Chapter 4 Non-ionising imaging

4.1 Ultrasonic imaging

Learning objectives:

- What are ultrasonic waves and how are they used in medical imaging?
- How does an A-scan differ from a B-scan?
- What determines how effectively an internal boundary in the body reflects ultrasonic waves?

Producing ultrasonics

Ultrasonics are sound waves at frequencies above the upper frequency limit of the human ear which is approximately 18 kHz. Ultrasonics at frequencies between 1 MHz and 10 MHz are used for medical applications. This frequency range represents a compromise between lower frequencies which would diffract and spread out too much and higher frequencies which would be absorbed too easily by tissue.

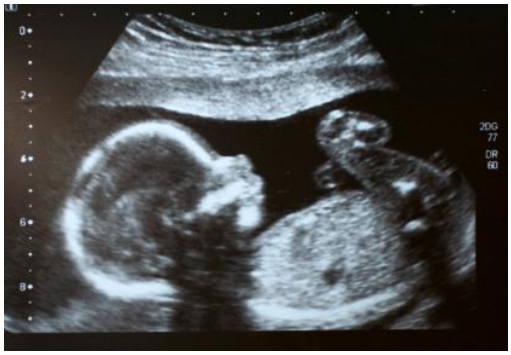

Figure 1 *An ultrasonic image*

When an ultrasonic scan is carried out:

1. pulses of ultrasonic waves are emitted by an ultrasonic probe on the body's surface
2. the ultrasonic waves travel into the body and partially reflect at any boundaries (including the skin) which they encounter
3. the reflected pulses return to the surface and are detected by the probe and are then used to generate an ultrasonic image.

The **higher the frequency, the smaller the wavelength of the ultrasonic waves and so the greater the detail of image** (because diffraction is less). The frequency used for a particular application depends on the depth and density of the organ to be imaged. Low density organs near the body's surface (e.g. the eye) can be imaged in more detail than high-density internal structures (e.g. a baby in the womb) because higher frequency ultrasonic waves can be used for lower density organs near the surface. Such high frequency ultrasonic waves would be mostly absorbed by tissue they have to pass through before they reach the internal organ.

The ultrasonic probe contains a piezoelectric transducer in the shape of a disc which vibrates when an alternating pd is applied across it. When the applied frequency is equal to the natural

frequency of vibration of the transducer disc, the disc vibrates in resonance and creates sound waves in the surrounding medium at the same frequency as the alternating pd.

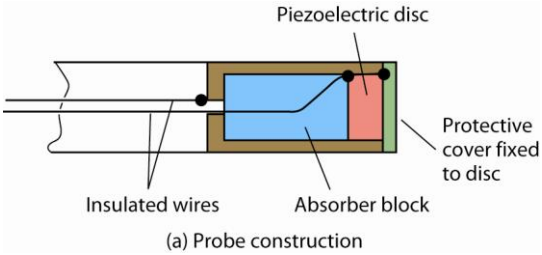

Figure 2 *An ultrasonic probe*

The disc thickness determines its resonant frequency in the same way that any vibrating object can be made to resonate by applying a periodic force of suitable frequency to it.

An absorber or 'backing' block behind the disc prevents ultrasonic waves being created at the rear surface of the disc otherwise the ultrasonic waves from the two disc surfaces would cancel each other out. The block is made of a suitable absorbing material (e.g. epoxy resin) which damps the disc vibrations rapidly at the end of each pulse before the next pulse is produced.

Application

Piezoelectricity

Piezoelectricity is the generation of a pd across opposite surfaces of an object made of certain materials when the object is compressed. The pd is proportional to the force applied to the object.

When a pd is applied across any piezoelectric material, the length of the material across which the pd is applied changes in proportion to the pd. If an alternating pd is applied, the length alternates due to the alternating pd.

Ultrasonic scanning systems

When image resolution is not a problem (e.g. scanning a baby in the womb), ultrasonic scanning is preferred to X-ray imaging. This is because ultrasonic waves, unlike X-rays, are non-ionising and therefore do not damage or kill living cells.

In making an ultrasonic scan, the transducer probe is connected to a control system that includes a visual display unit (VDU). In operation, the probe is held in contact with the body surface via a gel so that ultrasonic pulses are directed into the body. If the gel was not present, the ultrasonic waves would be almost completely reflected at the body surface and the pulses entering the body would be too weak to give reflected pulses that can be detected.

1. Each pulse entering the body is partially reflected at the surface of internal organs and at tissue boundaries. The reflected pulses are detected by the transducer probe which acts as a receiver when it is not producing pulses. As each boundary in the body is a partial reflector of pulses, each pulse from the transducer produces a series of reflected pulses which return to the transducer.
2. The reflected pulses are detected by the transducer when it is in 'receiver' mode so a pulsed signal is received by an amplifier connected to the transducer. The signal is amplified and displayed on an oscilloscope screen (A-scan) or used to modulate the brightness of an image built up on a VDU as the probe is moved across the body surface (B-scan).

