29. Remote Sensing

(a) *Candidates should be able to explain in simple terms the need for remote sensing (non-invasive techniques of diagnosis) in medicine .*

Historically, diagnosis consisted of two techniques – observing the patient outwardly for signs of fever, vomiting, changed breathing rate etc, and observing the patient inwardly by surgery. The first technique depended greatly on experience but was still blind to detailed internal conditions. The second quite often led to trauma and sometimes death of the patient. In earlier times there was also the significant risk of post-operative infection.

Modern diagnostic techniques have concentrated on using externally placed devices to obtain information from underneath the skin. X-rays have been used for a century. More recently, ultrasound has been used, especially in cases of pregnancy. Magnetic resonance imaging (MRI) is now becoming a frequently-used technique. Other techniques involve lasers that can shine through a finger or can be used in a very narrow tube that can be inserted into the body through various orifices.

In all these situations, the aim is to obtain detailed information concerning internal structures. This may be concerned, for example, with the functioning of an organ or the search for abnormalities. This is achieved without the need of investigative surgery and is described as a *non-invasive* technique. Non-invasive techniques are designed to present a much smaller risk than surgery and are, in general, far less traumatic for the patient.

(b) *Candidates should be able to explain the principles of the production of X-rays by electron bombardment of a metal target.*

X-rays are produced by bombarding metal targets with high-speed electrons. A typical spectrum of the X-rays produced is shown in Fig. 2.1.

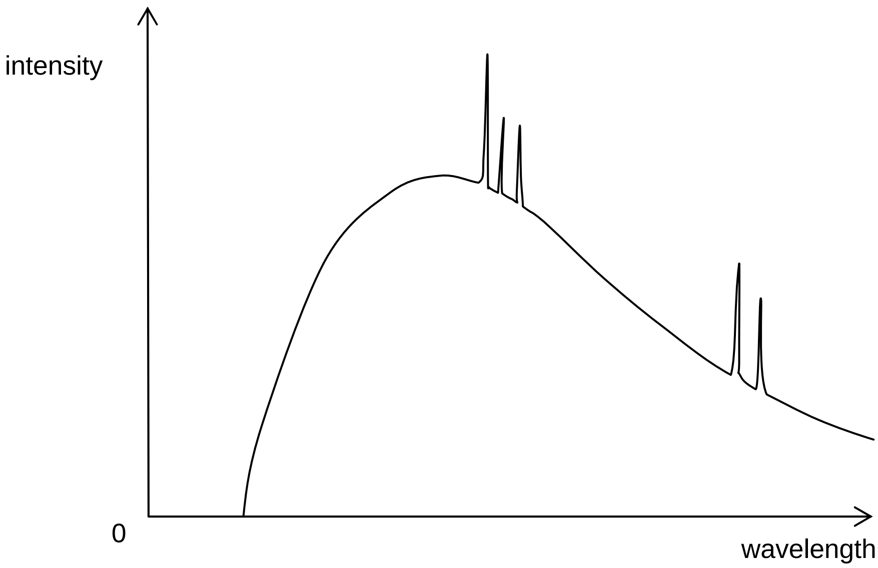


Fig. 2.1

The spectrum consists of two components. There is a continuous distribution of wavelengths with a sharp cut-off at short wavelength and also a series of high-intensity spikes that are characteristic of the target material.

Whenever a charged particle is accelerated, electromagnetic radiation is emitted. The greater the acceleration, the shorter is the wavelength of the emitted radiation. This radiation is known as Bremmstrahlung radiation. When high-speed electrons strike a metal target, large accelerations occur and the radiation produced is in the X-ray region of the electromagnetic spectrum. Since the electrons have a continuous distribution of accelerations, a continuous distribution of wavelengths of X-rays is produced. There is a minimum wavelength (a cut-off wavelength) where the whole of the energy of the electron is converted into the energy of one photon. That is,

$$\text{kinetic energy of electron} = eV = hc / \lambda,$$

where e is the charge on the electron that has moved through a potential difference V, h is the Planck constant, c is the speed of light and λ is the wavelength of the emitted X-ray photon.

As well as the continuous distribution of wavelengths, sharp peaks are observed. These peaks correspond to the emission line spectrum of the atoms of the target. The electrons that bombard the target excite orbital electrons in the lower energy levels and the subsequent de-excitation of electrons gives rise to the line spectrum.

(c) Candidates should be able to describe the main features of a modern X-ray tube, including control of the intensity and hardness of the X-ray beam.

A simplified diagram of a modern form of X-ray tube is shown in Fig. 2.2.

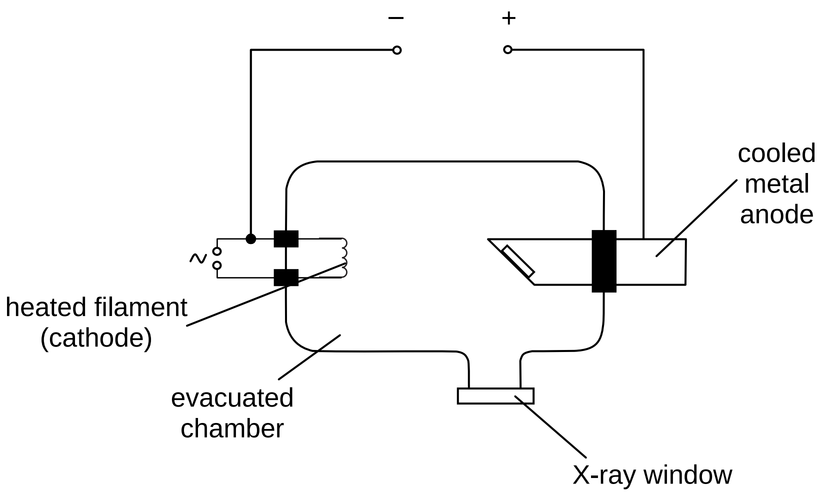


Fig. 2.2

Electrons are emitted from the heated cathode (thermionic effect). The electrons are accelerated through a large potential difference (20 kV → 100 kV for diagnosis) before bombarding a metal anode. The X-rays produced leave the tube via a ‘window’. Since the majority of the energy of the electrons in transferred to thermal energy in the metal anode, the anode is either water-cooled or is made to spin rapidly so that the target area is increased. The anode is held at earth potential.

The intensity of the X-ray beam is determined by the rate of arrival of electrons at the metal target, that is, the *tube current*. This tube current is controlled by the heater current of the cathode. The greater the heater current, the hotter the filament and hence the greater the rate of emission of thermo-electrons.

