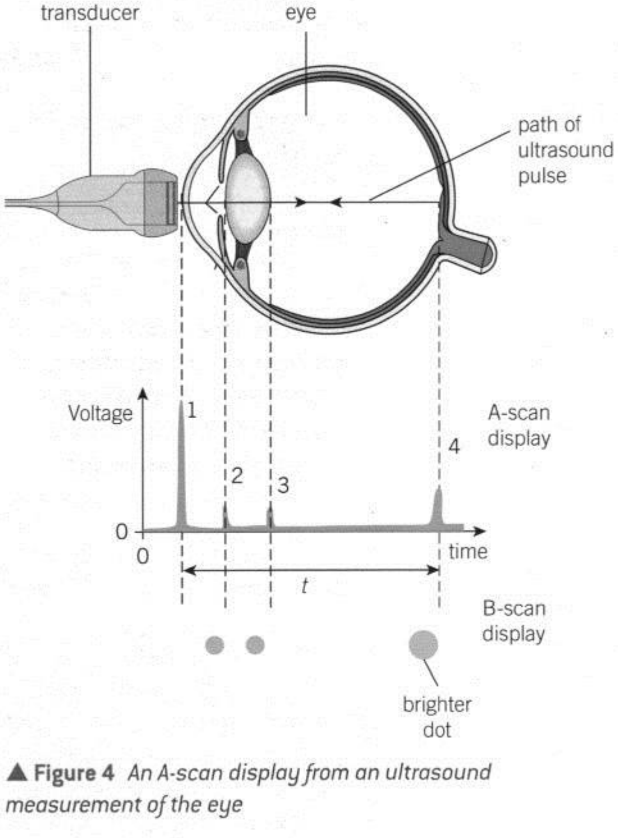
An ultrasound transducer emits *pulses* of ultrasound, typically 5000 pulses every second (a frequency of 5 kHz pulses of ultrasound of frequency 5 MHz).

The same transducer is also used to detect ultrasound. Any ultrasound incident on the crystal will make it vibrate, so the crystal is compressed and expanded by tiny amounts. This vibration generates an alternating e.m.f. across the ends of the crystal, which can be detected by electronic circuits.

Modern ultrasound transducers use either lead zirconate titanate (a ceramic) or polyvinylidene fluoride (a polymer) instead of quartz. Figure 3 shows the basic construction of an ultrasound transducer used in hospitals.

A-scans

The simplest type of ultrasound scan is called an A-scan. A single transducer is used to record along a straight line through the patient. An A-scan can be used to determine the thickness of bone or the distance between the lens and retina in the eye. This technique is being superseded by more elaborate techniques such as the B-scan (see later), but it provides a useful insight into the principles of using ultrasound to scan internal structures.



▲ **Figure 4** *An A-scan display from an ultrasound measurement of the eye*

Consider a transducer sending ultrasound pulses into the body of a patient. Each pulse of ultrasound will be partly reflected and partly transmitted at the boundary between any two different tissues. The reflected or 'echo' pulse will be received at the transducer. It will have less energy than the original pulse because of energy losses within the body and also because some of the energy of the original pulse is transmitted though the boundary.

The pulsed voltage at the ultrasound transducer is displayed on an oscilloscope screen or computer screen as a voltage against time plot. Figure 4 shows an idealised scan of the eye. The voltage pulse 1 is the voltage pulse responsible for sending the ultrasound pulse into the eye. The voltage pulses 2 and 3 are due to the reflections at the front and back of the eye lens. The voltage pulse 4 is due to the reflection at the back of the eye (retina). The amplitudes of the voltage signals are attenuated, as already explained.

The time interval t is the time taken for the ultrasound pulse to travel from the front of the transducer to the retina and then back to the transducer. The total distance travelled by the ultrasound pulse is $2L$, where L is the distance between the transducer and the retina. The value of L can be calculated if the average speed v of the ultrasound in the eye is known.

Study tip

The A in A-scan stands for amplitude.

Worked example: Eyeballing

The average speed of ultrasound in the eye is $1550\,\mathrm{m\,s^{-1}}$. The time interval t in the A-scan shown in Figure 4 is $27\,\mu\mathrm{s}$. Determine the approximate length L of the eyeball.

