Cambridge

A2 Level

Physics

CODE: (9702)

Chapter 31

Chapter 32: Medical imaging

The nature and production of X-rays X-rays are a form of electromagnetic radiation. They belong to the short-wavelength, high-frequency end of the electromagnetic spectrum, beyond ultraviolet radiation (Figure 32.2)

X-ray tube

Figure 32.3a shows a patient undergoing a pelvic X-ray to check for bone degeneration. The X-ray machine is above the patient; it contains the X-ray tube that produces the X-rays which pass downwards through the patient’s body.

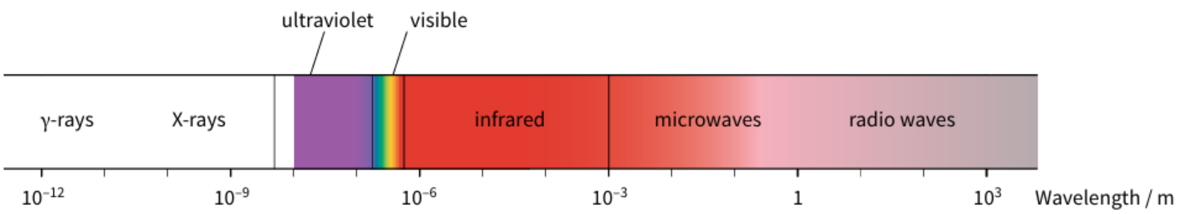

Figure 32.2 The electromagnetic spectrum; X-rays and γ-rays lie at the high-frequency, short-wavelength end of the spectrum.

- X-rays are produced when fast-moving electrons are rapidly decelerated. As the electrons slow down, their kinetic energy is transformed to photons of electromagnetic radiation.

- γ-rays are produced by radioactive decay. Following alpha (α) or beta (β) emission, a gamma photon is often emitted by the decaying nucleus

Figure 32.4 shows the principles of the modern X-ray tube. The tube itself is evacuated, and contains two electrodes:

■ ■ Cathode – the heated filament acts as the cathode (negative) from which electrons are emitted.

■ ■ Anode – the rotating anode (positive) is made of a hard metal such as tungsten. (The anode metal is often referred to as the ‘target metal’.)

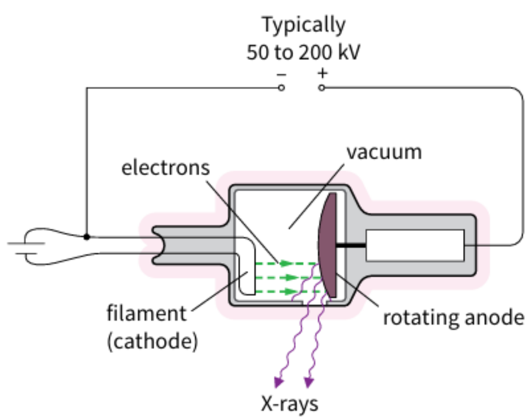

Figure 32.4 A simplified diagram of an X-ray tube.

The width of the X-ray beam can be controlled using metal tubes beyond the window to absorb X-rays. This produces a parallel-sided beam called a **collimated beam.**

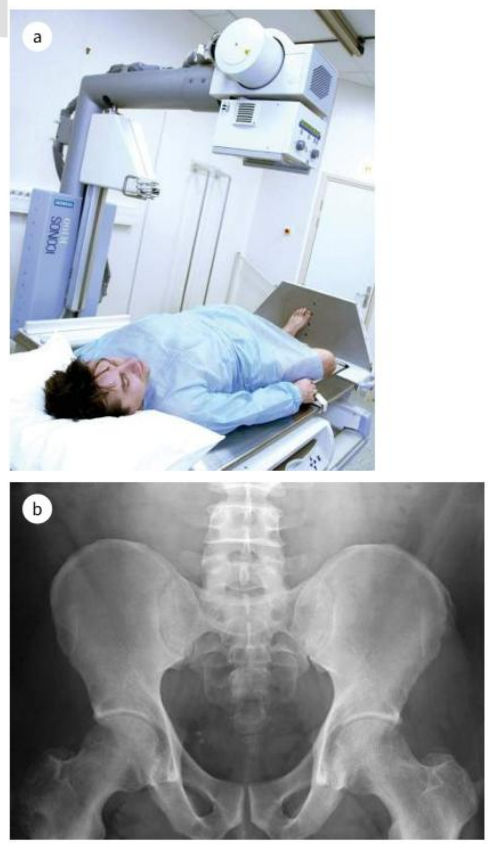

Figure 32.3 **a** A general-purpose X-ray system. **b** A typical X-ray image produced by such a machine, showing the region around the pelvis.

X-ray spectrum

The X-rays that emerge from an X-ray tube have a range of energies, as represented in the X-ray spectra shown in Figure 32.5.