The rate at which pulses are generated is determined by the speed of ultrasonic waves in the body and the distances they travel which can, back and for across the body, be over a metre. The speed of the waves varies according to the type of tissue. Using an average speed of 1500 m s^{-1}, gives a transit time for a pulse of less than a millisecond. Hence the pulses need to be generated at a rate of no more than about 1000 per second to allow the received pulses from each transmitted pulse to return to the probe before the next pulse is transmitted. Otherwise successive transmitted pulses result in reflected pulses that overlap and cannot be identified. In addition, the pulses must last no more than a few microseconds to ensure the end of each transmitted pulse is clear of the probe before the front end of the first reflected pulse returns to the probe.

The A-scan system

In an A-scan system, the effect of transmitted pulse and the reflected pulses on the transducer can be seen on the oscilloscope trace, as shown in Figure 3.

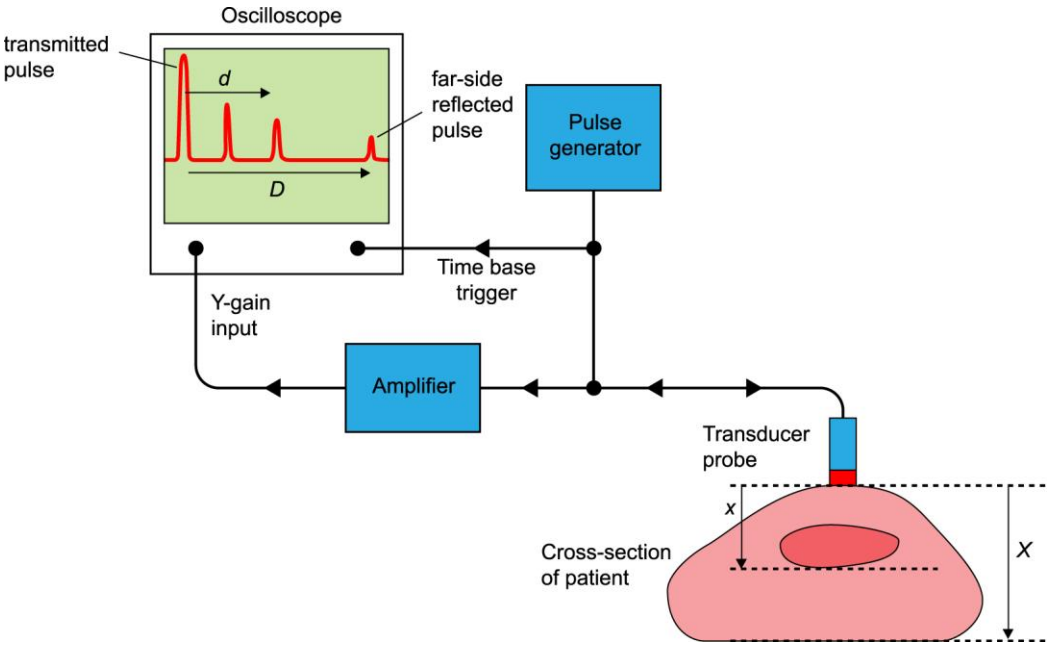

Figure 3 *The A-scan system*

- The transmitted pulse appears as the pulse nearest the left-hand edge of the screen. This is because the pulse generator used to generate the electrical pulses supplied to the transducer is also used to trigger the time base of the oscilloscope.
- The time base can be adjusted so the last reflected pulse towards the right-hand side of the screen is due to the body–air boundary on the far side of the body. The A-scan system is used where precise locations of internal boundaries are to be measured.
- The distance d from the transmitted pulse to each reflected pulse on the oscilloscope screen is proportional to the time taken by the reflected pulse to travel from the probe to the reflecting boundary and back. The distance x from the body surface to the reflecting boundary can be calculated by measuring distance d on the oscilloscope screen and:

  either using the time base setting to calculate the transit time, t, of the pulse (i.e. the time taken by the pulse to travel from the body to the boundary and back) using $t = d \times$ the time base setting in time per unit distance. Given the speed of the ultrasonic waves, c, distance x can then be calculated from the equation

  $x = \frac{1}{2} ct$ (= speed × half the transit time)

or by adjusting the time base so the far-side reflected pulse is visible on the screen, measuring the screen distance d as a proportion of the screen distance D from the transmitted pulse to the far-side reflected pulse from the body surface to the reflecting boundary, distance x can be calculated from the equation

$$x = \left(\frac{d}{D}\right)X$$

where X *is* the distance from the probe to the far side of the body.

Worked example

In an A-scan, the distance on the oscilloscope screen from the transmitted pulse to a reflected pulse was 3.5 cm. The oscilloscope time base setting was 0.20 ms cm^{-1}. Calculate the distance from the body surface to the internal boundary that caused the reflected pulse. Assume the speed of sound in the body is 1500 m s^{-1}.

Solution

Transit time of pulse, t = 3.5 cm × 0.20 ms cm^{-1} = 0.70 ms

Distance x from the body surface to boundary = $\frac{1}{2}ct$ = 0.5 × 1500 × 0.70 × 10^{-3} = 0.53 m

Link

See *AS Physics A* Topic 6.2 for the use of an oscilloscope.

The B-scan system

In a B-scan system, the probe contains several transducers which transmit pulses simultaneously. Position sensors attached to the probe provide signals to control the initial position and direction of the electron beam in the VDU. The strength of the received pulses controls the beam current and hence the image intensity. As the probe is moved across the patient, the B-scan system therefore gives a two-dimensional image.