The hardness of the X-ray beam (the penetration of the X-rays) is controlled by the accelerating voltage between the cathode and the anode. More penetrating X-rays have higher photon energies and thus a larger accelerating potential is required. Referring to Fig. 2.1, it can be seen that longer wavelength X-rays (‘softer’ X-rays) are always also produced. Indeed some X-ray photons are of such low energy that they would not be able to pass through the patient. These ‘soft’ X-rays would contribute to the total radiation dose without any useful purpose. Consequently, an aluminium filter is frequently fitted across the window of the X-ray tube to absorb the ‘soft’ X-ray photons.

(d) Candidates should be able to show an understanding of the use of X-rays in imaging internal body structures, including a simple analysis of the causes of sharpness and contrast in X-ray imaging.

X-ray radiation affects photographic plates in much the same way as visible light. A photographic plate, once exposed, will appear blackened after development. The degree of blackening is dependent on the total X-ray exposure.

X-ray photons also cause fluorescence in certain materials. The mechanism is similar to that by which visible light is produced on the screen of a cathode-ray oscilloscope.

X-ray beams are used to obtain ‘shadow’ pictures of the inside of the body to assist in the diagnosis or treatment of illness. If a picture is required of bones, this is relatively simple since the absorption by bone of X-ray photons is considerably greater than the absorption by surrounding muscles and tissues. X-ray pictures of other parts of the body may be obtained if there is sufficient difference between the absorption properties of the organ under review and the surrounding tissues.

The quality of the shadow picture (the image) produced on the photographic plate depends on its sharpness and contrast. Sharpness is concerned with the ease with which the edges of structures can be determined. A sharp image implies that the edges of organs are clearly defined. An image may be sharp but, unless there is a marked difference in the degree of blackening of the image between one organ and another (or between different parts of the same organ), the information that can be gained is limited. An X-ray plate with a wide range of exposures, having areas showing little or no blackening as well as areas of heavy blackening, is said to have good contrast.

In order to achieve as sharp an image as possible, the X-ray tube is designed to generate a beam of X-rays with minimum width. Factors in the design of the X-ray apparatus that may affect sharpness include

- the area of the target anode, as illustrated in Fig. 2.3,

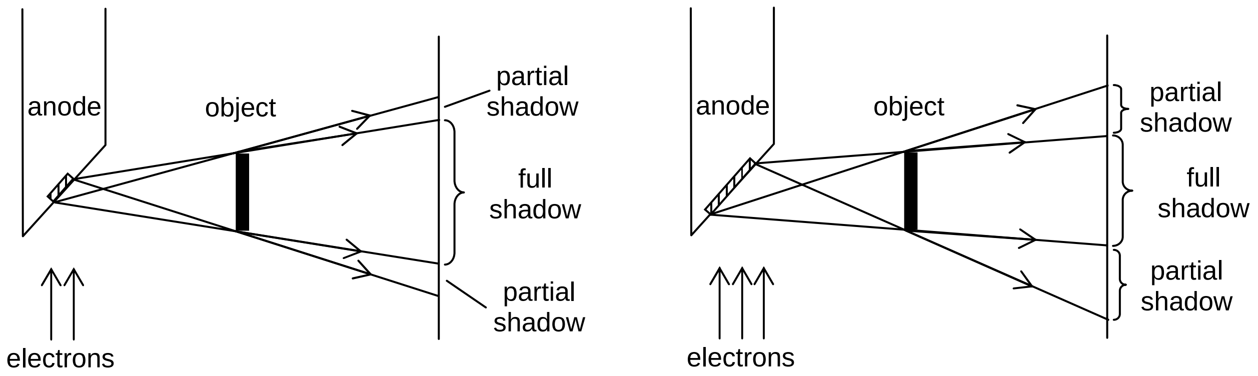


Fig. 2.3

- the size of the aperture, produced by overlapping metal plates, through which the X-ray beam passes after leaving the tube (see Fig. 2.4),

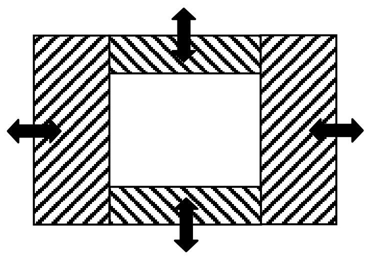


Fig. 2.4

- the use of a lead grid in front of the photographic film to absorb scattered X-ray photons, as illustrated in Fig. 2.5.

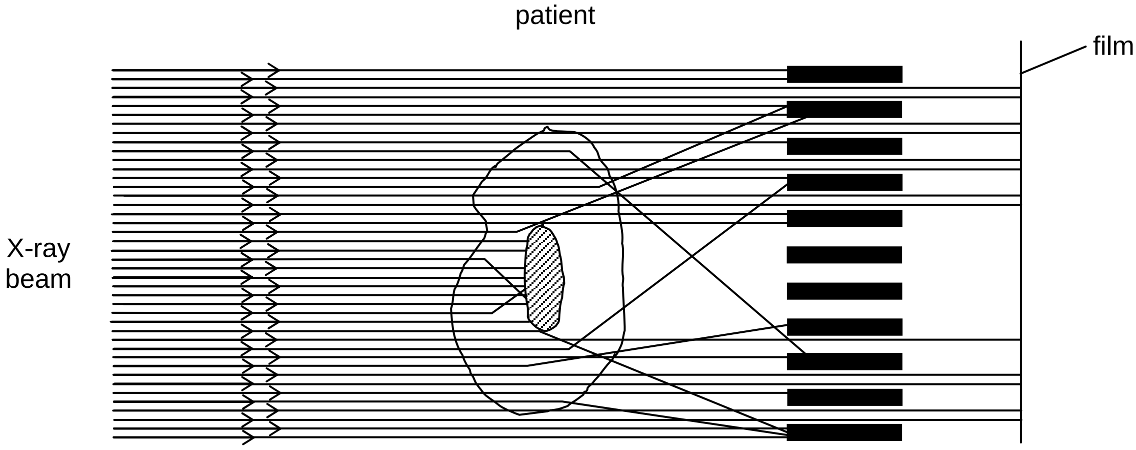


Fig. 2.5

In order to improve contrast, a 'contrast medium' may be used. For example, the stomach may be examined by giving the patient a drink containing barium sulphate. Similarly, to outline blood vessels, a contrast medium that absorbs strongly the X-radiation would be injected into the bloodstream.