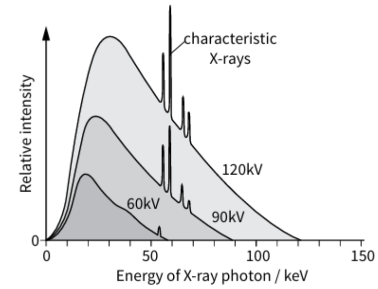

Figure 32.5 X-ray spectra for a tungsten target with accelerating voltages of 60 kV, 90 kV and 120 kV. The continuous curve shows the braking radiation while the sharp spikes are the characteristic X-rays.

Each spectrum has two components, the broad background 'hump' of **braking radiation** (also known as Bremsstrahlung radiation) and a few sharp 'lines' of **characteristic radiation.**

The energy E gained by the electron when it is accelerated through a potential difference of V between the cathode and the anode is given by E = Ev

$$f_{\max} = \frac{eV}{h}$$

Controlling intensity and hardness

The intensity of an X-ray beam is a measure of the energy passing through unit area (see the next section). Another consideration is the **hardness** of the X-rays. An X-ray may be thought of as 'hard' or 'soft'. Soft X-rays have lower energies and hence longer wavelengths than hard X-rays. Soft X-rays are less penetrating (they are more easily absorbed) and so they contribute more to the patient's exposure to hazardous radiation.

X-ray attenuation

As you can see if you look back to Figure 32.1, bones look white in an X-ray photograph. This is because they are good absorbers of X-rays, so that little radiation arrives at the photographic film to cause blackening.

The gradual decrease in the intensity of a beam of X-rays as it passes through matter is called **attenuation.**

Decreasing intensity

You should recall from Chapter 13 that the intensity of a beam of radiation indicates the rate at which energy is transferred across unit cross-sectional area. Intensity is defined thus:

Intensity is the power per unit cross-sectional area.

We can determine the intensity I using the equation:

$$I = \frac{P}{A}$$

We can write an equation to represent the attenuation of X-rays as they pass through a uniform material as follows:

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

where I_0 is the initial intensity (before absorption), x is the thickness of the material, I is the transmitted intensity and μ is the **attenuation (or absorption) coefficient** of the material.

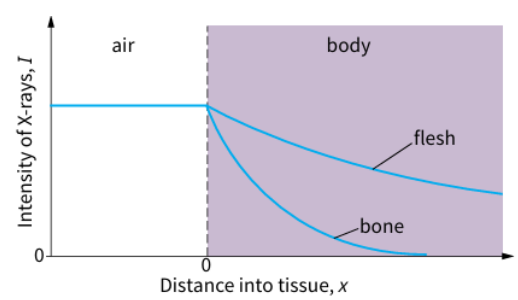

Figure 32.6 The absorption of X-rays follows an exponential pattern.

Half thickness

The attenuation of X-rays and the decay of radioactive nuclides are exponential decays, with the half-life of radioactive isotopes and half-thickness of absorbing materials influencing these processes.

Improving X-ray images

Radiographers (the people in charge of X-ray systems) have three main aims:

■ ■ to reduce as much as possible the patient's exposure to harmful X-rays

■ ■ to improve the sharpness of the images, so that finer details can be resolved

■ ■ to improve the contrast of the image, so that the different tissues under investigation show up clearly in the image

Reducing dosage

X -rays are only weakly absorbed by photographic film, so, historically, patients had to be exposed to long and intense doses of X-rays. Today, **intensifier screens** are used.

In digital systems, image **intensifiers** are used (Figure 32.7).

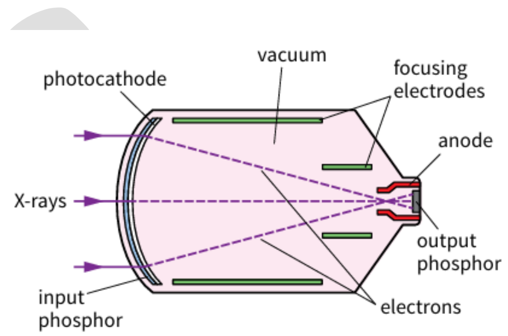

Figure 32.7 An X-ray image intensifier.

Improving sharpness

Figure 32.8 shows a remarkably sharp X-ray image of blood vessels in the human abdomen. So a good X-ray source must produce a **narrow** beam of **parallel** X-rays, as if they were coming from a distant point source.

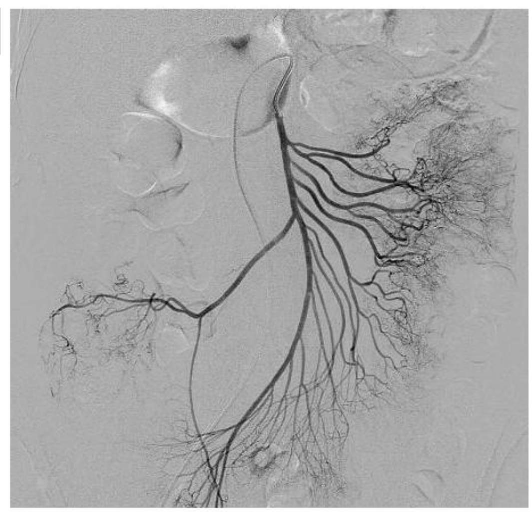
Figure 32.8 An X-ray image of blood vessels branching out from an artery carrying oxygenated blood to the intestines.