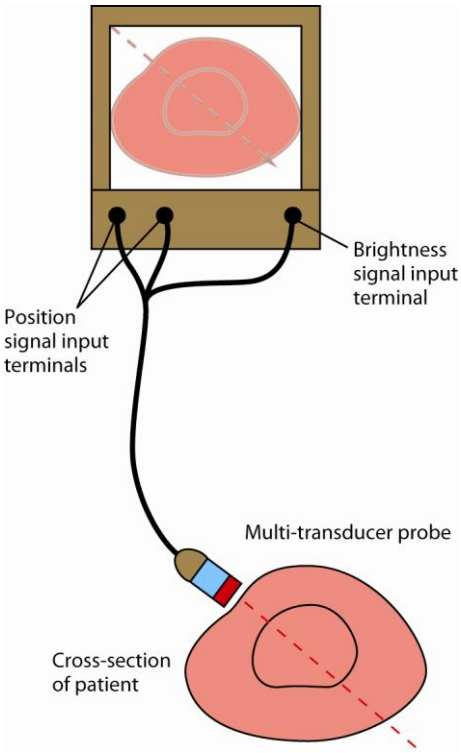

Figure 4 *The B-scan system*

Transmission and reflection of ultrasonic waves

When ultrasonic waves pass through a substance, some of the power from the waves is dissipated by the substance. The opposition to the passage of ultrasonic waves through a substance is referred to as the **acoustic impedance**, Z, of the substance. The acoustic impedance Z of a substance can defined as the product of its density ρ and the speed of sound c through the substance.

$$Z = \rho c$$

The unit of acoustic impedance is $\mathrm{kg\,m^{-2}\,s^{-1}}$, the same as the unit of density × the unit of speed. Table 1 shows some values of ρ, c and Z for different substances.

Notes on Table 1

1. The acoustic impedance of soft tissue is about 10% greater than that of water and is much greater than that of air. The acoustic impedance of bone is about 5 × that of soft tissue.
2. Z should technically be referred to as the specific acoustic impedance of the substance as it is a property of the substance and does not depend on the area of cross-section or length of the substance.

Table 1 *Ultrasonic properties*

Substance type	Density /kgm^{-3}	Speed / m s^{-1}	Acoustic impedance /kg m^{-2} s^{-1}
Air	1.2	340	410
Water	1000	1500	1.5×10^6
Soft tissue	1050	1550	1.6×10^6
Fat	900	1450	1.3×10^6
Muscle	1080	1600	1.7×10^6
Bone	1900	4000	7.8×10^6

Energy is absorbed by a substance when ultrasonic waves pass through it, so the amplitude of the waves decreases the further the waves travel through the substance. This reduction in amplitude with distance is referred to as **attenuation**. The greater the acoustic impedance of a substance, the greater the attenuation of an ultrasonic wave passing through it.

When ultrasonic waves reach a boundary between two substances with different acoustic impedances, partial reflection occurs so the waves passing through the boundary are reduced in amplitude. For incident waves of intensity I_0, the intensity of the reflected waves I_R is given by the equation

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

Where Z_1 and Z_2 are the acoustic impedances of the incident and reflected intensities respectively.

The **reflection coefficient** of the boundary, R is defined as $\frac{I_R}{I_0}$

Therefore $R = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$

Using the data given in Table 1, R can be calculated using the above formula for different types of boundaries in the body and at the body surface. Such calculations show:

- An air–skin boundary has a reflection coefficient of almost 1 which means almost 100% of the incident ultrasonic energy is reflected. This is why the probe is applied to the body via a suitable gel or a water bag so that most of the ultrasound energy enters the body.
- Ultrasonic waves reflect significantly at the boundaries between different types of soft tissue in the body. Hence an ultrasonic imaging system can detect and display such boundaries unlike an X-ray imaging system which cannot.
- The intensity of the waves transmitted through the boundary $I_T = I_0 - I_R$

Note that the strength of a received pulse depends on the distance travelled by the pulse in the body as well as the reflection coefficient at each boundary it encounters.

Worked example

In an ultrasound scan, ultrasonic waves of intensity $6.0 \times 10^{-8}\,\text{W m}^{-2}$ are directed through fat into soft tissue.

a Use the data in Table 1 to calculate the acoustic impedance of:

i fat

ii soft tissue.

b Calculate the reflection coefficient of the interface between the two substances.

c Calculate the intensity of:

i the reflected waves

ii the waves transmitted through the interface.

Solution

a **i** For fat, $Z_1 = \rho c = 900 \times 1450 = 1.31 \times 10^6\,\text{kg m}^{-2}\,\text{s}^{-1}$

ii For soft tissue, $Z_2 = \rho c = 1050 \times 1550 = 1.63 \times 10^6\,\text{kg m}^{-2}\,\text{s}^{-1}$

b $$R = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} = \frac{\left(1.63\times10^6 - 1.31\times10^6\right)^2}{\left(1.63\times10^6 + 1.31\times10^6\right)^2} = 0.0118$$

c **i** $I_R = R \times I_0 = 0.0118 \times 6.0 \times 10^{-8} = 7.1 \times 10^{-10}\,\text{W m}^{-2}$

ii $I_T = I_0 - I_R = 6.0 \times 10^{-8} - 7.1 \times 10^{-10} = 5.9 \times 10^{-8}\,\text{W m}^{-2}$

Summary questions

Use the data in Table 1 where necessary.