The contrast of the image produced on the photographic film is affected by exposure time, X-ray penetration and scattering of the X-ray beam within the patient's body. Contrast may be improved by backing the photographic film with a fluorescent material.

(e) Candidates should be able to recall and solve problems by using the equation $I = I_0 e^{-\mu x}$ for the attenuation of X-rays in matter.

When the energy of an X-ray beam radiates from the source in all directions in a vacuum, the intensity decreases in proportional to the inverse of the square of the distance from the source. This is a consequence of the energy being 'spread' over the surface of a sphere of radius r having surface area $4\pi r^2$. Thus, in a vacuum, $I \propto I_0/r^2$. The law also applies approximately to X-rays in air since there is little absorption of X-rays by air.

In a medium where absorption processes are occurring, the intensity I of a parallel beam decreases by a constant fraction in passing through equal small thicknesses of the medium. This gives rise to an exponential decrease in the intensity of the transmitted beam. For a parallel beam of radiation of initial intensity I_0 passing through a thickness x of a medium, then the transmitted intensity I is given by

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

where μ is a constant for the medium that is dependent on photon energy. The unit of μ is mm^{-1} or cm^{-1} or m^{-1}. μ is referred to as the *linear absorption coefficient* or *linear attenuation coefficient*.

The variation with thickness x of an absorber of the percentage transmission of a parallel beam of X-ray radiation is illustrated in Fig. 2.6.

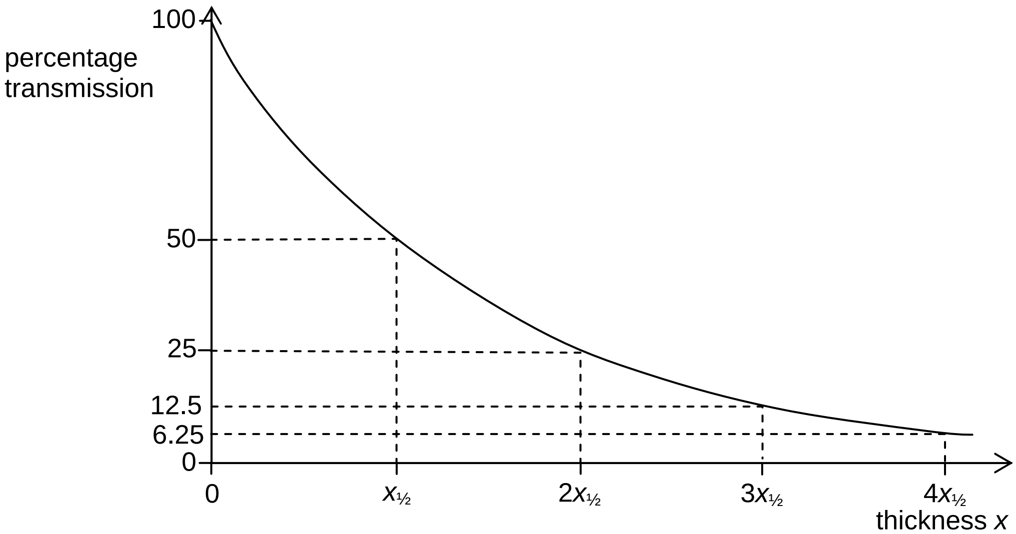


Fig. 2.6

The thickness of the medium required to reduce the transmitted intensity to one half of its initial value is a constant and is known as the *half-value thickness* $x_{½}$ or *HVT*. The half-value thickness $x_{½}$ is related to the linear absorption coefficient μ by the expression

$$x_{½} \times \mu = \ln 2.$$

In practice, $x_{½}$ does not have a precise value as it is constant only when the beam has photons of one energy only.

(f) Candidates should be able to show an understanding of the purpose of computed tomography or CT scanning.

The image produced on an X-ray plate as outlined in the section on 29(d) is a 'flat image' and does not give any impression of depth. That is, whether an organ is near to the skin or deep within the body is not apparent. Tomography is a technique by which an image of a slice, or plane, of the object may be obtained.

In this technique, a series of X-ray images are obtained from different angles through a slice but in the plane of the slice, as illustrated in Fig. 2.7.

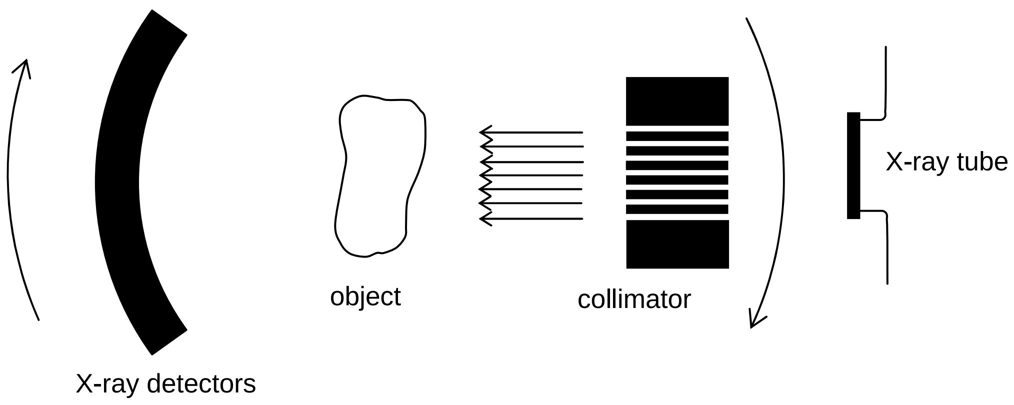


Fig. 2.7

Computer techniques make it possible to combine these images to give an image of the slice. The technique is called computed (axial) tomography or *CT scanning*.

Images of successive slices can be combined to give a three-dimensional image. The three-dimensional image can be rotated and viewed from any angle.

(g) *Candidates should be able to show an understanding of the principles of CT scanning.*

(h) *Candidates should be able to show an understanding of how the image of an 8-voxel cube can be developed using CT scanning.*

The aim of CT scanning is to make an image of a section through the body from measurements made about its axis, as illustrated in Fig. 2.7.

The section through the body is divided up into a series of small units called voxels. The image of each voxel would have a particular intensity, known as a pixel. The pixels are built up from measurements of X-ray intensity made along a series of different directions around the section of the body.

Suppose a section consists of four voxels with intensities as shown in Fig. 2.8.

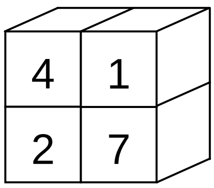


Fig. 2.8

The number on each voxel is the pixel intensity that is to be reproduced.