Three factors determine the width of the X-ray beam:

■ ■ the width of the electron beam and the target it strikes – as shown in Figure 32.10, the wider the electron beam, the wider the X-ray beam

■ ■ the size of the aperture at the exit window – this can be reduced using adjustable lead plates (Figure 32.11)

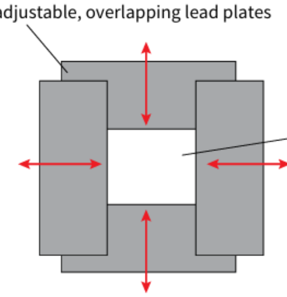

Figure 32.11 The smaller the aperture, the narrower the X-ray beam.

■ ■ collimation of the beam – the beam is passed through lead slits (Figure 32.12), ensuring that it is an approximately parallel-sided beam and does not fan out.

Inevitably some X-rays are scattered as they pass through the body. If these reach the detector they cause fogging and this reduces the sharpness of the image. Scattered X-rays approach the detector screen at an angle, and so an anti-scatter screen (Figure 32.13)

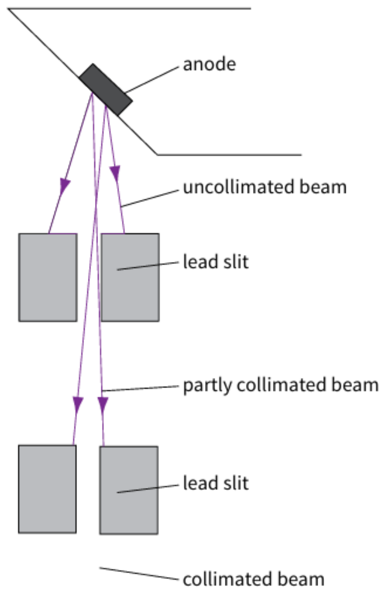

Figure 32.12 Collimating an X-ray beam. The first set of slits produces a partly collimated beam but, due to the finite size of the anode target, there is still some spreading of the beam. The second set of slits reduces this spread further, making the final beam almost parallel-sided.

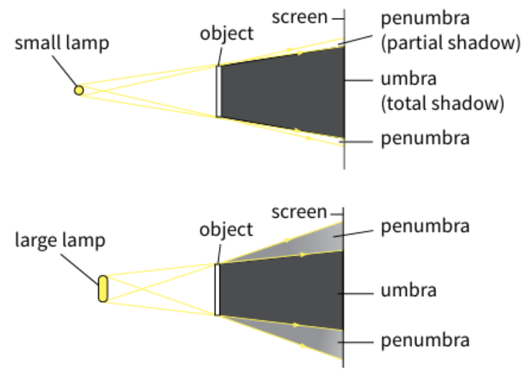

Figure 32.9 The small lamp casts a smaller penumbra and this improves the sharpness of the shadow.

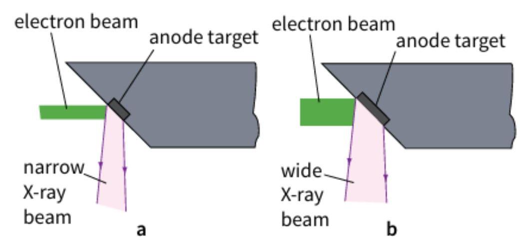

Figure 32.10 A wide anode target results in a wide X-ray beam, giving fuzzy edges to the shadow image.

Improving contrast

Good contrast is said to be achieved if there is a clear difference in the blackening of the photographic film as the X-ray passes through different types of tissue

In particular, bone can readily be distinguished from soft tissue such as muscle because it is a good absorber of X-rays. However, it is often desirable to show up different soft tissues that absorb X-rays equally. In order to do this, **contrast media** are used.

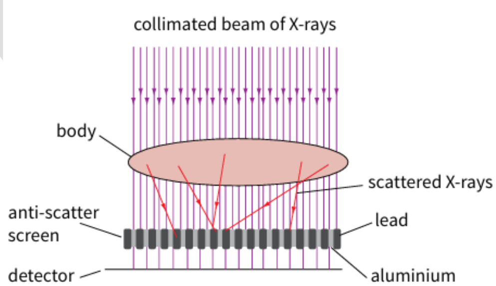

Figure 32.13 An anti-scatter screen absorbs X-rays which arrive at an angle to the main beam.

Figure 32.14 X-ray image of a patient's intestine after taking a barium meal. Barium shows up as pale in this image, which has also been artificially coloured to highlight features of interest.

Substance	Elements (*Z* values)	Average *Z*
soft tissue	H (1), C (6), O (8)	7
bone	H (1), C (6), O (8), P (15), Ca (20)	14
contrast media	I (53), Ba (56)	55

Table 32.1 Proton (atomic) numbers of the constituents of different tissues, and of contrast media.

