8 Read the passage below and answer the questions that follow.

X-ray and magnetic resonance imaging (MRI) are some modern imaging techniques in medicine that uses externally placed devices to obtain diagnostic information from underneath the skin.

A modern form of X-ray tube used to obtain the internal body structure of a patient is shown in Fig. 8.1 (not to scale).

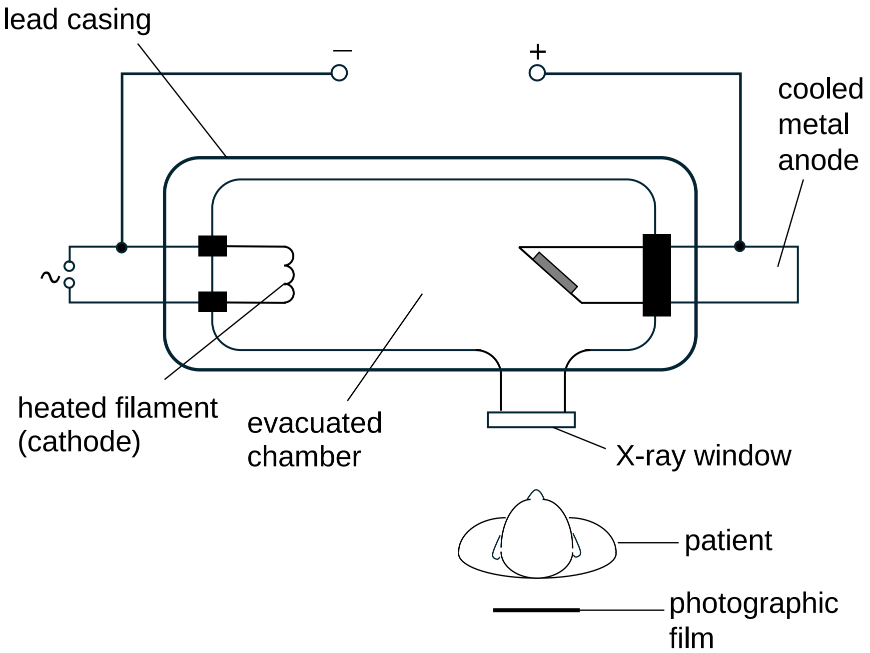

Fig. 8.1

In the X-ray tube, electrons emitted from the heated filament are accelerated through a large potential difference towards the metal anode, producing X-rays. The filament at the cathode is typically made of thin tungsten wire. The X-rays produced are controlled and directed to leave the X-ray tube via a window. As the X-ray beams pass through the patient, varying degree of X-ray gets absorbed, depending on the composition of the body. The remaining X-rays then reach the photographic film where a contrast image of the internal body structure is obtained. Good contrast is achieved if there is a clear difference in the blackening of the photographic film as the X-ray passes through and gets absorbed by different types of tissue in the patient. Typically, a good contrast is obtained when the ratio of the transmitted X-rays between different body parts has an order of magnitude of at least 1.

The gradual decrease in intensity of a beam of X-ray as it passes through matter is represented by the equation

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

where I_0 is the initial intensity, x is the thickness of the material, I is the transmitted intensity and μ is the absorption (attenuation) coefficient. Fig. 8.2 shows the absorption (attenuation) coefficient of some matter with 30 keV X-rays.

matter	μ / cm^{-1}
blood	0.41
bone	2.46
brain	0.41
muscle	0.40

Fig. 8.2

Magnetic resonance imaging (MRI) is another imaging technique that relies on the fact that some atomic nuclei behave like tiny magnets in an external magnetic field.

In MRI, it is usually the nuclei of hydrogen atoms that are studied, since hydrogen atoms are present in all tissues. The hydrogen nucleus contains only one proton, and it has a property called spin. When a very strong external magnetic field is applied, the magnetic axis of a hydrogen nucleus does not align itself directly along the external magnetic field, but rotates around it, just like the axis of a spinning top, as shown in Fig. 8.3. This rotation or gyration action is known as precession.

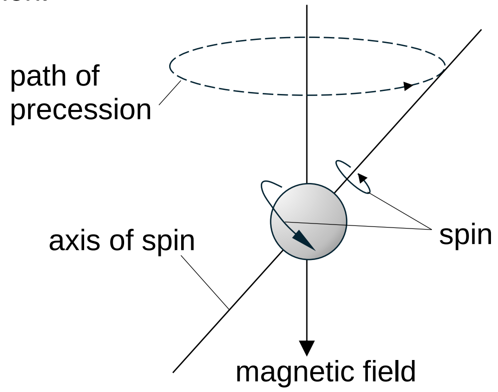

Fig. 8.3

The angular frequency of precession is called the Larmor frequency, ω_0, and depends on the individual nucleus and the magnetic flux density B_0 of the magnetic field.

$$\omega_0 = \gamma B_0$$

The quantity γ is the gyromagnetic ratio for the nucleus and is a measure of its magnetism. For hydrogen nucleus, the ratio is approximately 2.68×10^8 rad s^{-1} T^{-1}.

