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

X-rays have many uses today, including medical imaging, radiotherapy, X-ray diffraction and luggage scanning at airports.

In an evacuated X-ray tube, electrons are emitted from a heated filament (or cathode). They are then accelerated through a potential difference and strike a heavy-metal target (or anode), usually tungsten. The target is usually made to rotate at 3000 revolutions per minute. At any instant in time, the effective mass of the target in the electron beam is 12g. The X-ray tube is illustrated in Fig. 8.1.

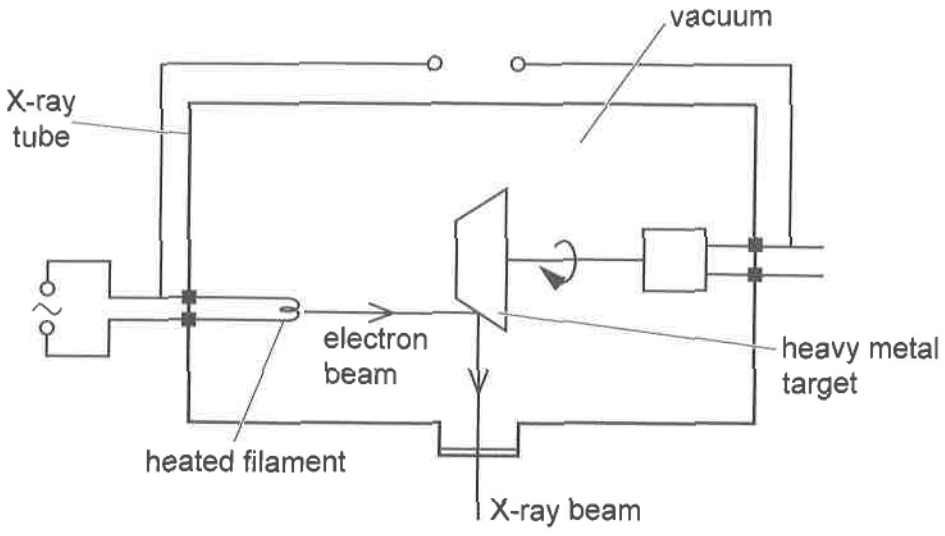

Fig. 8.1 (not to scale)

Typical data for producing an X-ray image are given in Table 8.1.

Table 8.1

accelerating voltage/kV	65
beam current/A	0.12
exposure time/s	1.1

The deceleration of the electrons at the target results in the emission of X-ray photons. These X-ray photons cover a range of wavelengths as shown in a simplified form in Fig. 8.2.

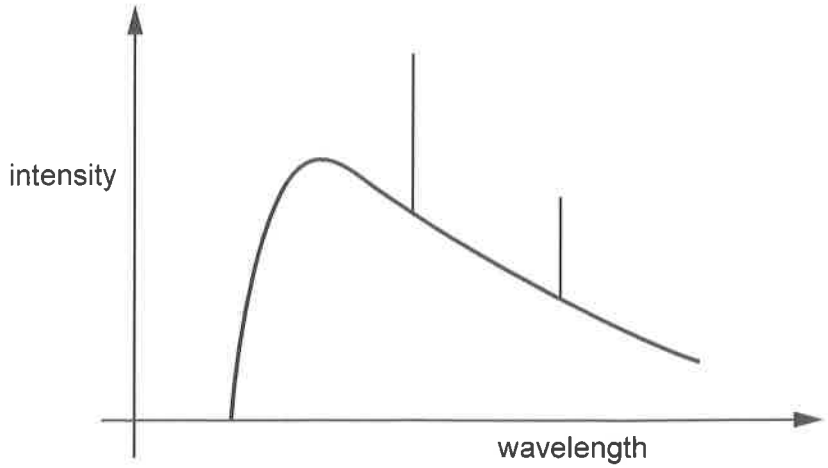

Fig. 8.2

The broad spectrum of photons is produced by the deceleration of the electrons by differing amounts. Only 1% of the electron beam energy becomes the energy of X-ray photons, with the remaining 99% dissipated as thermal energy.