Computerised axial tomography

A conventional X-ray image has an important limitation. Because an X-ray is essentially a two-dimensional shadow image, it shows the bones, organs, etc.

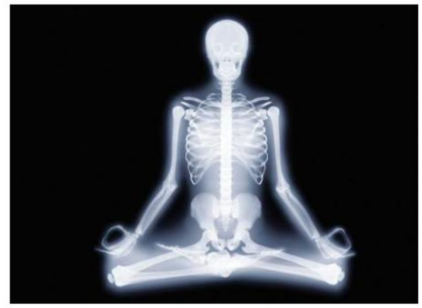

Figure 32.15 Computer-generated X-ray image of a person in a yoga position. This shows the difficulty of distinguishing one bone from another when they overlap.

An ingenious technique for extending this approach was invented by Geoffrey Hounsfield and his colleagues at EMI in the UK in 1971. Th ey developed the **computerised axial tomography scanner** (CAT scanner or CT scanner). Figure 32.16 illustrates the principle of a modern scanner.

■ ■ The patient lies in a vertical ring of X-ray detectors.

■ ■ The X-ray tube rotates around the ring, exposing the patient to a fan-shaped beam of X-rays from all directions.

Figure 32.17 A boy undergoes a CT scan in an investigation of an eye condition.

■ ■ Detectors opposite the tube send electronic records to a computer.

■ ■ The computer soft ware builds up a three-dimensional image of the patient.

■ ■ The radiographer can view images of ‘slices’ through the patient on the computer screen.

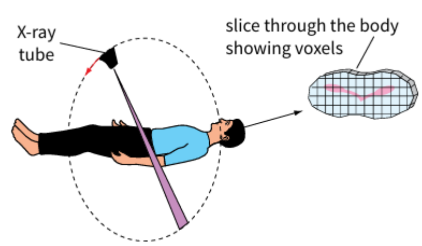

Figure 32.18 In CT scanning, we picture the body divided into an array of tiny cubic volumes called voxels.

Figure 32.17 shows a child undergoing a CT scan. On the monitor you can see a cross-section of the patient’s head.
T h is technique is called **computerised axial tomography**. because the X-ray tube rotates around an axis; and because it produces images of slices through the patient – the Greek word **tomos means slice.**

Building up the image

As the X-ray tube is rotated around the body, hundreds of pieces of information are gathered and an image is built up. As shown in Figure 32.18,

Advantages of a CT scan

Although single X-ray images still have many uses (and they can be made very quickly), CT scans have a number of advantages:

■ ■ They produce images that show three-dimensional relationships between different tissues.

■ ■ They can distinguish tissues with quite similar densities (attenuation coefficients).

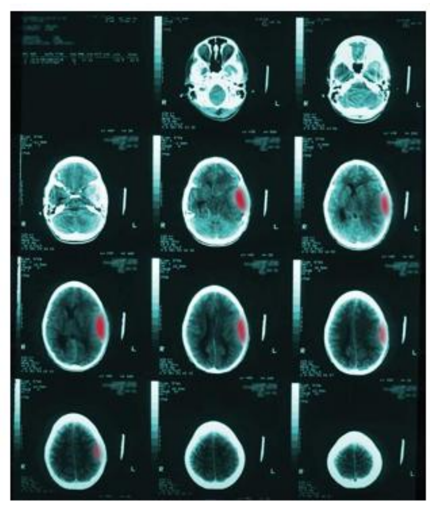

Figure 32.20 Sections through the head of a 10-year-old boy. You can see the haematoma (bruising) arising from being struck on the side of the head; this causes pressure on his brain.

