HL Paper 3

This question is about the use of ultrasound for diagnostic imaging.

a. Outline how ultrasound is produced for use in diagnostic imaging. [3]

b. In order to look for damage to the chambers of the heart, ultrasound is used to form an image of the heart. [2]

Suggest why it is better to use ultrasound rather than X-rays.

c. The speed of sound in skin is about five times the speed of sound in air. Given that the density of skin is about 700 times that of the density of air, compare the acoustic impedance of skin to that of air. [2]

d. Explain, using your answer to (c), why, in using ultrasound for imaging, a layer of gel is placed between the transducer and the skin. [2]

e. A wide range of frequencies of ultrasound may be used to image internal body organs. The choice of frequency for imaging a particular organ is determined by the depth of the organ beneath the skin. [4]

Outline, with reference to attenuation and resolution, why the depth of the organ determines the choice of ultrasound frequency.

Markscheme

a. an electric field applied along the axis of a piezoelectric crystal causes the crystal to expand or contract;

a high frequency alternating E field will cause the crystal to oscillate at the frequency of the applied field;

the oscillations are transferred to the surrounding air producing ultrasound;

b. no contrast between heart and surroundings as X-rays will not be absorbed by the heart;

ultrasound will be reflected/transmitted by different amounts by the slightly differing densities and depths of the heart tissue;

Do not accept answers based on "X-rays are harmful".

c. acoustic impedance=speed of sound×density;

acoustic impedance of skin=5×700=3500×acoustic impedance of air;

d. acoustic impedance of skin is very much greater than that of air so nearly all incident ultrasound is reflected at air/skin boundary;

gel has same acoustic impedance as skin so nearly all ultrasound will be transmitted through the skin;

e. high frequency ultrasound gives better resolution;

but is subject to more attenuation;

the further the distance the ultrasound travels the more it is attenuated;

the deeper an organ therefore the lower the frequency used in order to minimize attenuation / a compromise has to be made between resolution and attenuation;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]
e. [N/A]

This question is about medical imaging.

A patient is suspected of having a partial blockage in his intestine as it leads away from his stomach. Possible medical imaging techniques include X-ray photography, ultrasound and the use of an endoscope.

a. When producing the X-ray photograph, the dose is kept to a minimum by a technique called enhancement. [6]

(i) Outline why the dose needs to be kept to a minimum.

(ii) Describe **one** possible enhancement technique.

(iii) Discuss any extra procedures that are needed to get an appropriate image of the intestine in this situation.

b. A successful ultrasound scan relies on changes of acoustic impedance around the structure being imaged. [4]

(i) Define *acoustic impedance*.

(ii) State the SI unit in which it is measured.

(iii) Explain, in terms of acoustic impedance, why gel needs to be applied on the surface of the skin before the ultrasound scan.

Markscheme

a. (i) X-rays cause ionisations;

which could cause cell damage / increased risk of cancer;

(ii) intensifying screen placed next to the film;
X-rays absorbed by screen and energy re-radiated as light to film;

(iii) barium meal;
to increase contrast between inside and outside the intestine;

b. (i) density of material×speed of ultrasound in material;

(ii) $kg m^{-2} s^{-1}$;

(iii) strong reflections take place where there is a large change in acoustic impedance;
gel eliminates air gap between source/receiver of ultrasound and skin surface / acoustic impedance of gel matches that of skin (and source/receiver);

Examiners report

a. [N/A]
b. [N/A]

This question is about X-rays.

a. Define *half-value thickness*. [1]

b. The half-value thickness in tissue for X-rays of a specific energy is 3.50 mm. Determine the fraction of the incident intensity of X-rays that has been transmitted through tissue of thickness 6.00 mm. [3]

c. For X-rays of higher energy than those in (b), the half-value thickness is greater than 3.50 mm. State and explain the effect, if any, of this change on your answer in (b). [2]

Markscheme

a. the distance after which the intensity of the incident X-rays gets reduced to half;

b. $\mu = \left(\frac{\ln 2}{x_{\frac{1}{2}}} = \frac{\ln 2}{3.50} =\right)\ 0.198\ \text{mm}^{-1}$;

$\frac{I}{I_0} = \left(e^{-\mu x} =\right) e^{-1.98 \times 6.00}$;

$\frac{I}{I_0} = 0.305$;

or

X-rays travel $\frac{6}{3.5}$ $(= 1.71)$ half thicknesses;

$I = I_0\left[\frac{1}{2}\right]^{1.71}$;

$\frac{I}{I_0} = 0.350$;

c. it will be larger;

because a larger half-value thickness implies a smaller attenuation coefficient and so a smaller reduction in intensity;

or

X-rays travel further before their energy is reduced by a given factor;

hence intensity is greater;

Examiners report

a. Most candidates were able to correctly define half-value thickness.

b. Many candidates had problems with exponentials.

c. Many candidates had problems with exponentials in (b) and so were not able to answer part (c) sensibly.