Fig. 8.4 shows an MRI scanner comprising three set of coils: main coil, gradient coil and radio frequency (RF) coil. The main coil is a solenoid that is 2.2 m long and 1.0 m in diameter. It is made of superconducting wire that carries a current of 750 A and produces an external magnetic field of 1.5 T. To achieve superconductivity, the main coil is cooled using liquid helium to a temperature slightly below the boiling point of helium at 4.2 K.

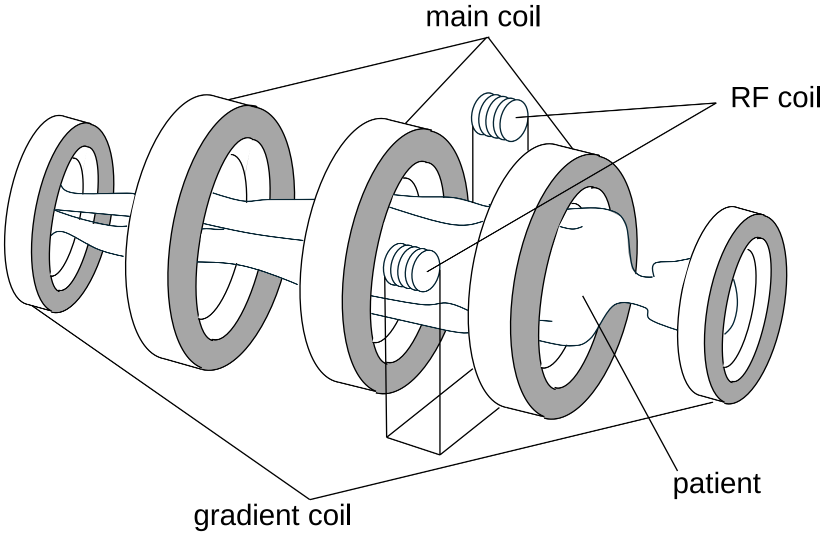

Fig. 8.4

A set of gradient coils produces an additional external magnetic field that alters the magnitude of the magnetic flux density across the length, depth and width of the patient. A radio frequency (RF) coil transmits RF pulses into the body that causes nuclear magnetic resonance of the hydrogen nuclei.

When the RF coil is switched off, the hydrogen nuclei relax and release energy in the form of RF waves that can be detected. The rate of relaxation of the nuclei follows an exponential decay curve. This can be characterised by a spin-lattice relaxation time, t.

Fig. 8.5 shows t of some matter in a magnetic flux density of 1.5 T.

matter	t / ms
blood, oxygenated	1200 – 1600
bone	< 100
brain, gray matter	900 – 1300
brain, white matter	600 – 800
muscle	900 – 1000

Fig. 8.5

Different tissues can be distinguished by the different rates at which they release energy after they have been forced to oscillate.

(a) Explain the principles of production of the continuous X-ray spectrum.

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....[3]

(b) Suggest a reason why tungsten is used for the filament at the cathode of an X-ray tube.

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....[1]

(c) A cross-section of a model arm is shown in Fig. 8.6.
In an investigation into the absorption of X-ray radiation in the model arm, parallel X-ray beams of 30 keV are directed along the line MM and along the line BB.

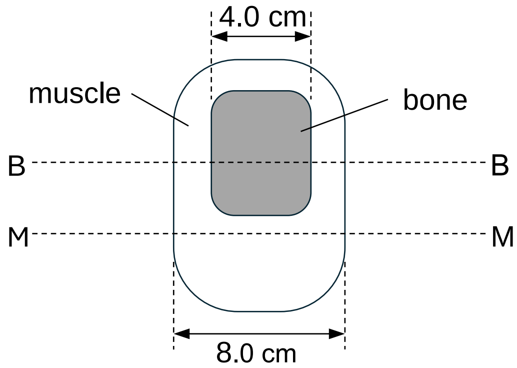

Fig. 8.6

(i) Calculate the ratio

$$\frac{\text{intensity of transmitted X-ray beam from model}}{\text{intensity of incident X-ray beam on model}}$$

for a parallel X-ray beam directed along the line

1. MM,

ratio = …………………………………… [2]

2. BB.

ratio = …………………………………… [3]

(ii) Explain whether the X-ray image obtained has good contrast.

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……………………………………………………………………………………………….... [2]

(d) MRI scanning typically takes 30 minutes to more than 1 hour. Explain why MRI is particularly suitable for producing detailed images of the brain compared to X-ray, despite the longer duration compared to X-ray.

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……………………………………………………………………………………………...[2]

(e) State one disadvantage of using MRI.

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……………………………………………………………………………………………...[1]

(f) Determine the number of turns in the main coil of the MRI scanner.

number of turns = …………….………....... [2]

(g) Determine the frequency of the pulse of the RF waves required to cause nuclear magnetic resonance of hydrogen nuclei in the MRI scanner.

frequency = …………….……….... Hz [2]

(h) During an MRI procedure, a small segment of the main coil loses its superconductivity, and the resistance of the wire suddenly increases to 0.0045 Ω. An increase in temperature of the main coil occurs, causing liquid helium to rapidly vaporise. The latent heat of vaporisation of helium is 21 kJ kg^{-1}.

Determine the initial rate of vaporisation of liquid helium.

initial rate of vaporisation = ………………………….. kg s^{-1} [2]

[Total: 20]