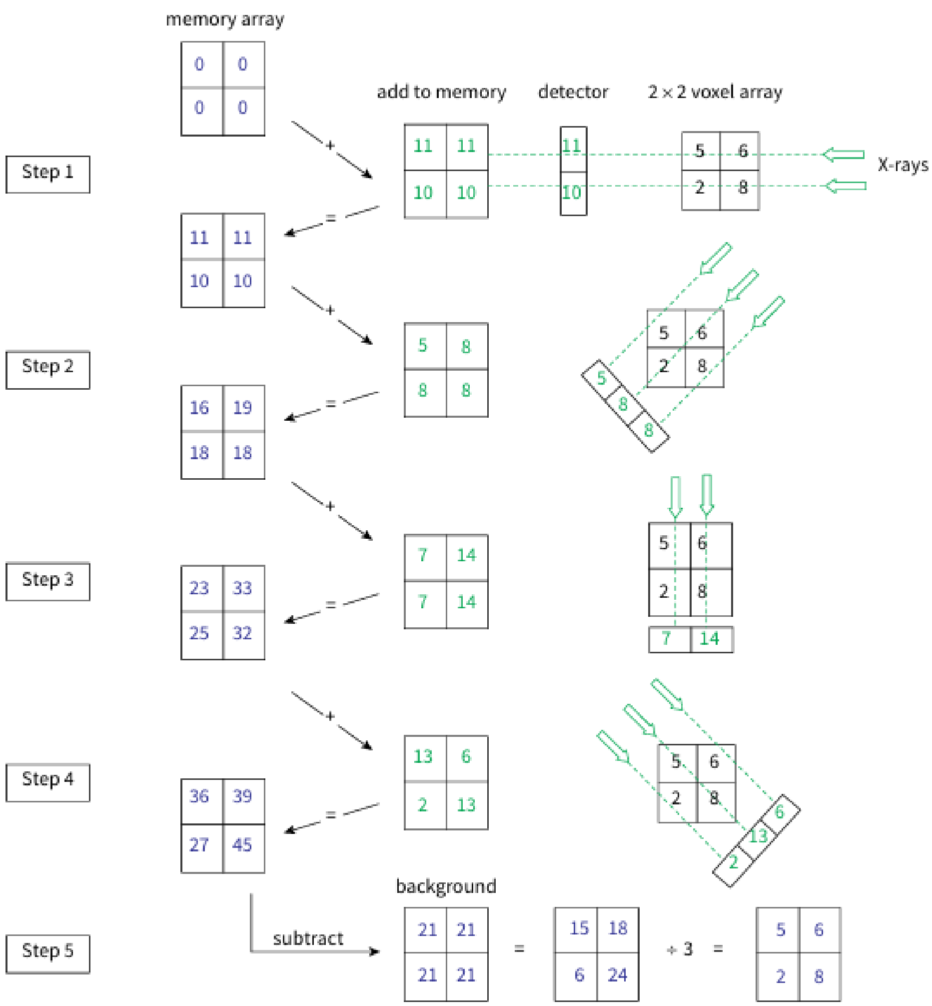

Figure 32.19 Data is built up from a CT scan of a 2 × 2 voxel array, and then processed to deduce the original array.

Using ultrasound in medicine

Ultrasound scanning is routinely used to check the condition of a baby in the womb (Figure 32.21).

Figure 32.21 An expectant mother undergoes an ultrasound scan. The image of her baby is built up by computer and appears on the monitor.

Ultrasound scanning is a technique used in medicine to detect gallstones and kidney stones, and is similar to echo sounding in detecting seabeds and fish shoals. It measures blood flow rate.

Working with ultrasound

Ultrasound is any sound wave that has a frequency above the upper limit of human hearing. Using the wave equation v = f λ, we can calculate the wavelength of 2.0 MHz ultrasound waves in tissue:

$$\lambda = \frac{v}{f} = \frac{1500}{2.0} \times 10^{6}$$
$$= 7.5 \times 10^{-4}\,\mathrm{m} \approx 1\,\mathrm{mm}$$

Producing ultrasound

Like audible sound, ultrasound is produced by a vibrating source. The frequency of the source is the same as the frequency of the waves it produces.

At the heart of the transducer is a **piezo-electric crystal**, such as quartz. This type of crystal has a useful property: when a voltage is applied across it in one direction, it shrinks slightly – see Figure 32.22a

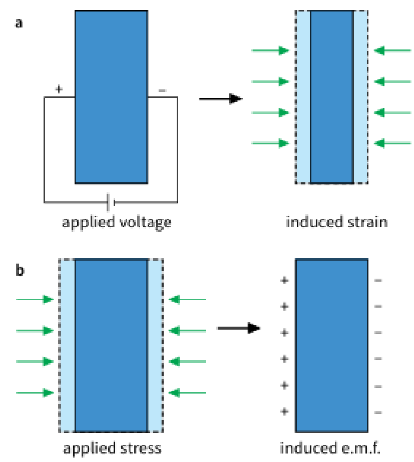

Figure 32.22 The piezo-electric effect. a An applied voltage causes a piezo-electric crystal to contract or expand. b An applied stress causes an induced e.m.f. across the crystal.

Detecting ultrasound

The transducer also acts as the detector of reflected ultrasound waves.

Figure 32.23 shows the construction of a piezo-electric ultrasound transducer. Note the following features:

■ ■ The crystal is now usually made of polyvinylidene difluoride. Previously, quartz and lead zirconate titanate were used.

■ ■ The outer case supports and protects the crystal.

■ ■ At the base is the acoustic window, made from a material that is a good transmitter of ultrasound.

■ Behind the crystal is a large block of damping material (usually epoxy resin).

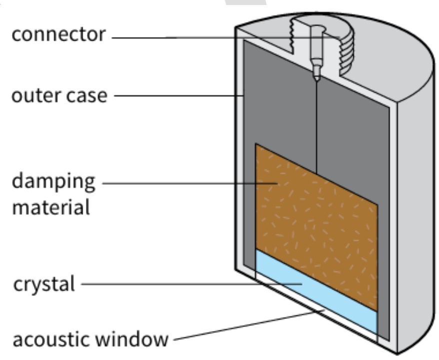

Figure 32.23 A section through an ultrasound transducer.