1 An ultrasonic probe generates ultrasonic waves at a frequency of 2.5 MHz.

a Calculate the wavelength of the ultrasonic waves from this probe:

i in air

ii in soft tissue.

b Explain why ultrasonic waves of much lower frequency are unsuitable for medical imaging.

2 **a** **i** With the aid of a diagram, describe the construction of an ultrasonic probe and how it produces ultrasonic waves.

ii Explain the function of the backing block in an ultrasonic probe.

b In the A-scan arrangement shown in Figure 3:

i explain the presence of each pulse on the screen in terms of the cross-section of the patient shown in Figure 3

ii calculate the distance the ultrasonic waves travel in each direction through the internal organ shown in Figure 3 if the distance across the patient X is 0.60 m.

3 **a** Use the data in Table 1 to calculate the reflection coefficient of the boundary between:

i air and skin

ii water and skin.

Assume skin is soft tissue.

b Use the results of your calculation to explain why a gel must be applied between an ultrasonic probe and the skin when the probe is used.

c In Figure 3, the organ shown has a density of $1040\,\text{kg m}^{-3}$ and the speed of sound through it is

1580 m s^{-1}.

i Calculate the acoustic impedance of the organ tissue.

ii Use the data from (a) and in Table 1 to calculate the reflection coefficient of the boundary between the organ and the surrounding soft tissue.

4 **a** State the main differences between an A-scan and a B-scan.

b Ultrasonic waves and X-rays are both used for medical imaging. Explain why an ultrasonic scan rather than an X-ray scan is used for scanning a baby in the womb whereas an X-ray scan instead of an ultrasonic scan is used to scan an air-filled organ such as the lungs.

4.2 Endoscopy

Learning objectives:

- What is a step-index optical fibre?
- How does an endoscope work?
- Why do the fibres in an endoscope need to be very thin?

Total internal reflection

When a light ray travels from one substance to another, **total internal reflection** takes place at the point of incidence on the interface between the two substances if:

1 the incident substance has a **larger refractive index** than the other substance

2 the angle of incidence exceeds the **critical angle**.

If both conditions above are met, the light ray reflects at the interface without loss of intensity.

If only the first condition is met and the angle of incidence is equal to the critical angle i_c, the angle of refraction is 90° because the light ray emerges along the boundary. Therefore, as explained in *AS Physics A* Topic 13.3, applying the law of refraction $n_1 \sin i_c = n_2 \sin 90$ where n_1 is the refractive index of the incident substance and n_2 is the refractive index of the other substance. Since sin90 = 1, then

$$\sin i_c = \frac{n_2}{n_1}$$

If the angle of incidence is less than the critical angle, i_c, the light ray is partially transmitted and partially reflected at the interface.

Figure 1 shows these different situations.

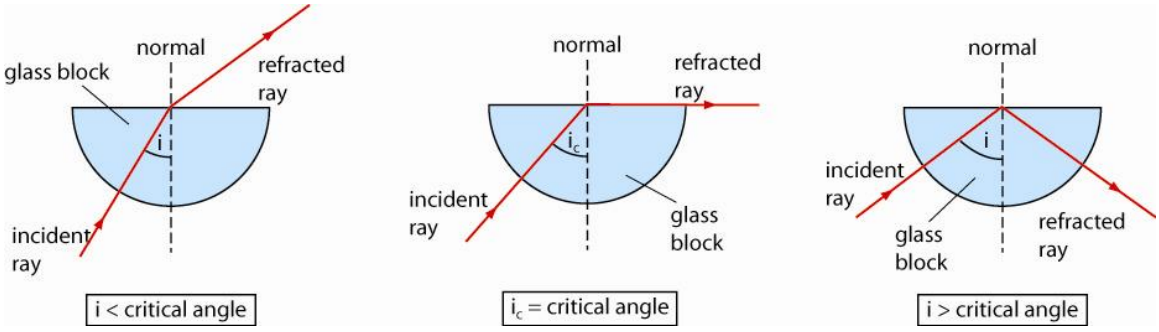

Figure 1 *Total internal reflection*

Link

See *AS Physics A* Chapter 13 for refraction and total internal reflection.

Optical fibres used in medical endoscopes, to see inside the body, consist of a transparent core surrounded by transparent cladding of lower refractive index. A **step-index** optical fibre has a core with the same refractive index throughout and cladding of constant refractive index that is

lower than the core refractive index. The core area of cross-section is typically about 60% of the total area of cross-section.

A light ray travelling non-axially along a straight section of step-index fibre, as shown in Figure 2, travels in straight lines across the core, repeatedly undergoing total internal reflection at the core–cladding boundary.

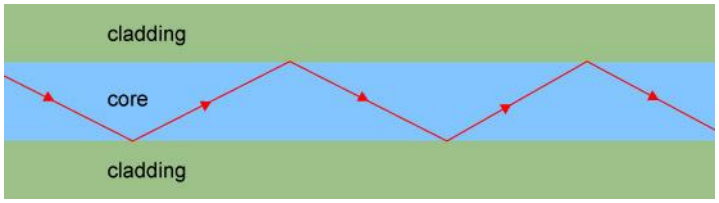

Figure 2 *Total internal reflection in an optical fibre*

If angle of incidence of a light ray at the core–cladding boundary is less than or equal to the critical angle, the light ray will enter the cladding. This can happen if the fibre is bent too much, as shown in Figure 3. The light ray in the cladding could then leave the cladding at the air–cladding boundary if:

1 the angle of incidence at this boundary is less than or equal to the critical angle for this interface, or

2 the outer surface is rough or greasy or in contact with another fibre at the point of incidence.