Step 1: Calculate the total distance travelled by the ultrasound in the time interval t.

$$\text{distance} = vt = 1550 \times 27 \times 10^{-6} = 0.04185\,\mathrm{m}$$

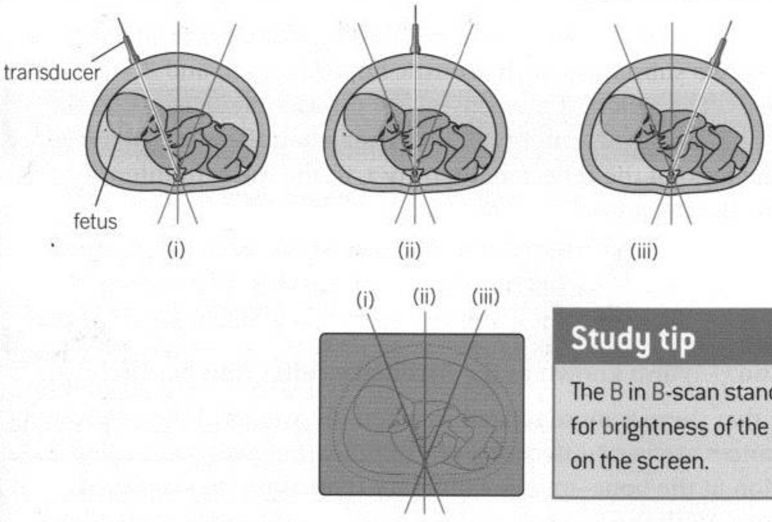
Step 2: The distance 0.042 m is equal to twice the distance L (the ultrasound has to travel to the retina and then back to the transducer).

Therefore, $L = \dfrac{0.04185}{2} = 0.021\,\mathrm{m}$ (2 s.f.)

The length L of the eyeball is 2.1 cm.

B-scans

When you see images of an ultrasound scan, they are most likely to be a B-scan, which provides a two-dimensional image on a screen. In a B-scan (also known as a 2D scan), the transducer is moved over the patient's skin. The output of the transducer is connected to a high-speed computer. For each position of the transducer, the computer produces a row of dots on the digital screen – each dot corresponds to the boundary between two tissues. The brightness of the dot is proportional to the intensity of the reflected ultrasound pulse. The collection of dots produced correspond to the different positions of the transducer over the patient, making a two-dimensional image of a section though the patient (Figure 5).



▲ **Figure 5** *A B-scan is effectively a multiple of A-scans*

Study tip

The B in B-scan stands for brightness of the dots on the screen.

Summary questions

1 State the nature of ultrasound. *(1 mark)*

2 State the typical frequency of ultrasound used for ultrasound scanning. *(1 mark)*

3 The speed of ultrasound in air is about $340\,\mathrm{m\,s^{-1}}$.
  a Calculate the wavelength of ultrasound in air from a transducer working at 10 MHz. *(2 marks)*
  b Ultrasound travels faster in the body than in air. State and explain how this will affect the wavelength of sound from the same transducer in the body. *(2 marks)*

4 State the major difference between an A-scan and a B-scan. *(1 mark)*

5 The ultrasound pulses from the transducer are emitted at a rate of about 5 kHz. The speed of ultrasound in the body is about $1600\,\mathrm{m\,s^{-1}}$. Explain why such a pulse rate would be suitable for ultrasound scanning of a patient. *(4 marks)*

27.7 Acoustic impedance

Specification reference: 6.5.3

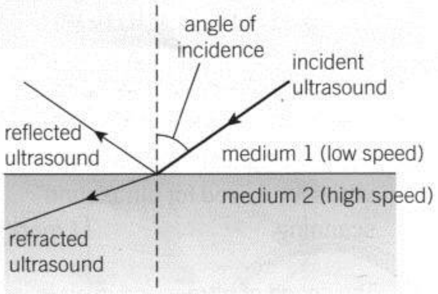
Learning outcomes

Demonstrate knowledge, understanding, and application of:

- ➔ acoustic impedance of a medium; $Z = \rho c$
- ➔ reflection of ultrasound at a boundary
- ➔ $\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$
- ➔ impedance (acoustic) matching
- ➔ the use of gel in ultrasound scanning.