If a beam of X-rays is directed from the left, then detectors will give readings of 5 and 9. This allows the four voxels to be "reconstructed", as shown in Fig. 2.9.

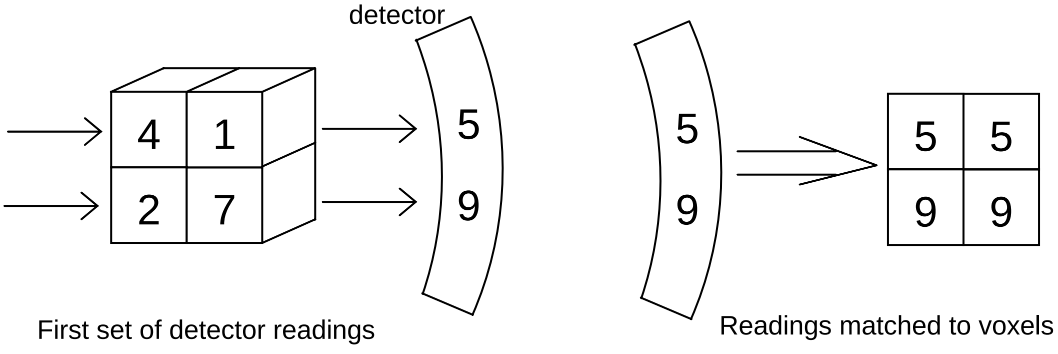
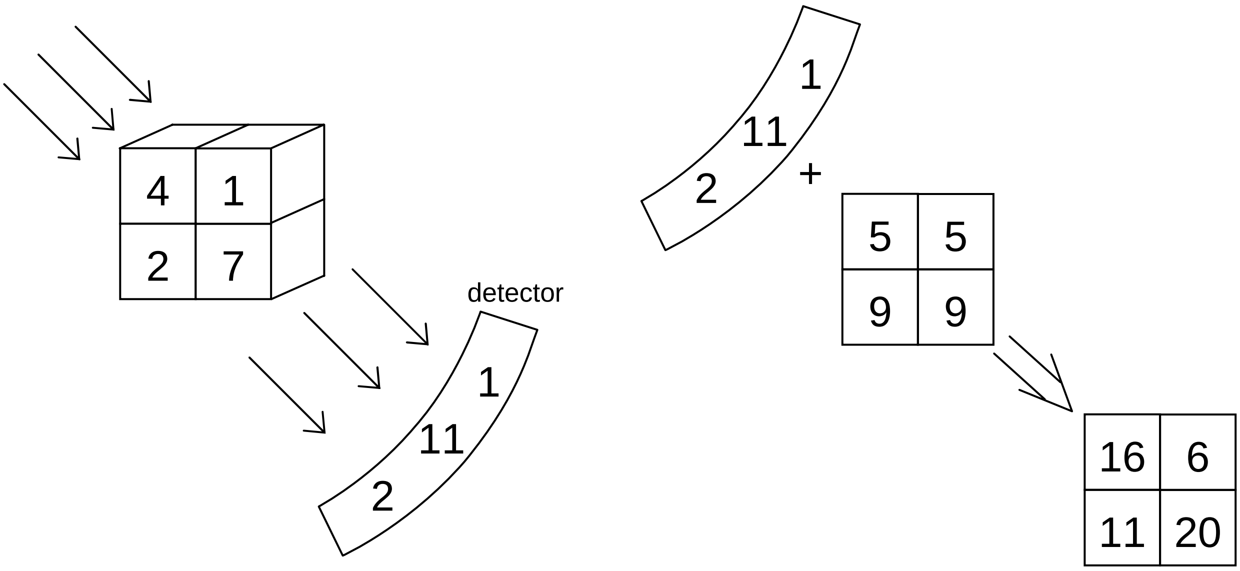


Fig. 2.9

The X-ray tube and detectors are now rotated through 45° and new detector readings are found, as shown in Fig. 2.10. These new detector readings are added to the readings already obtained for the voxels.

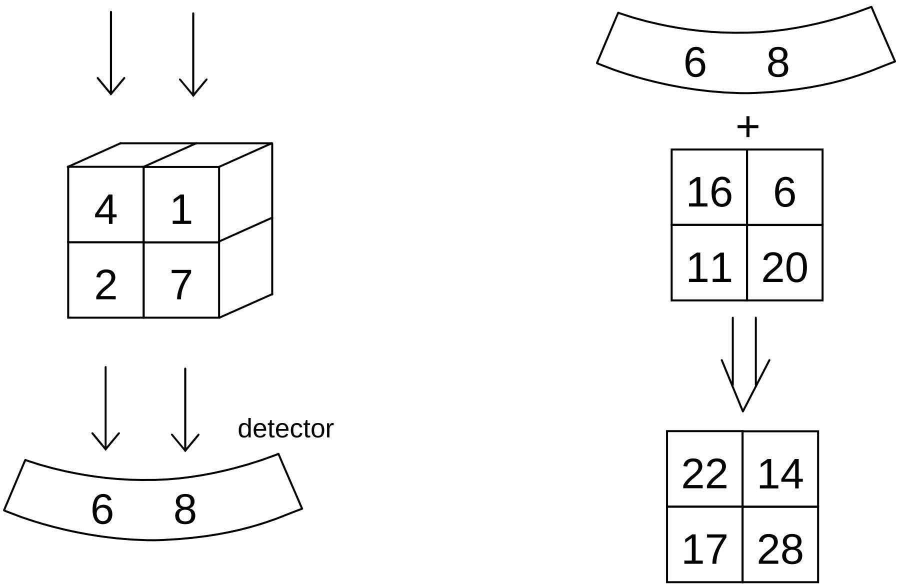


Second set of detector readings

Readings added to voxels

Fig. 2.10

The procedure is repeated after rotating the X-ray tube and the detectors through a further 45°. The result is shown in Fig. 2.11.

