Medical Imaging

Name _____ Date _____

By the end of this topic I can...

- explain how X-rays are produced, and use $I = I_0 e^{-\mu x}$
- describe X-ray imaging and CT scanning
- explain ultrasound production, impedance and reflection
- describe nuclear magnetic resonance and MRI

Diagnosis without cutting the patient open needs _____ techniques: _____, _____, PET scans and _____.

X-ray imaging

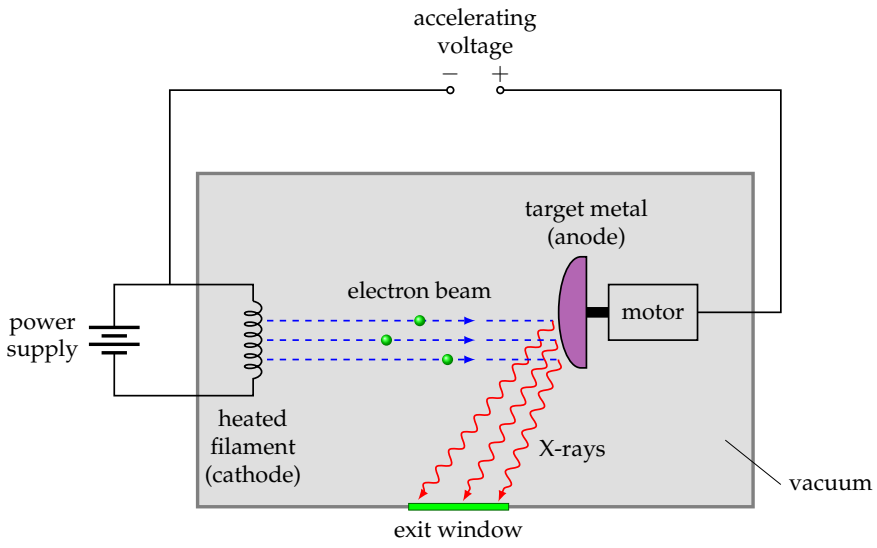
Nature of X-rays

• X-rays are _____ of short wavelength ($\sim 10^{-12}$ to 10^{-8} m), so high frequency

• _____ is the penetrating ability: _____ X-rays have higher f, shorter λ, more energy. _____ X-rays are absorbed easily by the body and do not help form the image, so an _____ sheet filters them out.

• radiation emitted by _____ is called X-rays; radiation emitted by _____ is called γ-rays

Production of X-rays



• electrons are pulled from a heated _____ and accelerated through a high p.d. towards the target _____ (tungsten, etc.)

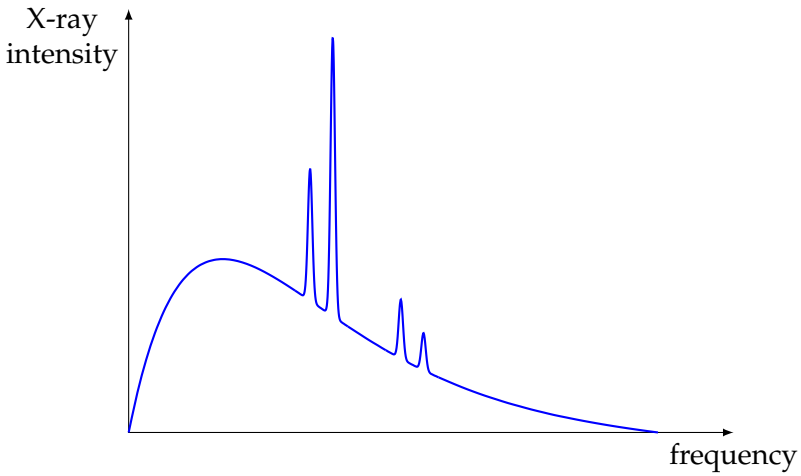
• the electrons' kinetic energy is converted to _____, which leave through the exit window

• **accelerating voltage** V_{ac} controls the _____: larger V_{ac}, more energetic photons

• **cathode (filament) current** controls the _____ of electrons, so the _____ of the beam

• only a tiny fraction of the energy becomes X-rays, most is _____ energy in the anode. The anode is _____ by a motor and cooled (e.g. by water).

X-ray spectrum



X-ray spectrum from an X-ray tube.