Echo sounding

The principle of an ultrasound scan is to direct ultrasound waves into the body. These pass through various tissues and are partially reflected at each boundary where the wave speed changes. The reflected waves are then detected and used to construct an internal image of the body.

For ultrasound, we are interested in the fraction of the incident intensity of ultrasound that is reflected at the boundary. This depends on the **acoustic impedance** Z of each material.

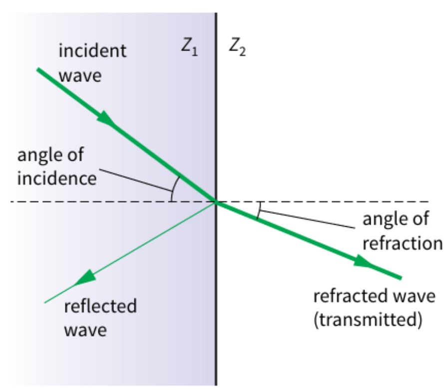

Figure 32.24 An ultrasound wave is both refracted and reflected when it strikes the boundary between two different materials.

Calculating reflected intensities

When an ultrasound beam reaches the boundary between two materials, the greater the difference in acoustic impedances, the greater the reflected fraction of the ultrasound waves.

the ratio of the reflected intensity I_r to the incident intensity I_0 is given by:

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

or

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

Material	Density / kg m^{-3}	Speed of sound / m s^{-1}	Acoustic impedance / 10^6 kg m^{-2} s^{-1}
air	1.3	330	0.0004
water	1000	1500	1.50
Biological			
blood	1060	1570	1.66
fat	925	1450	1.34
soft tissue (average)	1060	1540	1.63
muscle	1075	1590	1.71
bone (average; adult)	1600	4000	6.40
Transducers			
barium titanate	5600	5500	30.8
lead zirconate titanate	7650	3790	29.0
quartz	2650	5700	15.1
polyvinylidene difluoride	1780	2360	4.20

Table 32.3 The density (ρ), speed of sound in air (c) and acoustic impedance (Z) of some materials important in medical scanning.

Comparing acoustic impedances

A big change in acoustic impedance gives a large fraction of reflected intensity. Inspection of Table 32.3 shows that:

- a very large fraction ($\frac{I_r}{I_0} \approx 99.95\%$) of the incident ultrasound will be reflected at an air–tissue boundary
- a large fraction will be reflected at a tissue–bone boundary (as shown in Worked example 2)
- very little will be reflected at a boundary between soft tissues including fat and muscle.

Figure 32.25 Ultrasound scan of a fetus at 20 weeks; the baby's skin is clearly visible, as are its bony skull and ribs.

Ultrasound scanning

There are several different types of ultrasound scan which are used in practice. To illustrate the basic principles, we will concentrate on the A-scan and the B-scan.

A-scan

This is the simplest type of scan. A pulse of ultrasound is sent into the body and the reflected 'echoes' are detected and displayed on an oscilloscope or computer screen as a voltage–time graph.

In Figure 32.26, pulses 1, 2 and 3 are reflected at the various boundaries. Pulse 1 is the reflection at the muscle–bone boundary at B. Pulse 2 is the reflection at the bone–muscle boundary at C. The time Δt is the time taken for the ultrasound to travel **twice** the thickness of the bone

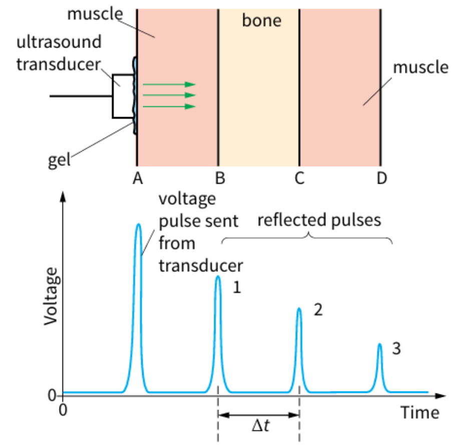

Figure 32.26 An A-scan. Information about the depth of reflecting tissues can be obtained from the positions of the spikes along the time axis; their relative amplitudes can indicate the nature of the reflecting surfaces.

time interval between pulses 1 and 2 = Δt

$$\text{thickness of bone} = \frac{\text{distance travelled by ultrasound}}{2}$$

$$= \frac{c\Delta t}{2}$$

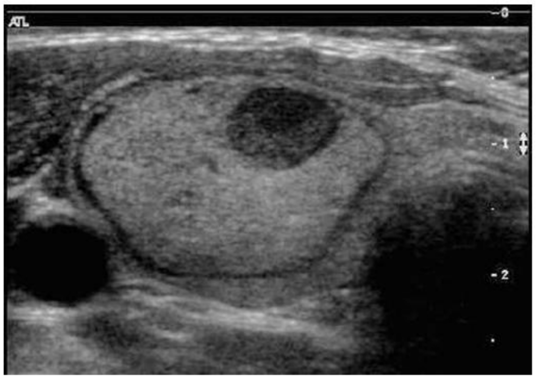

Figure 32.28 An ultrasonic B-scan of an abnormal thyroid gland.