What happens at a boundary?

When a uniform beam of ultrasound is incident at a boundary between two substances (media), a proportion of its intensity will be reflected and the remainder will be refracted (Figure 1). The fraction of the ultrasound intensity reflected at the boundary depends on the **acoustic impedance** of both media.



▲ **Figure 1** *Ultrasound will be both reflected and refracted at a boundary between two media*

Acoustic impedance Z

The acoustic impedance Z of a substance is defined as the product of the density ρ of the substance and the speed c of ultrasound in that substance, that is

$$Z = \rho c$$

The SI unit of acoustic impedance is $\mathrm{kg\,m^{-2}\,s^{-1}}$.

Table 1 lists data for some important substances in ultrasound scanning.

▼ **Table 1** *Data for some substances encountered in ultrasound scans*

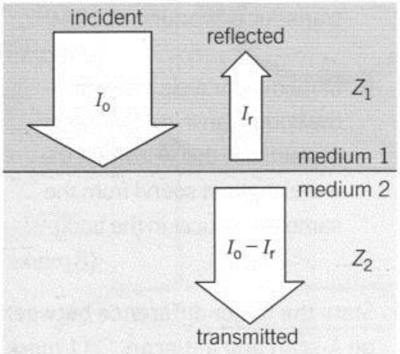
Substance	ρ / kg m^{-3}	c / km s^{-1}	Z / 10^6 kg m^{-2} s^{-1}
air	1.3	0.340	0.000 442
fat	950	1450	1.38
soft tissue (average)	1060	1540	1.63
muscle	1070	1580	1.69
skin	1070	1590	1.70
bone (average)	1900	4000	7.60

Reflected intensity

Consider a collimated beam of ultrasound incident at a boundary between two substances with acoustic impedances Z_1 and Z_2 (Figure 2). The reflected intensity of the ultrasound depends on the values of Z_1 and Z_2. For normal incidence, when the angle of incidence is 0°, the ratio of the reflected intensity I_r to the incident intensity I_0 is given by the equation

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} \qquad \text{or} \qquad \frac{I_r}{I_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

The ratio $\frac{I_r}{I_0}$ is also known as the **intensity reflection coefficient**. Notice that there is more reflection when the values of the acoustic impedances are very different. For example, there will be greater reflection at the bone–muscle boundary than at the blood–muscle boundary. With the exception of bone, the acoustic impedances of most substances that make up the human body are quite similar, so bones are easier to distinguish in an ultrasound scan than different types of soft tissues (Figure 3).



▲ **Figure 2** *Reflection and transmission of normally incident ultrasound at a boundary between media*

Study tip

Be careful: c is the speed of the ultrasound in the substance and not the speed of light.

Worked example: Reflected intensities

A beam of ultrasound is incident normally at the boundary between muscle and bone. Calculate the percentage of the incident intensity reflected at this boundary.

Step 1: Use Table 1 to find the values of the acoustic impedances. It does not matter which is Z_1 and which is Z_2 – the answer will be the same because of the squaring.

$Z_{1\,(\text{muscle})} = 1.69 \times 10^6\,\text{kg}\,\text{m}^{-2}\,\text{s}^{-1}$ and $Z_{2\,(\text{bone})} = 7.60 \times 10^6\,\text{kg}\,\text{m}^{-2}\,\text{s}^{-1}$

Step 2: Substitute the values carefully and solve the equation. You do not have to include the 10^6 factors, because they cancel each other out.

$$\frac{I_r}{I_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = \left(\frac{1.69 - 7.60}{1.69 + 7.60}\right)^2 = 0.40 \text{ (2 s.f.)}$$

The percentage of the incident intensity reflected at the boundary is 40%. The remainder is transmitted through the boundary.

