A LEVEL PHYSICS 9702 · A LEVEL · TOPIC 24 · ~5 MIN READ

Medical physics

Ultrasound production by piezoelectric crystals, acoustic impedance and reflection at boundaries, A-scans; X-ray production, attenuation and CT scanning; and PET scanning with tracers and electron–positron annihilation.

Piezoelectric transducers | Acoustic impedance Z = ρc | Intensity reflection coefficient | Coupling gel | Attenuation I = I$_o$e^{−μx} | X-ray production | Image sharpness & contrast | CT scanning

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Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **Ultrasound** (above 20 kHz, typically MHz) is made and detected by a piezoelectric crystal. Echoes from boundaries between tissues build up an image.
- **Reflection depends on acoustic impedance Z = ρc.** The intensity reflection coefficient is $(Z_2 - Z_1)^2/(Z_2 + Z_1)^2$: a big difference in Z means a strong echo.
- **X-rays and ultrasound are both attenuated exponentially:** $I = I_0e^{-\mu x}$.
- **PET:** a β^+ tracer emits positrons, which annihilate with electrons to produce two 511 keV γ-ray photons travelling in opposite directions.

BY THE END YOU CAN

- Explain the production and detection of ultrasound with a piezoelectric transducer.
- Use Z = ρc and the intensity reflection coefficient, and explain the need for a coupling gel.
- Use $I = I_0e^{-\mu x}$ for ultrasound and X-rays.
- Explain X-ray production, image sharpness and contrast, and CT scanning.
- Explain PET scanning, including tracers and annihilation.

1 Ultrasound

Production and reflection

- **Piezoelectric effect:** an alternating p.d. makes the crystal vibrate (emitter); returning pressure waves make it produce a p.d. (receiver). Pulses are sent and echoes timed.

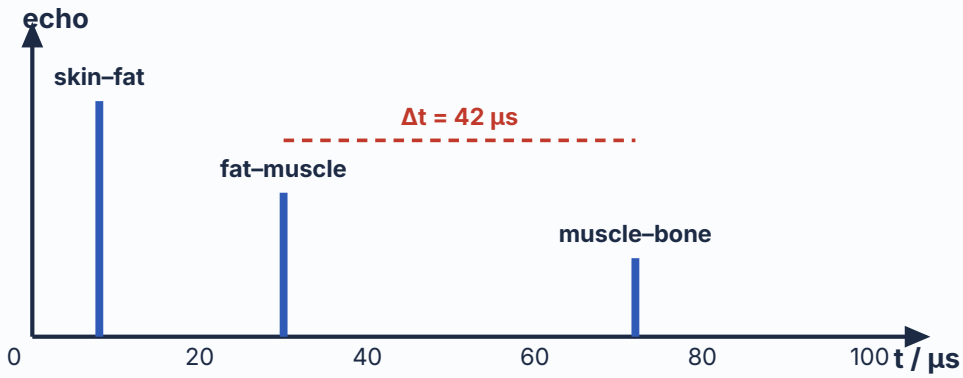
$$Z = \rho c \; ; \; I_R/I_0 = (Z_2 - Z_1)^2/(Z_2 + Z_1)^2$$ DATA & FORMULAE

c = speed of sound in the medium

WORKED EXAMPLE

Explain, with numbers, why gel is used. Z_{air} = 430 kg m^{-2} s^{-1}, $Z_{skin} = 1.7 \times 10^6$, $Z_{gel} = 1.5 \times 10^6$.

1. air–skin: $(1.7 \times 10^6 - 430)^2/(1.7 \times 10^6 + 430)^2$ = **0.999**, so almost all reflected C1 A1
2. **gel–skin: $(0.2/3.2)^2$ = 0.0039, so almost all transmitted** A1



Depth between boundaries = v × Δt/2 (the pulse goes there and back).

Smaller echoes: less reflected and more attenuated.

A-scan: each boundary gives an echo; the time delay gives the depth.

WORKED EXAMPLE

Echoes from two boundaries are 42 μs apart. The speed of sound in tissue is 1540 m s^{-1}. Find the distance between the boundaries.

1. distance = v × Δt/2 C1
2. **= 1540 × 42 × 10^{-6}/2 = 3.2 cm** A1

COMMON MISTAKE

Forgetting to halve the time (the pulse travels there and back).