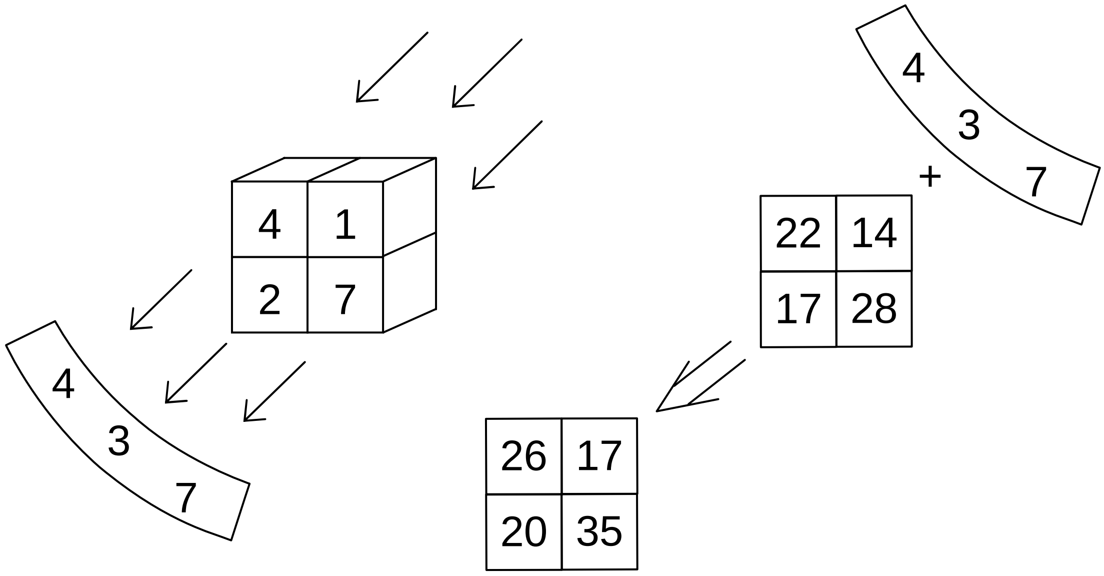


Third set of detector readings

Readings added to voxels

Fig. 2.11

The final images are taken after rotating the X-ray tube and the detectors through a further 45°. The result is shown in Fig. 2.12.



Fourth set of detector readings

Readings added to voxels

Fig. 2.12

The final pattern of pixels is shown in Fig. 2.13.

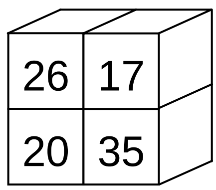


Fig. 2.13

In order to obtain the original pattern of pixels, two operations must be performed.

1. The 'background' intensity must be removed. The 'background' intensity is the total of each set of detector readings. In this case, 14 is deducted from each pixel.
2. After deduction of the 'background', the result must be divided by three to allow for the duplication of the views of the section.

These processes are illustrated in Fig. 2.14.

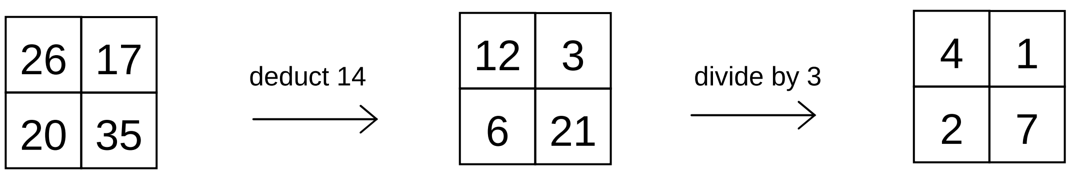


Fig. 2.14

The pattern of pixels for the section now emerges.

In practice, the image of each section is built up from many small pixels, each viewed from many different angles. The collection of the data and its construction into a display on a screen requires a powerful computer and complicated programmes. In fact, the reconstruction of each pixel intensity value requires more than one million computations. The contrast and brightness of the image of the section as viewed on the TV screen can be varied to achieve optimum results.

In order to build up an image of the whole body, the procedure would be repeated for further sections through the body. All the data for all the sections can be stored in the computer memory to create a three-dimensional image. Views of the body from different angles may be construct.

(i) *Candidates should be able to explain the principles of the generation and detection of ultrasonic waves using piezo-electric transducers.*

Ultrasonic waves may be produced using a piezo-electric transducer. The basis of this is a piezo-electric crystal such as quartz. Two opposite sides of the crystal are coated with thin layers of silver to act as electrical contacts, as illustrated in Fig. 2.15.

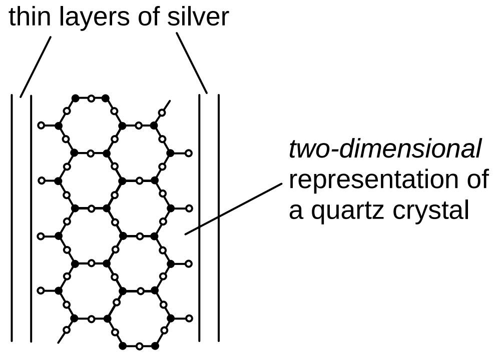


Fig. 2.15

Quartz has a complex structure made up of a large number of repeating tetrahedral silicate units, as illustrated in Fig. 2.16.

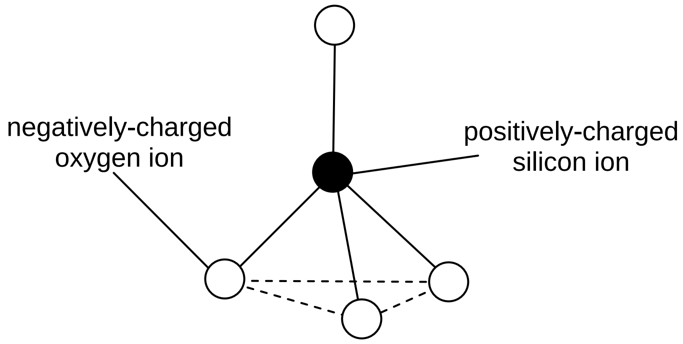


Fig. 2.16

The positions of the oxygen links are not rigidly fixed in these units, or lattices, and since the oxygen ions are negatively charged, movement can be encouraged by applying an electric field.

When the crystal is unstressed, the centres of charge of the positive and the negative ions bound in the lattice of the piezo-electric crystal coincide, so their effects are neutralised, as shown in Fig. 2.17(a).