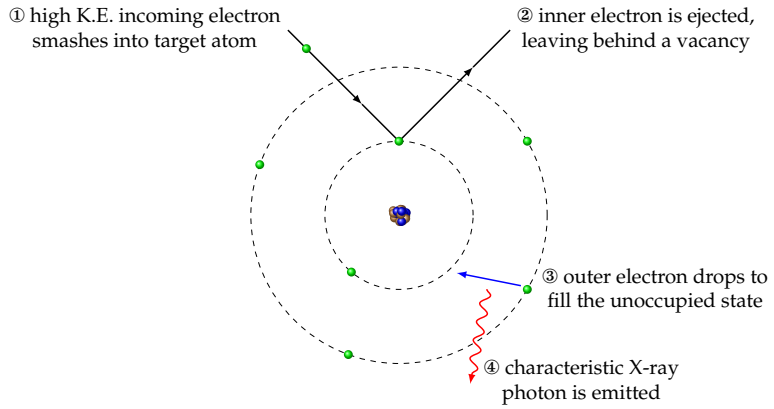
The spectrum has a _____ and a few _____.

• **braking radiation** (continuous): electrons _____ in the target and lose kinetic energy as photons. There is no constraint on the energy lost, so a _____ of photon energies.

• there is a _____: the photon of highest energy comes from an electron losing _____ its kinetic energy in one collision:

Example 32.1 An X-ray tube uses an accelerating voltage of 5000 V. What is the highest frequency of X-ray produced?

Question 32.1 Explain why the spectrum of X-rays has a minimum wavelength.



Production of characteristic radiation.

- **characteristic radiation** (spikes): an incoming electron knocks an _____ electron out of a target atom. An electron from a _____ level drops to fill the vacancy and emits an _____.
- energy levels are _____, so only certain _____ are emitted. The lines depend only on the _____.

Question 32.2 If the accelerating voltage is increased, suggest and explain the changes to the spectrum.

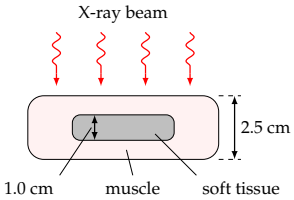
Question 32.3 Summarise the principles of production of X-rays.

X-ray attenuation

_____ is the gradual _____ of an X-ray beam as it passes through a substance.

For a _____ beam: where μ is the _____.

- μ is the _____ per unit distance that a photon is absorbed, so the intensity falls _____ (compare nuclear decay)
- a _____ beam loses intensity even without absorption, so the law applies to _____ beams only
- a high-μ substance is a _____: bone absorbs far more than soft tissue ($\mu_{\text{bone}} > \mu_{\text{tissue}}$)
- μ depends on the _____: higher frequency, _____ μ
- **half-value thickness** $x_{1/2}$: thickness that halves the intensity.



Example 32.2 A parallel beam of 30 keV X-rays of intensity I_0 passes through a specimen 2.5 cm thick, which has soft tissue ($\mu = 0.40\ \text{cm}^{-1}$) and, in the middle, a bone 1.0 cm thick ($\mu = 2.55\ \text{cm}^{-1}$). Find the emergent intensity if the beam passes through (a) soft tissue alone, (b) bone and tissue.

Question 32.4 Copper has $\mu = 0.41\ \text{mm}^{-1}$ for 100 keV X-rays. What thickness reduces the intensity of a parallel beam by 90%?

Image quality

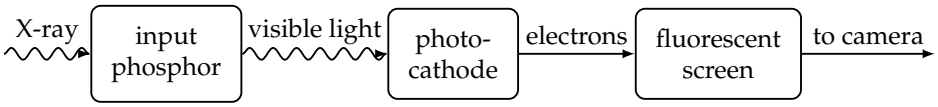
A film or detector records the attenuated X-rays as a _____. Good quality needs good _____, good _____ and minimal _____.

- **sharpness**: depends mainly on the _____ of the beam, so a narrow _____ beam is wanted. Achieve this by a _____, a small _____, lead slits (_____), an _____ screen, and a patient who keeps _____.
- **contrast**: different structures must be blackened by _____, so a large difference in μ. Soft tissues are all poor absorbers, so a _____ of high atomic number (_____ injection, _____ meal) is used.

Question 32.5 The table gives μ for bone and muscle. Why is it better to use low-energy X-rays to distinguish bone from muscle?

energy/keV	bone μ/cm^{-1}	muscle μ/cm^{-1}
30	2.55	0.40
80	0.43	0.19
200	0.25	0.14
800	0.14	0.082