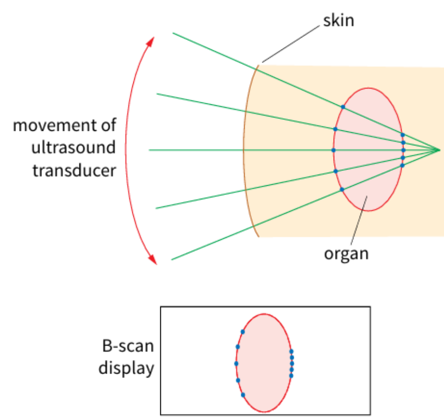

Figure 32.27 In a B-scan, dots are produced on the screen rather than pulses as in the A-scan. By moving the transducer, a series of dots on the screen traces out the shape of the organ being examined.

Magnetic resonance imaging

Magnetic resonance imaging, or MRI, is a diagnostic technique used in medicine.

(MRI was originally known as nuclear magnetic resonance imaging, but the word 'nuclear' was dropped because it was associated in patients' minds with bombs and power stations. To emphasise: MRI does **not** involve radioactive decay, fission or fusion.)

Principles of nuclear magnetic resonance

The nuclei of certain atoms have a property called spin, and this causes them to behave as tiny magnets in a magnetic field. In MRI, it is usually the nuclei of hydrogen atoms that are studied, since hydrogen atoms are present in all tissues. A hydrogen nucleus is a proton, so we will consider protons from now on.

A proton does not align itself directly along the external field. In practice, its magnetic axis rotates around the direction of the external field (Figure 32.31), just like the axis of a spinning top. This rotation or gyration action is known as **precession**.

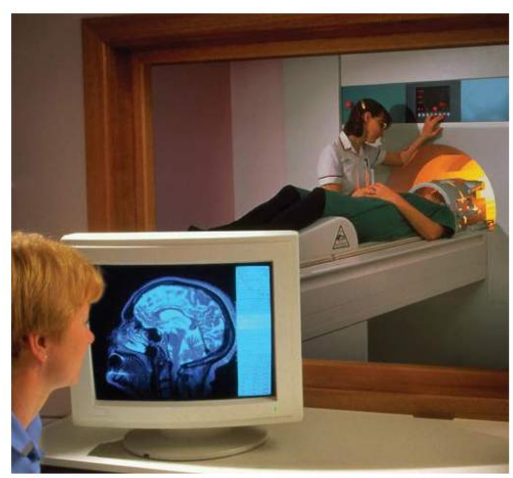

Figure 32.29 A patient undergoing an MRI scan of the brain. This is a form of tomography; the display shows different 'slices' through the patient's brain.

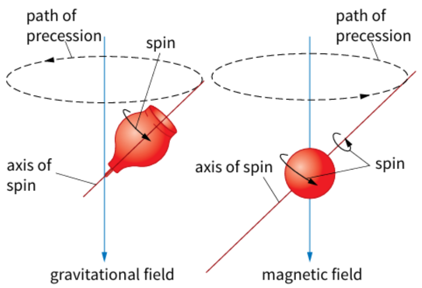

Figure 32.31 A spinning top (left) rotates about its axis; at the same time, its axis precesses about the vertical, which is the direction of the gravitational field. In a similar way, a proton (right) spins and its axis of rotation precesses about the direction of the external magnetic field.

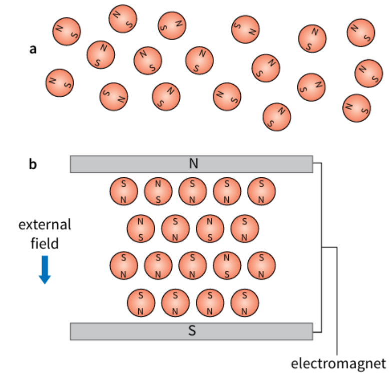

Figure 32.30 How protons behave in a strong magnetic field. **a** Protons are randomly directed when there is no external magnetic field. **b** Because protons are magnetic, a strong external magnetic field causes most of them to align themselves with the field.

The angular frequency of precession is called the **Larmor frequency** ω0, and depends on the individual nucleus and the magnetic flux density B0 of the magnetic field:

$$\omega_0 = \gamma B_0$$

So, the stronger the external field, the faster the protons precess about it. The quantity γ is called the **gyromagnetic ratio** for the nucleus in question and is a measure of its magnetism

$$f_0 = \frac{2.68 \times 10^8 \times 1.5}{2\pi} = 6.4 \times 10^7\,\text{Hz} = 64\,\text{MHz}$$

T his frequency lies in the radio frequency (RF) region of the electromagnetic spectrum. You should recall that **resonance** requires a system with a natural frequency of vibration; when it is stimulated with energy of the same frequency, it absorbs energy.