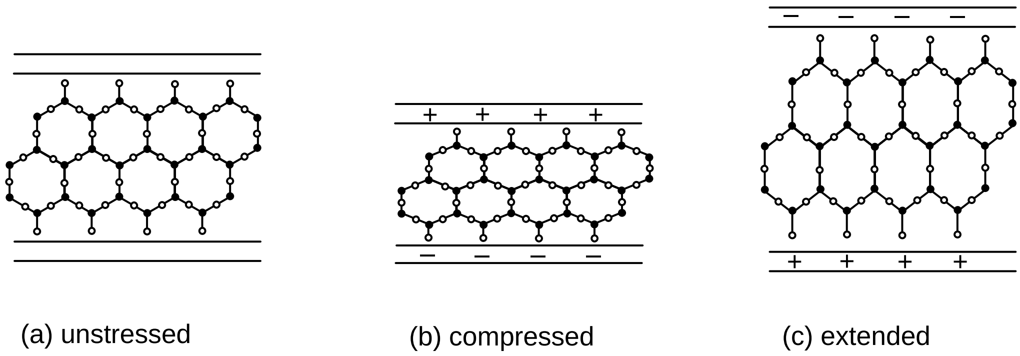


Fig. 2.17

If a constant voltage is then applied across the electrodes (i.e. across the layers of silver), the positive silicon ions are attracted towards the cathode and the negative oxygen ions towards the anode. This causes distortion of the silicate units. Depending on the polarity of the applied voltage, the crystal becomes either thinner or thicker as a result of the altered charge distribution. These effects are illustrated in Fig. 2.17(b) and Fig. 2.17(c).

An alternating voltage applied across the silver electrodes will set up mechanical vibrations in the crystal. If the frequency of the applied voltage is the same as the natural frequency of vibration of the crystal, resonance occurs and the oscillations have maximum amplitude. The dimensions of the crystal can be such that the oscillations are in the ultrasonic range (i.e. greater than 20 kHz), thus producing ultrasonic waves in the surrounding medium.

Ultrasonic transducers can also be used as receivers. When an ultrasonic wave is incident on an unstressed piezo-electric crystal, the pressure variations alter the positions of positive and negative ions within the crystal. This induces opposite charges on the silver electrodes, producing a potential difference between them. This varying potential difference can then be amplified and processed.

A simplified diagram of a typical piezo-electric transducer/receiver is illustrated in Fig. 2.18.

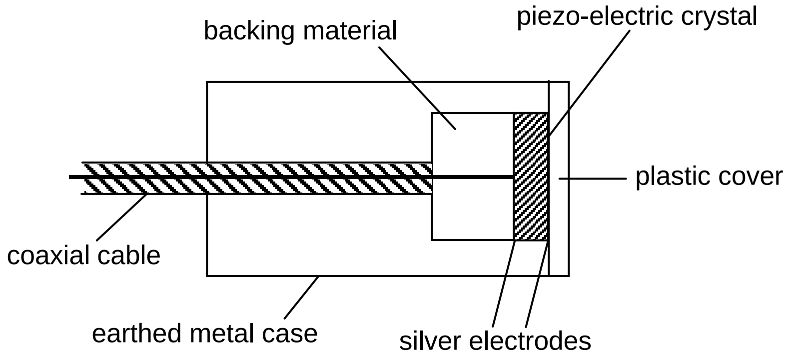


Fig. 2.18

Such devices operate in the MHz frequency range, up to a maximum of about 600 MHz.

(j) *Candidates should be able to explain the main principles behind the use of ultrasound to obtain diagnostic information about internal structures.*

(k) *Candidates should be able to show an understanding of the meaning of acoustic impedance and its importance to the intensity reflection coefficient at a boundary.*

In order to be able to explain the principles of the use of ultrasound in diagnosis, it is necessary to have an understanding of the reflection of ultrasound at boundaries and its absorption in media.

Ultrasound obeys the same laws of reflection and refraction at boundaries as audible sound and light. When an ultrasound wave meets the boundary between two media, some of the wave energy is reflected and some is transmitted, as illustrated in Fig. 2.19.

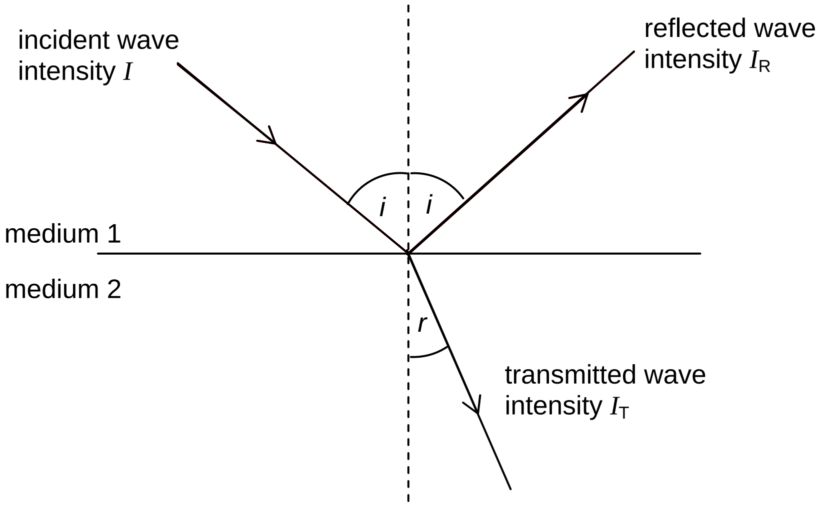


Fig. 2.19

For an incident intensity I, reflected intensity I_R and transmitted intensity I_T, then from energy considerations,

$$I = I_R + I_T.$$

The relative magnitudes of the reflected and transmitted intensities depend not only on the angle of incidence but also on the two media themselves.

For any medium, a quantity known as the *specific acoustic impedance* Z is defined as

$$Z = \rho c,$$

where c is the speed of the wave in the medium of density ρ. When a wave is incident normally on a boundary between two media having specific acoustic impedances of Z_1 and Z_2, the ratio I_R / I of the reflected intensity to the incident intensity is given by the expression

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

The ratio I_R / I is known as the *intensity reflection coefficient* for the boundary and is usually given the symbol α. Clearly, the value of α depends on the difference between the specific acoustic impedances of the media on each side of the boundary. Some approximate values of specific acoustic impedance Z are given in Fig. 2.20.

medium	$Z = \rho c$ / kg m^{-2} s^{-1}
air	430
quartz	1.52×10^7
water	1.50×10^6
blood	1.59×10^6
fat	1.38×10^6
muscle	1.70×10^6
soft tissue	1.63×10^6
bone	$(5.6 - 7.8) \times 10^6$

Fig. 2.20

It can be seen that the intensity reflection coefficient is very large for ultrasound entering or leaving the human body (a boundary between air and soft tissue). In order that ultrasound waves may be transmitted from the transducer into the body (and also return to the transducer after reflection from the boundaries of body structures), it is important to ensure that there is no air trapped between the transducer and the skin. This is achieved by means of a coupling medium such as a gel that fills any spaces between the transducer and the skin.

A second factor that affects the intensity of ultrasonic waves passing through a medium is absorption. As a wave travels through a medium, energy is absorbed by the medium and the intensity of a parallel beam decreases exponentially. The temperature of the medium rises. The heating effect caused by ultrasound of suitable frequencies is, in fact, used in physiotherapy to assist with recovery from sprained joints.