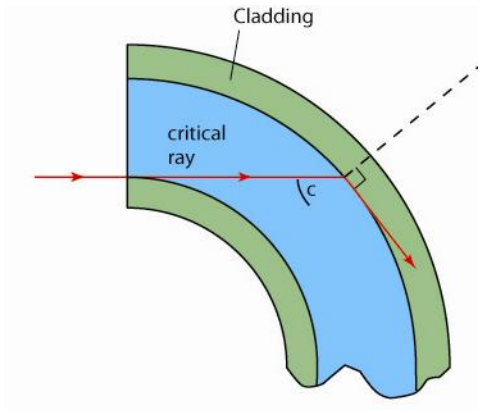

Figure 3 *Critical curvature*

Loss of light from a fibre reduces the brightness of the contribution of the fibre to the image. In addition lost light may enter a different fibre. This fibre will then give a contribution that is brighter than it would be if no light was lost from other fibres. Thus, although some light in the cladding may re-enter the core, light loss through the outer cladding surface will cause a loss in the quality of the image.

In effect, as much light as possible needs to be retained in the core with as little as possible entering the cladding.

Worked example

Calculate the critical angle for the core–cladding boundary of an optical fibre that has a core of refractive index 1.62 and cladding of refractive index 1.52.

Solution

$$\sin i_c = \frac{n_2}{n_1} = \frac{1.52}{1.62} = 0.938$$

$i_c = 70°$

The principle of the endoscope

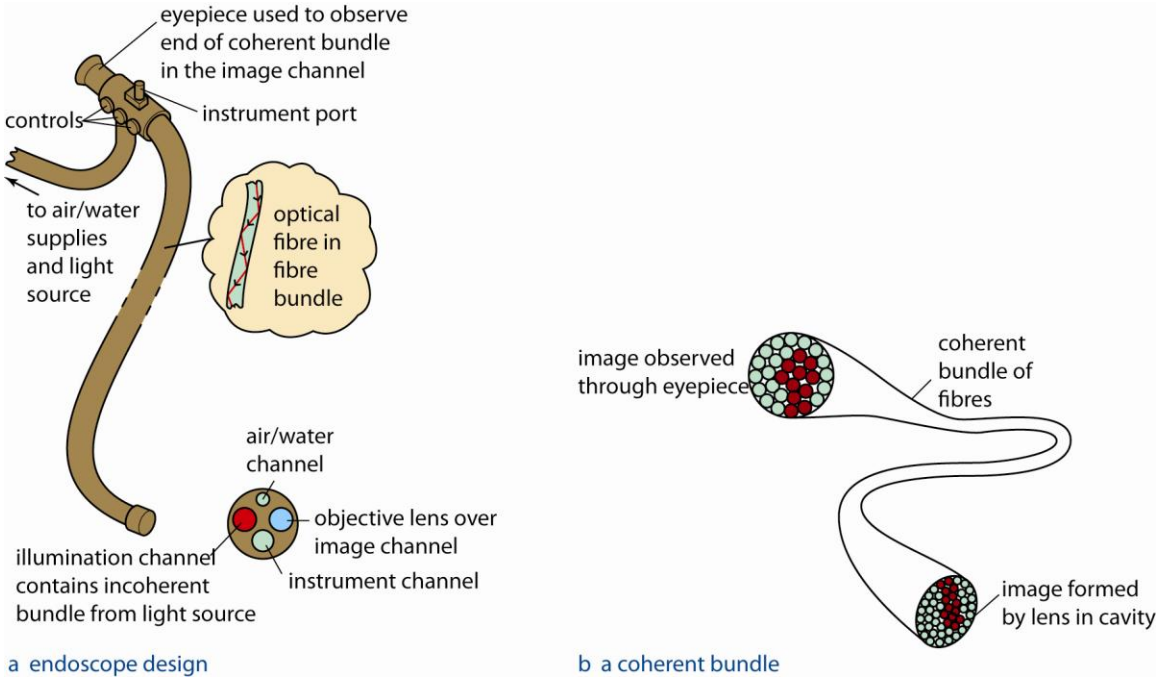

Figure 4 *The endoscope*

The endoscope contains two bundles of fibres, the **coherent** bundle which transmits light out of the body and the **incoherent** bundle which transmits light into the body. The endoscope is inserted into a body cavity to be observed which is then illuminated using light sent through the incoherent fibre bundle. A lens over the end of the coherent fibre bundle is used to form an image of the body cavity on the end of the fibre bundle. The light that forms this image enters the fibres and travels along the fibres to the other end of the fibre bundle where the image can be observed. The image on the outside end of the coherent bundle consists of dots, each being at the end of a fibre that carries light from inside the body.