Each proton absorbs a photon of RF energy and flips up into the higher energy state; this is nuclear **magnetic resonance (Figure 32.32).**

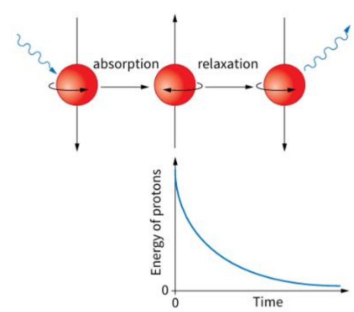

Figure 32.32 In nuclear magnetic resonance, a spinning nucleus is flipped into a higher energy state when it absorbs a photon of RF energy; then it relaxes back to its lower energy state.

As they do so, they release their excess energy in the form of RF waves. These can be detected, and the rate of **relaxation** tells us something about the environment of the protons.

In Figure 32.32, you can see that the relaxation of the protons follows an exponential decay pattern. Curves like this are characterised by two relaxation times:

■ ■ T1, the spin–lattice relaxation time, where the energy of the spinning nuclei is transferred to the surrounding ‘lattice’ of nearby atoms

■ ■ T2, the spin–spin relaxation time, where the energy is transferred to other spinning nuclei.

These relaxation times depend on the environment of the nuclei. For biological materials, it depends on their water content:

■ ■ Water and watery tissues (e.g. cerebrospinal fluid) have relaxation times of several seconds.
■ ■ Fatty tissues (e.g. white matter in the brain) have shorter relaxation times, several hundred milliseconds.
■ ■ Cancerous tissues have intermediate relaxation times.

MRI scanner

Figure 32.34 shows the main components of an MRI scanner. The main features are:

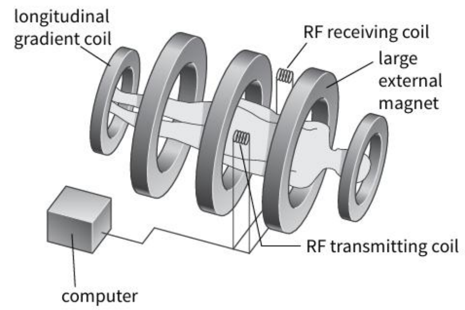

Figure 32.34 The main components of an MRI scanner.

■ ■ A large superconducting magnet which produces the external magnetic field (up to 2.0 T) needed to align the protons. Superconducting magnets are cooled to 4.2 K (−269 °C) using liquid helium.

■ ■ An RF coil that transmits RF pulses into the body.

■ ■ An RF coil that detects the signal emitted by the relaxing protons.

■ ■ A set of gradient coils. (For clarity, only one pair of gradient coils is shown in Figure 32.34.)

■ ■ A computer that controls the gradient coils and RF pulses, and which stores and analyses the received data, producing and displaying images.

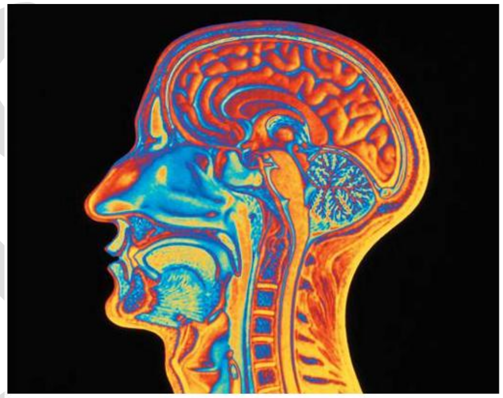

Figure 32.35 MRI scan through a healthy human head. Different tissues, identified by their different relaxation times, are coloured differently.

Procedure

The patient lies on a bed which is moved into the centre of the electromagnet. The central imaging section is about 0.9 m long and 0.6 m in diameter.

Advantages and disadvantages of MRI MRI has several advantages compared to other scanning techniques:

■ ■ It does not use ionising radiation which causes a hazard to patients and staff.

■ ■ There are no moving mechanisms, just changing currents and magnetic fields.

■ ■ The patient feels nothing during a scan (although the gradient coils are noisy as they are switched), and there are no after-effects.

■ ■ MRI gives better soft-tissue contrast than a CT scan, although it does not show bone as clearly.

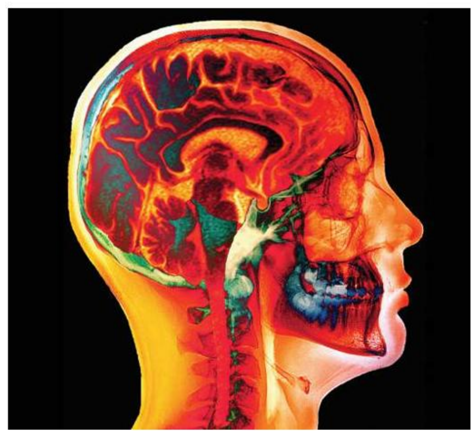

Figure 32.36 A combined CT scan and MRI scan, showing how the tissues revealed by MRI relate to the bone structure shown by X-rays.

■ ■ Computer images can be generated showing any section through the volume scanned, or as a three-dimensional image.