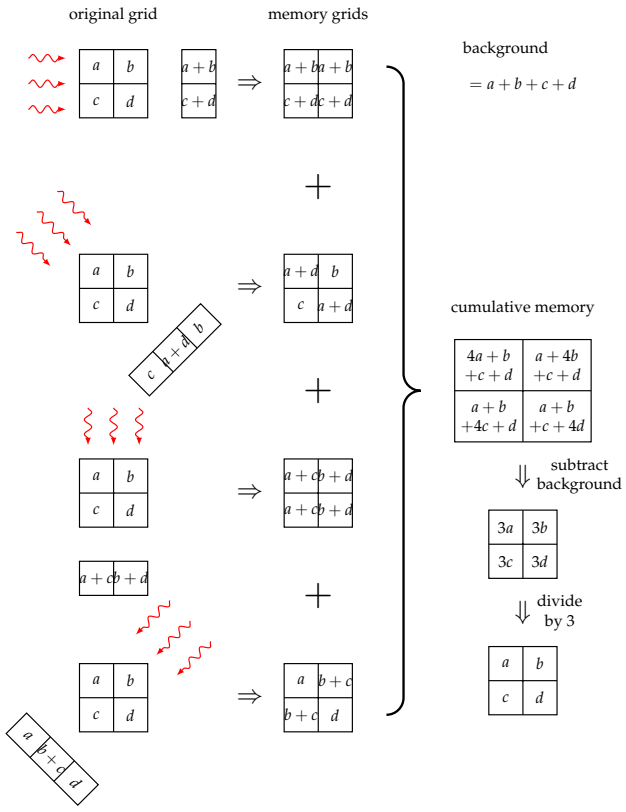
- **dosage**: X-rays are _____ and harmful, so keep exposure short. An _____ converts X-rays to light, then to electrons, and amplifies the image so a lower dose is needed.



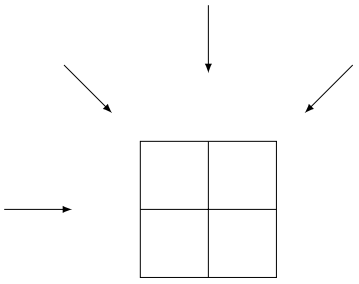
CT scans

- a conventional X-ray gives a _____: no information on _____. A _____ (computerised axial tomography) builds a _____ image.
- the body is treated as many 2D _____, each divided into a grid of _____. The X-ray tube rotates and exposes the slice from _____; detectors opposite measure the emergent intensities; a _____ deduces each voxel's attenuation. The slice images are combined into a 3D image.
- **advantages**: shows precise _____; can distinguish tissues with _____ μ
- **disadvantages**: more _____; _____ of radiation

Toy model: a 2×2 grid of voxels a, b, c, d is scanned from four directions. Each reading is stored in a memory grid, and the four grids are added. Each voxel then appears _____ times and each of the others once, so cumulative $= 3 \times (\text{voxel}) + (a+b+c+d)$. So: subtract the _____ $(a+b+c+d)$, then divide by ____.



Question 32.6 A 2×2 section is exposed from four directions (see figure). For any one direction, the detector readings total 19. The cumulative readings are shown. (a) Find the value of each pixel. (b) State the detector readings for each direction.



beam directions

34	28
40	31

cumulative reading

Question 32.7 By reference to the principles of CT imaging, suggest why the dose from a CT scan is greater than from a simple X-ray image.

Ultrasound scans

Nature of ultrasound

• sound is a _____, _____ wave: it needs a material _____. _____ has $f >$ _____ Hz (human hearing is about 20 Hz to 20 kHz).

• for a given medium the speed v is constant, and , so higher frequency means _____ wavelength and better _____: fine detail can be seen

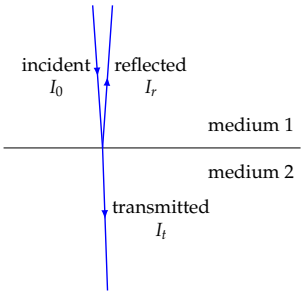
Question 32.8 Sound travels at 1600 m s^{-1} in soft tissue. Compare the wavelengths at (a) 500 Hz, (b) 10 MHz.

Production of ultrasound

- a _____ crystal vibrates when an _____ voltage is applied, producing ultrasound with $f_{\text{sound}} = f_{\text{a.c.}}$
- the amplitude is largest (_____) for crystal thickness $d =$ _____
- the same transducer _____ the echoes. After each pulse the vibration must _____, so a _____ (epoxy resin) is used. The parts: _____, _____, damping block, _____.

Attenuation and reflection of ultrasound

- intensity falls exponentially: _____ (α is the _____). Scans rely on _____ waves, so weak echoes from deep tissue are _____.