▲ **Figure 3** *An ultrasound scan of a thirteen-week-old fetus in the womb – the head is at the bottom right, and the bones of the spine and ribs in the centre are much easier to see than the soft organs*

Acoustic matching – coupling gel

When an ultrasound transducer is placed on the skin of a patient air pockets will always be trapped between the transducer and the skin. The air–skin boundary means that about 99.9% of the incident ultrasound will be reflected before it even enters the patient. To overcome this problem, a special gel, called a **coupling gel**, with acoustic impedance similar to that of skin is smeared onto the skin and the transducer. The gel fills air gaps between the transducer and the skin and ensures that almost all the ultrasound enters the patient's body. The terms **impedance matching** or **acoustic matching** are used when two substances (e.g. coupling gel and skin) have similar values of acoustic impedance. In this case negligible reflection occurs at the boundary between the two substances.

Summary questions

1 Define acoustic impedance of a substance. *(1 mark)*

2 State what causes a large fraction of reflection of ultrasound at the boundary between substances. *(1 mark)*

3 Lead zirconate titanate is used in the construction of modern ultrasound transducers. It has acoustic impedance $2.9 \times 10^7\,\text{kg}\,\text{m}^{-2}\,\text{s}^{-1}$ and density $5600\,\text{kg}\,\text{m}^{-3}$. Calculate the speed of ultrasound in this material. *(2 marks)*

4 Calculate the percentage of the incident intensity reflected at the fat–muscle boundary. *(2 marks)*

5 The coupling gel used in ultrasound scans has acoustic impedance of $1.65 \times 10^6\,\text{kg}\,\text{m}^{-2}\,\text{s}^{-1}$.
  a Show that the percentage of the incident intensity reflected at the air–skin boundary is 99.9%. *(2 marks)*
  b Calculate the percentage of the incident intensity reflected at the gel–skin boundary. *(2 marks)*

27.8 Doppler imaging

Specification reference: 6.5.3

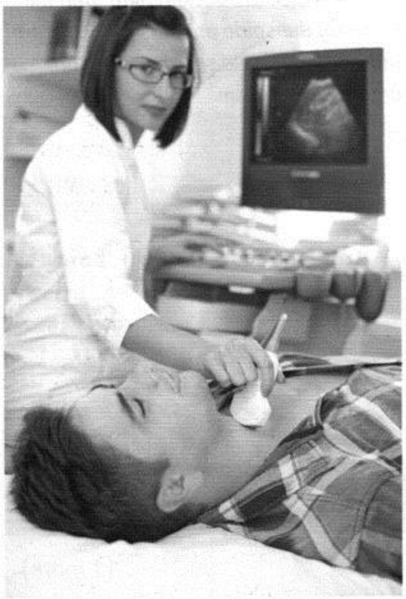
Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → the Doppler effect in ultrasound
- → the speed of blood v in the body: $\frac{\Delta f}{f} = \frac{2v\cos\theta}{c}$.

Synoptic link

You have already met the Doppler effect with electromagnetic waves in Topic 20.2, The Doppler effect.



▲ **Figure 1** *A patient undergoing a Doppler ultrasound investigation of the thyroid gland*

Doppler ultrasound

The frequency of ultrasound changes when it is reflected off a moving object – the Doppler effect. Doppler ultrasound, a non-invasive technique, uses the reflection of ultrasound from iron-rich blood cells to help doctors to evaluate blood flow through major arteries and veins, such as those in the arms, legs, neck, and even the heart. The technique can be used to reveal blood clots (thrombosis), identify the narrowing of the walls caused by accumulation of fatty deposits (atheroma), and evaluate the amount of blood flow to a transplanted kidney or liver.

Colour Doppler scans

During Doppler ultrasound, the ultrasound transducer is pressed lightly over the skin above the blood vessel. The transducer sends pulses of ultrasound and receives the reflected pulses from inside the patient. Ultrasound reflected off tissues will return with the same frequency and wavelength, but that reflected off the many moving blood cells will have a changed frequency. The frequency is increased when the blood is moving towards the transducer and decreased when the blood is receding from the transducer. The frequency shift or change in frequency, Δf, is directly proportional to the speed v (of approach or recession) of the blood (see later). The transducer is connected to a computer that produces a colour-coded image to show the direction and speed of the blood flow on a screen (Figure 2).