The coherent bundle contains tens of thousands of fibres, each with a diameter of about 0.01 mm, forming a bundle several millimetres in diameter. The bundle is constructed so that the fibre ends at each end are in the same relative positions. This ensures the image formed by the lens is seen as a 'coherent' image on the end outside the body by the observer. Without this arrangement, the observer would see a 'scrambled' image without discernible features. A TV camera is usually used to display the 'coherent' image on a TV monitor.

In addition, the endoscope also includes a tube to insert and manipulate small cutting tools and to supply a jet of water for cleaning the lens and the fibre ends in the cavity. The endoscope is used to observe internal body surfaces such as the gastro-intestinal tract. It is also used to take tissue samples and to remove obstructions or diseased tissue. As the use of an endoscope or a miniature camera (now used in some situations) does not require cutting into the body, patients can be treated more quickly, at less cost and are much less likely to need a prolonged stay in hospital. However, endoscopy is not risk free as internal organs may be damaged if the endoscope is not used extremely carefully or if the internal organs are in very poor condition.

Laser light

Laser light may be used in an endoscope fitted with a second incoherent bundle to destroy diseased tissue or seal off leaking blood vessels. This is possible with laser light because, in comparison with non-laser light, laser light delivers much more energy per second per unit area. This is because laser light can be focused to a very small area because it is monochromatic. Its very narrow range of wavelengths means that the variation of refractive index with wavelength which causes images formed with white light to be tinged with colour does not affect laser light. In addition, the colour of laser light can be matched to the tissue for most effective absorption by choosing an appropriate laser source.

The effect of different refractive index values

The viewing cone at the end of each coherent fibre in the body as shown in Figure 5 defines the field of view of the fibre.

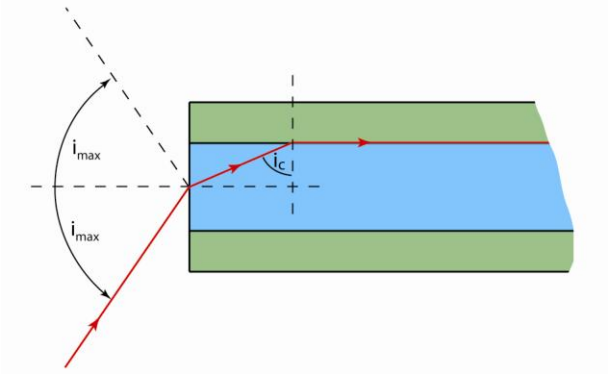

Figure 5 *The viewing cone of an optical fibre*

Consider a light ray on the edge of the viewing cone that enters the flat end of the fibre core. This light ray will refract towards the normal on entry to the core such that it reaches the core–cladding boundary at the critical angle.

- Any light ray that enters the flat end of the core from within the viewing cone will undergo total internal reflection at the core–cladding boundary of a straight fibre because its angle of incidence at the core–cladding boundary is greater than the critical angle.
- Any light ray that enters the flat end of the core from outside the fibre will be refracted at the core–cladding boundary into the cladding because its angle of incidence at the core–cladding boundary is less than the critical angle.

For total internal reflection at the core–cladding boundary, the maximum angle of incidence at the point of entry, i_{max}, is equal to half the angle of the viewing cone. This angle can be calculated from the critical angle of the core–cladding boundary, i_c, refractive index of the core (n_1) and of the substance outside the fibre (n_0) as the angle of refraction at the flat end for the core–cladding critical ray is equal to $90° - i_c$.

Applying the law of refraction to this ray at the flat end therefore gives the following equation from which i_{max} can be calculated.

$$n_0 \sin i_{max} = n_1 \sin(90 - i_c)$$

If the viewing cone is too narrow, the coherent bundle will only receive light in a small cone and only a restricted area of the organ will be seen. If the viewing cone is too wide, loss of contrast may occur as each fibre will collect light from a wide area.

Worked example

Calculate the angle of the viewing cone for an optical fibre in air which has a critical angle of 70° for its core–cladding boundary and a core refractive index of 1.52.

Solution

$n_0 = 1$ for air, $n_1 = 1.52$, $i_c = 70°$

Therefore $\sin i_{max} = n_1 \sin(90 - i_c) = 1.52 \times \sin 20 = 0.520$

Hence $i_{max} = 31°$

Note: When carrying out trigonometric calculations, always check before you start that your calculator is in degree mode.

The extent to which a fibre can be bent without loss of light depends on the diameter of the core. Figure 6 shows a curved section of a fibre in which a light ray enters the section horizontally at O and refracts at the core–cladding boundary at P along the boundary.

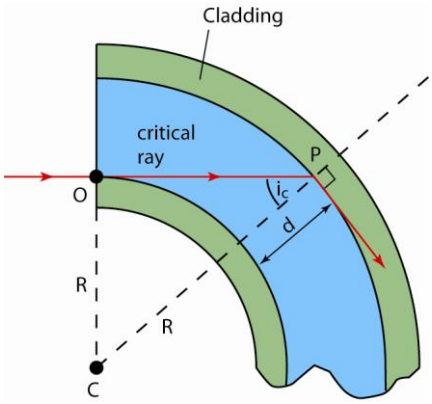

Figure 6 *Critical curvature*

Since the light ray is the critical ray at P, angle OPC is equal to the critical angle of the boundary. Therefore, considering triangle OPC where C is the centre of curvature of this section, it can be seen that

$$\sin i_c = \frac{R}{(R + d)}$$

where R = the radius of curvature of this section of the fibre and d is the diameter of the core.