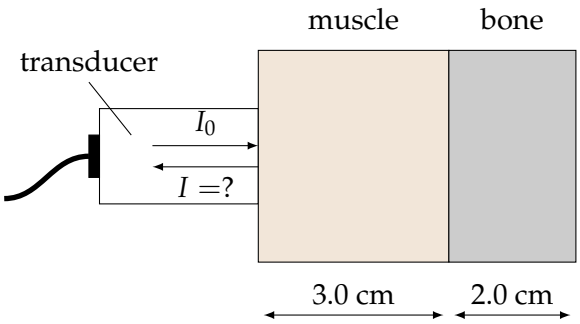


- at a boundary $I_0 =$ _____. For _____:

- the _____ of a medium: _____

(density × speed of sound)

Example 32.3 Air: $\rho = 1.29\ \text{kg m}^{-3}$, $c = 330\ \text{m s}^{-1}$. Soft tissue: $\rho = 1060\ \text{kg m}^{-3}$, $c = 1540\ \text{m s}^{-1}$. What happens when ultrasound goes from air into the body at right angles?



Example 32.4 An ultrasonic pulse of intensity I_0 enters a layer of muscle 3.0 cm thick, then reaches a muscle-bone boundary (bone 2.0 cm thick). Muscle: $c = 1600\ \text{m s}^{-1}$, $Z = 1.7 \times 10^6$, $\mu = 23\ \text{m}^{-1}$. Bone: $c = 4000\ \text{m s}^{-1}$, $Z = 6.4 \times 10^6$, $\mu = 130\ \text{m}^{-1}$ (Z in $\text{kg m}^{-2}\ \text{s}^{-1}$). (a) Find the intensity of the echo back at the muscle surface. (b) Find its arrival time.

Question 32.9 A gel has $Z = 1.65 \times 10^6$ kg m^{-2} s^{-1}. Using the soft-tissue value above, find the reflection coefficient from gel into the body, and hence explain why gel is used.

Question 32.10 Is it a good idea to use ultrasound to image the lungs? Give your reasons.

Question 32.11 In the muscle-bone example, a detector is coupled to the far side of the bone. What intensity would be measured?

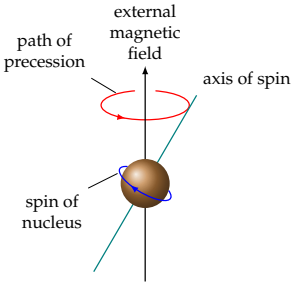
Ultrasound imaging

- _____ from a piezo-electric transducer enter the body and are _____ at boundaries. The _____ detects the echoes, and a computer builds the image.
- _____ gives the _____ of structures; echo _____ depends on Z and attenuation, so gives the _____ of structures
- **advantages**: _____ (no ionising radiation, can image a fetus); _____ images; _____; _____
- **disadvantages**: structures behind _____ or _____ are hard to image; needs a _____ operator

MRI

Nuclear magnetic resonance

• nuclei of some atoms have a property called _____: they behave like tiny _____



• **step 1: energy levels split.** With no field the orientations are _____ and have equal energy. In a strong field B_0 most nuclei line up _____ (low energy) and a few _____ (high energy).

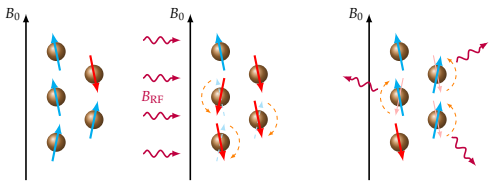
• **step 2: precession.** The spin axis is slightly tilted and _____ about the field direction at the _____:

(γ is the _____, which depends on the nucleus)

• **step 3: resonance.** _____ pulses at the Larmor frequency are applied. Low-energy nuclei _____ photons and flip to the higher state: _____.

Example 32.5 For protons $\gamma = 2.68 \times 10^8$ rad s^{-1}T^{-1}. What frequency of pulse causes resonance of hydrogen nuclei in a field of 1.8 T?

• **step 4: relaxation.** When the pulse stops the nuclei flip back and _____. The _____ depends on the surroundings, so it identifies the _____. Two processes:
_____ (T_1): energy passes to the surrounding _____;
_____ (T_2): energy passes to other spinning nuclei.



1. aligned in B_0 2. resonance with B_{RF} 3. relaxation: RF photons emitted

Magnetic resonance imaging

• a large _____ electromagnet gives a strong uniform field B_0; the nuclei align and precess at the _____

• _____ add a _____ field, so nuclei at different positions have different precession frequencies: this gives the _____

• _____ transmit pulses at the Larmor frequency; other RF coils _____ the signals emitted on relaxation. A computer builds the image. The _____ gives the _____ of the tissue.

• **advantages**: radio waves, so no known biological _____; good _____ between soft tissues; 3D images, any slice

• **disadvantages**: very _____ (superconducting coils at very low temperature); unsuitable with metal _____ or pacemakers; patient must lie _____; _____ show up poorly

Question 32.12 State the main components of an MRI scanner and describe their functions.