Fig. 2.21 illustrates a parallel beam of ultrasound waves of intensity I_0 incident on a medium of thickness x.

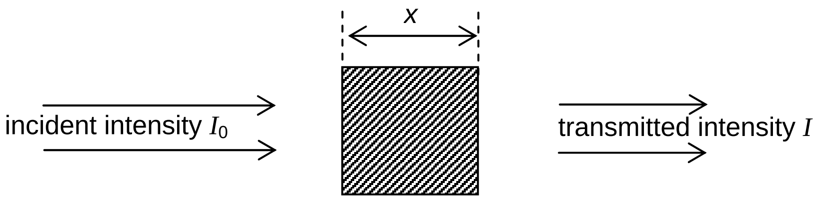


Fig. 2.21

The intensity I of the beam after passing through the medium is related to the incident intensity by the expression

$$I = I_0 e^{-kx},$$

where k is a constant for the medium referred to as the *absorption coefficient*. This coefficient is dependent on the frequency of the ultrasound. Fig. 2.22 gives some values for ultrasound of frequency 1 MHz.

medium	absorption coefficient / m^{-1}
air	120
water	0.02
muscle	23
bone	130

Fig. 2.22

In order to obtain diagnostic information about internal body structures, the transducer is placed in contact with the skin, with a gel acting as a coupling medium. The gel reduces the size of the impedance change between boundaries at the skin and thus reduces reflection at the skin. Short pulses of ultrasound are transmitted into the body. These pulses are partly reflected and partly transmitted at boundaries between media in the body (e.g. a fat – muscle boundary). The reflected pulses return to the transducer where they are detected and transformed into voltage pulses. These voltage pulses can then be amplified and processed to give an image on an oscilloscope screen. Two techniques, A-scan and B-scan, are in common use for the display of an ultrasound scan.

The A-scan system basically measures the distance of different boundaries from the transducer, with the transducer held in one position. A short burst of ultrasound is transmitted to the body through the coupling medium. At each boundary between different media in the body, some ultrasound is reflected and some is transmitted. The reflected pulse is picked up be the transducer which now acts as a receiver. The signal is amplified and displayed on a cathode-ray oscilloscope (c.r.o.). The reflected pulse also meets boundaries as it returns to the transducer. This causes some of the energy of the reflected pulse to be lost and energy is also lost due to absorption in the media. Consequently, echoes from deeper in the body tend to be of lower intensity. To compensate for this, the later an echo is received at the transducer, the more it is amplified before display on the c.r.o. A vertical line appears on the screen each time an echo is received. The time-base on the X-plates is adjusted so that all of the reflections are seen on the screen for one scan (pulse). The distance between boundaries can be calculated if the speed of ultrasound in the various media is known. An example of an A-scan for the brain is shown in Fig. 2.23.

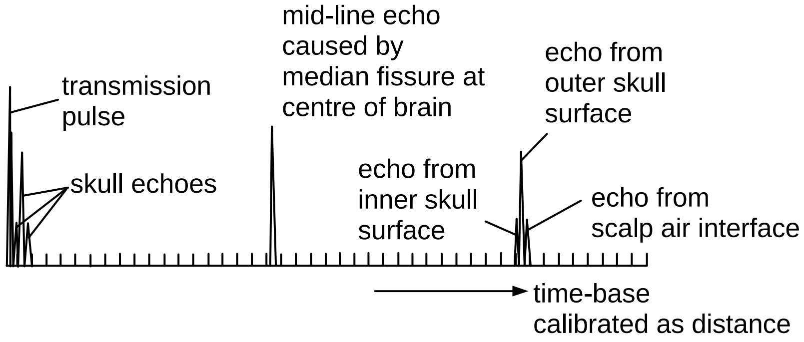


Fig. 2.23

The B-scan technique basically combines a series of A-scans, taken from a range of different angles, to form a two-dimensional picture. As before, each A-scan corresponds to a single ultrasound pulse being emitted by the transducer and producing a series of reflected pulses from boundaries within the body.

The ultrasound probe for a B-scan consists of a series of small crystals, each having a slightly different orientation. The signals received from the crystals in the probe are processed by a computer. Each reflected pulse is shown as a bright spot in the correct orientation of the crystal on the screen of a c.r.o. Consequently, the completed pattern of spots from all the crystals in the probe builds up into a two-dimensional representation of the boundary positions in the body being scanned. This image may be photographed or stored in the computer memory.

The main advantage of ultrasonic scanning is that the health risk factor to human patients, and to those operating the system, is considered to be very much less than in X-ray diagnosis. Other advantages are that the equipment may be portable and is relatively simple to use. With higher frequencies, smaller features within the body can be identified. Modern techniques allow low intensity echoes to be detected and as a result, boundaries between soft tissues, as well as between hard and soft tissues, may be detected.

(l) *Candidates should be able to explain the main principles behind the use of magnetic resonance to obtain diagnostic information about internal structures.*

(m) *Candidates should be able to show an understanding of the function of the non-uniform magnetic field, superimposed on the large constant magnetic field, in diagnosis using magnetic resonance.*

Many atomic nuclei behave as if they possess a ‘spin’. Such nuclei have an odd number of protons and/or an odd number of neutrons. Their ‘spin’ causes the nuclei of these atoms to behave as tiny magnets. If an external magnetic field is applied to these atoms, they will tend to line up in the magnetic field. This alignment is not perfect and the nuclei rotate about the direction of the field as they spin. This type of motion is referred to as *precession*. The motion is similar to the motion of a top spinning in a gravitational field.

The frequency of precession (the Lamour frequency) depends on the nature of the nucleus and the strength of the magnetic field. The Lamour frequency is found to lie in the radio-frequency (RF) region of the electromagnetic spectrum.

If a short pulse of radio waves of frequency equal to the Lamour frequency is applied, the atoms will resonate, absorbing energy. When the pulse ends, the atoms will return to their original equilibrium state after a short period of time, called the *relaxation time*. In so doing, RF radiation is emitted by the atoms. There are, in fact, two relaxation processes and it is the times between these that forms the basis of magnetic resonance imaging (MRI).

Examples of nuclei that show this effect include hydrogen, carbon and phosphorus. Because of its abundance in body tissue and fluids, hydrogen is the atom used in this scanning tehnique.

A schematic diagram of a magnetic resonance (MR) scanner is shown in Fig. 2.24.