Since $\sin i_c = \frac{n_2}{n_1}$, $\frac{R}{(R+d)} = \frac{n_2}{n_1}$

Rearranging this equation gives $R = \dfrac{d}{\frac{n_1}{n_2} - 1}$

The equation shows that the thinner the core is, the smaller the radius of curvature can be before the fibre loses light from the core. Typically, the diameter of the core is 0.01 mm. For n_1 = 1.62 and n_2 = 1.52, prove for yourself that a diameter of 0.01 mm gives R = 0.15 mm. As fibre bundles are usually of the order of a millimetre in width, bending into a circular arc of radius 0.15 mm is unlikely so light loss from the core of each fibre in the bundle is unlikely. However, if the fibre's core diameter was ten times greater at 0.10 mm, light loss would occur if a circular arc of radius 1.5 mm was formed.

From the above detailed discussions, it may be concluded that for a given core refractive index, if the cladding refractive index is too large, the viewing angle will be too small and also the fibre will lose light more easily due to bending. However, if the cladding refractive index is too small, the viewing angle will too large. As explained above and in the worked example, refractive index values of 1.62 and 1.52 for the core and cladding respectively gives over 60° for the viewing angle (= 2 × i_{max}) and a minimum radius of curvature about 15 times the core diameter.

Summary questions

1 **a** State the function of the cladding of an optical fibre.

b **i** Sketch a graph to show how the refractive index of an optical fibre varies across the diameter of its cross-sectional area if the refractive index values of the core and the cladding are 1.55 and 1.50 respectively.

ii Calculate the critical angle of the core–cladding boundary.

2 **a** State the function of a coherent bundle and an incoherent bundle in an endoscope and describe the difference between their construction.

b State one example of the use of a medical endoscope and give a reason why it is advantageous compared with the necessary procedure without an endoscope.

3 **a** Describe the features of an endoscope that enables an image to be seen of an internal body cavity.

b Explain why the optical fibres in the coherent bundle of an endoscope need to be very thin and why they should not be bent too much.

4 **a** **i** State the significance of the viewing cone of an endoscope.

ii With the aid of a diagram, explain why the angle of the viewing cone depends on the critical angle of the cladding of the optical fibre.

b Calculate the angle of the viewing cone for a fibre which has a core of refractive index 1.60 and cladding of refractive index:

i 1.55

ii 1.50

4.3 The MR scanner

Learning objectives:

- What is nuclear magnetic resonance?
- How is it used in an MR scanner?
- Why is an MR scanner able to distinguish different tissues?

Nuclear magnetic resonance

The magnetic resonance (MR) scanner is used in hospitals to scan the hydrogen content in the body. Hydrogen atoms are present in the body mostly in water molecules but also in many other molecules in the body. As explained later, the type of tissue which the molecules are in affects the way hydrogen nuclei in the molecules respond to changing magnetic fields which is why MR scans can distinguish different types of tissue.

A hydrogen nucleus (and certain other nuclei) is like a tiny bar magnet as it possesses intrinsic magnetism, technically referred to as a magnetic moment, which makes it turn in a magnetic field. This intrinsic magnetism is due to the motion of the nucleons in the nucleus which also makes the nucleus spin.

In a strong magnetic field:

- a bar magnet can be either lined up in the direction of the magnetic field or in a higher energy state in the opposite direction to the magnetic field in an unstable state.
- a nucleus which has a magnetic moment acts like a spinning top in a magnetic field as its spin axis precesses about the direction of the external magnetic field just as the axis of a tilted spinning top precesses about a vertical line. Relative to the magnetic field, the nucleus has just two energy levels corresponding to the two different alignments relative to the magnetic field as shown in Figure 1.

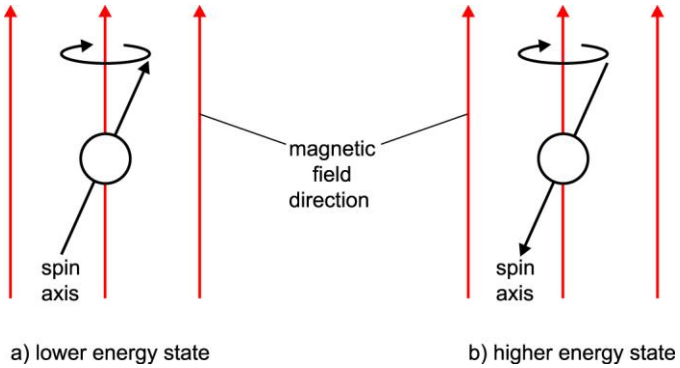

Figure 1 *Precession*

A hydrogen nucleus in a magnetic field can be excited into the higher energy level using radio waves of the same frequency as the frequency of precession of the nucleus. This process of excitation is known as **nuclear magnetic resonance**. As the frequency of precession is proportional to the magnetic flux density of the external magnetic field, it can be changed by changing the magnetic flux density of the external field. Nuclear magnetic resonance can therefore occur by adjusting the magnetic flux density until the precession frequency is equal to the frequency of the radio waves.