As the X-ray beam passes through matter, its intensity is attenuated (reduced) by a number of processes. One of these is the Compton effect where the X-ray photon is scattered from an outer shell electron, giving energy to the electron in the process. The electron is ejected from the atom. Another process is the photoelectric effect, where the incident X-ray photon is completely absorbed, ejecting an inner, orbital electron. For low energy X-ray imaging, the photoelectric effect is the dominant process and the attenuation through matter is proportional to the atomic number cubed, Z^3. The average Z number of soft tissue is 7 and the average Z number of bone is 14. X-ray photons that usefully contribute to the X-ray image travel straight through the body.

The transmitted X-ray photons are incident on a thin sheet of photographic film which is developed to reveal the image. In modern, digital X-ray machines, flat-panel detectors are used in order to detect the incoming X-ray photons. This process is much more sensitive than using photographic film.

The attenuation of the incident intensity of a parallel X-ray beam as it passes through matter results in its intensity decreasing exponentially. The transmitted intensity depends on the thickness x of the matter and the linear attenuation coefficient μ of the matter. This is similar to the exponential decrease with time in the activity of a radioactive element. A successful X-ray image has a good contrast if there are significant differences between the transmitted X-ray photon intensities in different regions of the image.

Where an X-ray image is to be produced of similar tissues, a contrast medium may be used. For example, a patient may be asked to drink a solution containing barium (Z = 56) in order to investigate their digestive system.

In X-ray imaging, a single exposure to X-rays is used to produce a two-dimensional image of an object. Computed tomography (CT) scanning uses X-ray beams in order to produce a three-dimensional image. In CT scanning, the X-ray source spirals down the object taking many X-ray images which are combined to produce a three-dimensional image.

(a) Explain why the X-ray tube is evacuated.

.....

..... [1]

(b) On Fig. 8.2, draw the spectrum of X-ray photons produced when both the beam current and the accelerating potential difference are increased.

[3]

(c) **(i)** Calculate the thermal energy produced in the target as a result of producing a typical X-ray image.

energy = ... J [2]

(ii) Assume that all the energy in **(c)(i)** is absorbed by the effective mass of a stationary tungsten target.

Estimate its temperature rise.

The specific heat capacity of tungsten is $130\,J\,kg^{-1}\,K^{-1}$.

temperature rise = ... °C [2]

(iii) The melting point of tungsten is 3400 °C. Explain why the anode is rotated.

.....

..... [1]

(d) (i) The Compton effect involves the scattering of an incident X-ray photon.

Complete the diagram in Fig. 8.3 to show possible paths of the electron and scattered X-ray photon. Label your diagram.

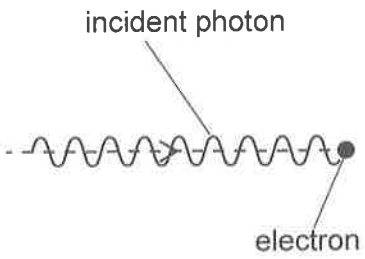

Fig. 8.3

[2]

(ii) State and explain the change, if any, of the wavelength of the X-ray photon due to scattering.

.....

.....

..... [1]

(iii) Suggest the effect on the X-ray image of photons produced by Compton scattering.

.....

.....

..... [2]

(e) An X-ray beam is attenuated in matter due to the photoelectric effect.

Calculate the ratio

$$\frac{\text{attenuation of X-rays in bone}}{\text{attenuation of X-rays in soft tissue}}.$$

ratio = ... [1]

(f) Derive an expression, in terms of the linear attenuation μ, for the thickness $x_{1/2}$ of matter needed to decrease the intensity of a parallel X-ray beam to half of its incident intensity. Show your working.

[2]

(g) Suggest an advantage to the patient of the use of more sensitive detectors.

.....

..... [1]

(h) Explain why a patient drinks a barium solution in order that a successful image of the digestive system may be produced.

.....

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..... [2]

(i) Suggest and explain a disadvantage to the patient who has a CT scan rather than a single two-dimensional X-ray.

.....

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..... [2]

[Total: 22]