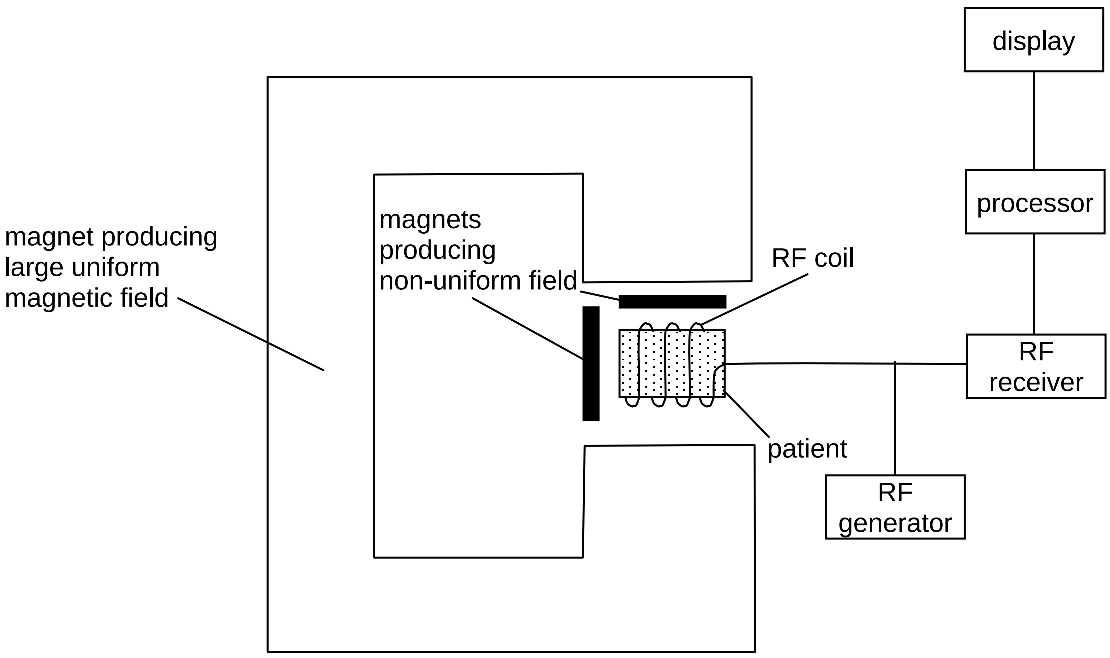


Fig. 2.24

The person under investigation is placed between the poles of a very large magnet that produces a uniform magnetic field in excess of 1 tesla. All the hydrogen nuclei within the person would have the same Lamour frequency because this frequency is dependent on the magnetic field strength. In order to locate a particular position of hydrogen atoms within the person, a non-uniform magnetic field is also applied. This non-uniform field is accurately calibrated so that there is a unique value of magnetic field strength at each point in the person. This value, coupled with the particular value of the Lamour frequency, enables the hydrogen nuclei to be located.

Radio-frequency pulses are transmitted to the person by means of suitable coils. These coils are also used to detect the RF emissions from the patient. The received emissions are processed in order to construct an image of the number density of hydrogen atoms in the patient. As the non-uniform magnetic field is changed, then atoms in different parts of the person will be detected. One such MR scan, which shows a section through the spine and back muscles, is shown in Fig. 2.25.

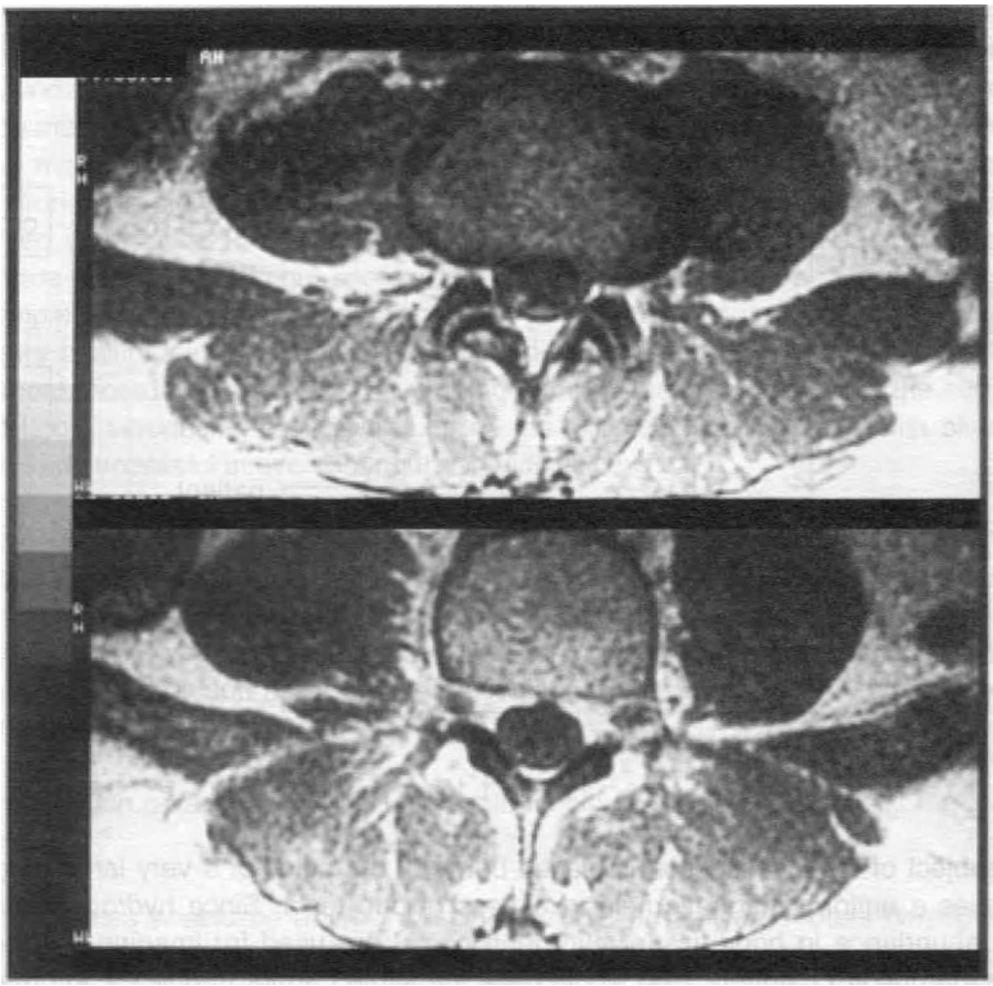


Fig. 2.25