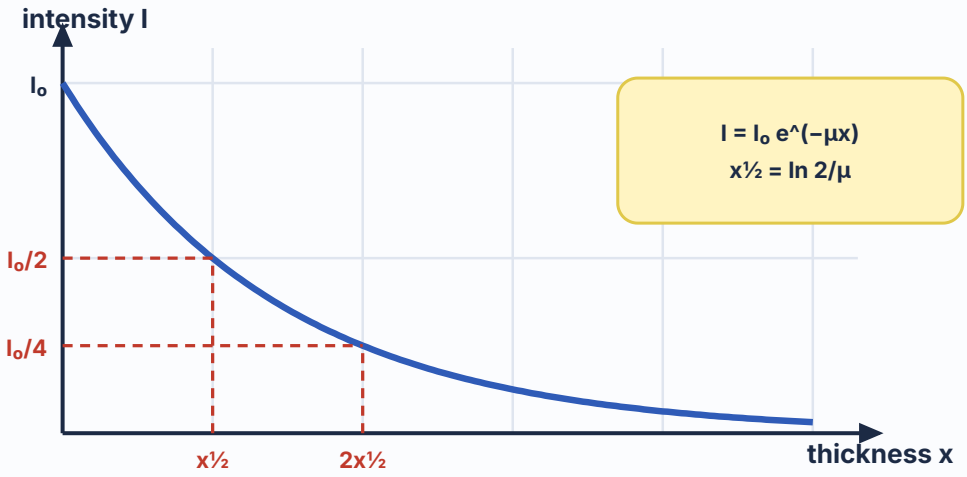
2 X-rays

Production and attenuation

- **Production:** electrons accelerated through a large p.d. hit a metal target (tungsten); a tiny fraction of their energy becomes X-rays (braking radiation plus characteristic lines). The maximum photon energy is eV.
- **Sharpness:** a small focal spot on the target. **Contrast:** large differences in μ between tissues (bone vs soft tissue), or a contrast medium.

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

μ = linear attenuation coefficient; half-value thickness $x_{½} = \ln 2/\mu$



X-ray attenuation: each half-value thickness halves the intensity.

Each half-value thickness halves the intensity.

WORKED EXAMPLE

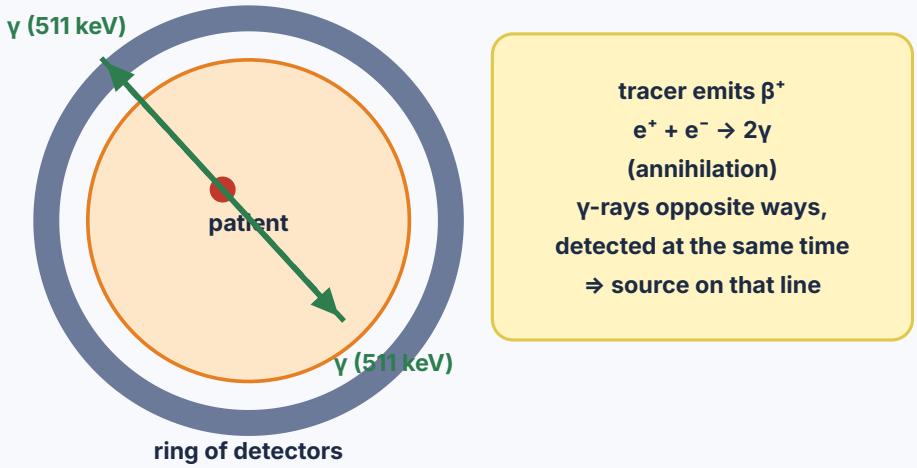
X-rays pass through 2.0 cm of bone with μ = 60 m^{-1}. Find the fraction transmitted and the half-value thickness.

1. $I/I_o = e^{-60 \times 0.020} = e^{-1.2} = 0.30$ C1 A1
2. $x_{½} = \ln 2/60 = 1.2$ cm A1

- **CT scanning:** an X-ray tube and detectors rotate around the patient, taking many images of a thin slice. A computer combines them into a 3D image built from voxels.

3 PET scanning

Tracers and annihilation



Two 511 keV photons leave in opposite directions; detecting both at once locates the source.

WORKED EXAMPLE

Show that each photon from electron–positron annihilation (at rest) has energy about 0.51 MeV, and find its wavelength.

1. $2mc^2$ shared between two photons, so $E = mc^2 = 9.11 \times 10^{-31} \times (3.00 \times 10^8)^2 = 8.2 \times 10^{-14}$ J C1
2. = **0.51 MeV** A1
3. **$\lambda = hc/E = 2.4 \times 10^{-12}$ m** A1

- **Tracer:** a β^+ emitter (e.g. fluorine-18 in a glucose-like molecule) collects where cells are most active. Short half-life keeps the dose low.
- **Why two photons in opposite directions:** momentum is conserved (it was about zero before annihilation).

COMMON MISTAKE

Saying the γ-rays come from the tracer. The tracer emits positrons; the γ-rays come from annihilation. 2024 Paper 4 candidates often missed this step.

LINKING QUESTION

Exponential attenuation matches the decay equations in Nuclear physics; β^+ decay and antiparticles are in Particle physics; and photon energies are in Quantum physics.

Test yourself — cover the answers first

QUICK CHECK

1. What does a piezoelectric crystal do in an ultrasound probe?
2. Define acoustic impedance.
3. Why is coupling gel used?
4. What particle does a PET tracer emit?
5. Find the half-value thickness for $\mu = 0.35$ cm^{-1}.

EXAM-STYLE

6. Muscle has $\rho = 1080$ kg m^{-3} and $c = 1580$ m s^{-1}. Find Z.
7. X-ray intensity falls to 20% through 3.0 cm of tissue. Find μ.
8. An X-ray tube uses an accelerating p.d. of 80 kV. Find the minimum wavelength produced.

Show answers

1. converts an alternating p.d. into vibrations, and echoes back into a p.d.
2. $Z = \rho c$ (density × speed of sound)
3. to avoid almost total reflection at the air–skin boundary
4. a positron (β^+)
5. 1.98 cm
6. 1.71×10^6 kg m^{-2} s^{-1}
7. $\ln 5/0.030 = 54$ m^{-1}
8. $E = 80$ keV $= 1.28 \times 10^{-14}$ J ⇒ $\lambda = hc/E = 1.55 \times 10^{-11}$ m

Stuck on a question?

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