▲ **Figure 2** *Coloured Doppler ultrasound scan showing umbilical blood flow – the fetus is lying across the bottom left, and oxygenated (arterial) blood, which is flowing from mother to fetus, is red, whilst deoxygenated (venous) blood, which is flowing from fetus to mother, is blue*

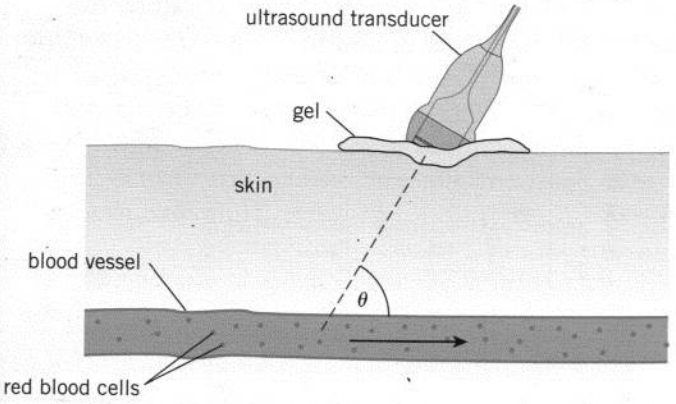
Determining the speed of blood

Ultrasound in scans has a frequency in the range 5 to 15 MHz, and in blood flow analysis this can give a Doppler shift up to 3 kHz.

Figure 3 shows an ultrasound transducer placed over a blood vessel. The axis of the probe is held at an angle θ to the blood vessel. The change in the observed ultrasound frequency Δf is given by the equation

$$\Delta f = \frac{2fv\cos\theta}{c}$$

where f is the original ultrasound frequency, v is the speed of the moving blood cells, and c is the speed of the ultrasound in blood. Note that the Doppler shift in frequency is directly proportional to the speed of the blood flow. The probe has to be held at an angle to the skin – holding it at right angles would give no observed change in frequency because $\cos 90° = 0$. The typical angle used is about 60°.



▲ **Figure 3** *Ultrasound transducer used to determine the speed of blood flow*

Worked example: The speed of blood

Doppler ultrasound technique is used on a patient's blood vessel. The transducer is held at an angle of 60° to the blood vessel and emits ultrasound of frequency 10 MHz. The observed Doppler shift is 1.5 kHz. The speed of ultrasound in blood is $1600\,\mathrm{m\,s^{-1}}$. Calculate the speed of blood flow.

Step 1: List all the quantities given.

$$\Delta f = 1500\,\mathrm{Hz},\ f = 10 \times 10^{6}\,\mathrm{Hz},\ \theta = 60°,\ c = 1600\,\mathrm{m\,s^{-1}}\ (2\ \text{s.f.})$$

Step 2: Rearrange the equation and then substitute the values to calculate the speed v of the blood flow.

$$v = \frac{c\Delta f}{2f\cos\theta} = \frac{1600 \times 1500}{2 \times 10 \times 10^{6} \times \cos 60°} = 0.24\,\mathrm{m\,s^{-1}}\ (2\ \text{s.f.})$$

The speed of the blood flow is about $24\,\mathrm{cm\,s^{-1}}$.

Summary questions

1. In the technique of Doppler ultrasound, what is responsible for producing the change in frequency of the ultrasound? *(1 mark)*
2. Explain why the transducer is not placed at right angles to the surface of the patient's skin. *(2 marks)*
3. The Doppler shift in frequency for blood travelling at a speed of $12\,\mathrm{cm\,s^{-1}}$ is 500 Hz. Calculate the speed of blood for a Doppler shift of 700 Hz. Explain your answer. *(3 marks)*
4. Ultrasound of frequency 7.0 MHz is directed at an angle of 60° to the blood vessel of a patient. The diameter of the blood vessel is about 1.5 mm and the Doppler shift in frequency is 900 Hz. The speed of ultrasound in the blood is $1600\,\mathrm{m\,s^{-1}}$. Calculate the volume of blood flowing thorough the patient's blood vessel per second. *(4 marks)*