In a sample of hydrogen nuclei in a magnetic field, some nuclei will be in the higher energy level due to the thermal energy of the atoms. At room temperature, there is a slightly higher proportion of nuclei in the lower energy state.

- When a pulse of radio waves of the same frequency as the precession frequency is applied to the sample, some of the nuclei in the lower energy state each absorb a radio-wave photon and flip into the higher energy level.
- When the radio pulse ends, some of excited nuclei flip back to the lower energy state, each emitting a radio wave photon. In an MR scanner, the detection of the emitted photons is used by the scanning software to determine the location of the nucleus that emitted it.

Link

See *AS Physics A* Topic 3.5 for energy levels and photons.

In the MR scanner

The key design feature of an MR scanner is that it applies a magnetic field of specific flux density to the patient at a precise and well-defined location that changes systematically with time so as to scan a cross-section of the patient. At this specific flux density, the magnetic field causes excitation of the hydrogen nuclei at a definite location. As the nuclei de-excite before the next pulse is emitted, the signal received by the detector must therefore have come from that location. The intensity of the signal depends on the number of nuclei excited at that location.

In the scan, the location of the excited nuclei changes along a 'raster' of successive straight lines in a single plane through the patient, like the lines that build up a visual image on a TV screen. The detector, pulse transmitter and magnetic field coils that create the scanning raster are connected to a computer which is programmed to create a visual image of a cross-section of the patient. By scanning adjacent cross-sections systematically, a three-dimensional image of any scanned part of the patient can be displayed.

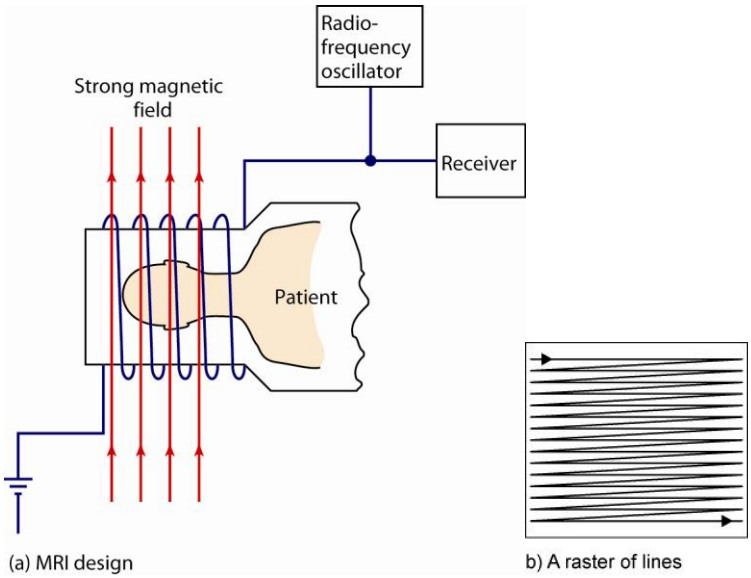

Figure 2 *The MR scanner*

Tissue discrimination is possible because the rate of decay of the detected signal after each pulse, the relaxation time, depends on the type of molecules surrounding the water molecules. The magnetic fields of surrounding magnetic nuclei delay the de-excitation of excited nuclei to

different extents, according to their relative arrangement. For example, grey matter in the brain has a relaxation time of 0.37 s compared with 0.30 s for white matter. In addition, the strength and length of the pulse affects the proportion of excited to unexcited nuclei in different types of tissue and therefore contributes to the relaxation time of the signal. The relaxation time is therefore used to identify tissue types.

MRI scans do not expose patients to ionising radiation as X-ray scans do and seem to cause little or no physiological harm. Brain research and medical diagnosis have moved forward very dramatically as a result of MRI scanners which although extremely expensive are now in operation at major hospitals in Britain and other countries. Examples of brain research include monitoring the sites in the brain of increased blood flow due to increase of brain activity when undertaking specific physical or mental activities.

Examples of MRI applications in medicine generally involve distinguishing between different types of soft tissue including imaging:

- arteries to detect narrowing or potential ruptures
- brain tissue to detect scars, tumours and other damage
- spinal discs to assess damage such as rupture or movement out of place
- hip and knee joints to detect early osteoarthritis (by early detection of a chemical substance known to be associated with osteoarthritis).

Note

Details of the arrangement used to generate the magnetic field is not required in this specification. In outline, it consists of a large superconducting electromagnet which generates a large constant magnetic field and coils that provide magnetic fields with gradients that ripple through the patient in perpendicular directions. The combined effect is to scan the patient with a magnetic field of the required flux density. In addition a radio frequency coil supplied with a high-frequency alternating current is used to excite the nuclei.

Summary questions

1 Give two reasons why MR scanners are used to detect the location of hydrogen nuclei in the body?

2 **a** Why is it necessary to apply radio waves to a patient in an MR scan?

b **i** What physical quantity is changed systematically when an MR scan is carried out?

ii What physical property of hydrogen nuclei is made use of in an MR scan?

3 **a** Describe the changes that take place to the hydrogen nuclei in the body when they absorb radio wave photons in an MR scan?

b What physical quantity is detected in an MR scan?

4 **a** What characteristic of the detected signals in an MR scan is used to discriminate between different types of tissue?

b State and explain one advantage of an MR scan in comparison with:

i an X-ray scan

ii an ultrasonic scan.