The attenuation values for fat and muscle at different X-ray energies are shown.

Energy of X-rays / keV	Fat attenuation coefficient / cm^{-1}	Muscle attenuation coefficient / cm^{-1}
1	2030.9767	3947.2808
5	18.4899	43.8253
10	2.3560	5.5720
20	0.4499	0.8490

a. Outline the formation of a B scan in medical ultrasound imaging. [3]

b.i. State what is meant by half-value thickness in X-ray imaging. [1]

b.ii A monochromatic X-ray beam of energy 20 keV and intensity I_0 penetrates 5.00 cm of fat and then 4.00 cm of muscle. [3]

Calculate, in terms of I_0, the final beam intensity that emerges from the muscle.

b.iii Compare the use of high and low energy X-rays for medical imaging. [3]

Markscheme

a. many/array of transducers send ultrasound through body/object

B scan made from many A scans in different directions

the reflection from organ boundaries gives rise to position

the amplitude/size gives brightness to the B scan

2D/3D image formed «by computer»

[3 marks]

b.i. the thickness of tissue that reduces the intensity «of the X-rays» by a half

OR

$x_{\frac{1}{2}} = \frac{\ln 2}{\mu}$ where $x_{\frac{1}{2}}$ is the half value thickness and μ is attenuation coefficient

Symbols must be defined for mark to be awarded

[1 mark]

b.ii after fat layer, $I_{fat} = I_0 e^{-0.4499 \times 5.00}$

after muscle layer, $I = I_{fat} e^{-0.8490 \times 4.00}$

$I = 0.003533\ I_0$ ***or*** 0.35%

[3 marks]

b.iii «high energies factors:»

less attenuation/more penetration

more damage to the body

«so» stronger signal leaves the body

OR

«so» used in «most» medical imaging techniques

«low energy factors:»

must be used with enhancement techniques

greater attenuation/less penetration

«so» more damage to the body «on surface layers»

OR

«so» unwanted in «most» medical imaging techniques

[3 marks]

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]
b.iii. [N/A]

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a. State **one** advantage and **one** disadvantage of magnetic resonance imaging (MRI) compared to X-ray imaging. [2]

b. Explain why a gradient field is required in nuclear magnetic resonance (NMR) imaging. [3]

Markscheme

a. *Advantage:*

no ionizing radiation ***OR*** high res images of soft tissue ***OR*** 3D images

Disadvantage:

«generally» more expensive ***OR*** takes much longer ***OR*** less detail of bony structures «than X-ray» ***OR*** noisy for patient ***OR*** claustrophobic for patient ***OR*** cannot be used for patients with metal implants

Do not accept advantages that are also true of X-rays, eg non-invasive.

b. a gradient field is added to a magnetic field that is originally uniform across patient

the gradient field varies linearly across patient

as the protons relax a «radio frequency» signal is emitted

the emitted signal frequency is proportional to the total strength of the magnetic field

the signal frequency depends on the emission position in the patient

Examiners report

a. [N/A]
b. [N/A]

---

a. State the property of protons used in nuclear magnetic resonance (NMR) imaging. [1]

b. Explain how a gradient field and resonance are produced in NMR to allow for the formation of images at a specific plane. [3]

Markscheme

a. «proton» spin

b. strong B field applied to align proton spins

OWTTE

cross-field applied to give gradient field
OR
each point in a plane has a unique B

RF field excites spins

protons emit RF at resonant/Larmor frequency dependent on Total B field

RF detected shows position in the plane / is used to form 2D images

Allow features to be mentioned in any order

Examiners report

a. [N/A]
b. [N/A]

The density of muscle is 1075 kg m^{-3} and the speed of ultrasound in muscle is 1590 m s^{-1}.

a. State a typical frequency used in medical ultrasound imaging. [1]

b. Describe how an ultrasound transducer produces ultrasound. [3]

c.i. Calculate the acoustic impedance Z of muscle. [1]

c.ii. Ultrasound of intensity 0.012 W cm^{-2} is incident on a water–muscle boundary. The acoustic impedance of water is 1.50 x 10^6 kg m^{-2} s^{-1}. [2]

The fraction of the incident intensity that is reflected is given by

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

where Z_1 and Z_2 are the acoustic impedances of medium 1 and medium 2.

Calculate the intensity of the reflected signal.

Markscheme

a. accept any value between 1 MHz to 20 MHz

[1 mark]

b. an alternating electrical signal is applied to a crystal

crystal vibrates emitting sound

frequency of vibration of crystal is the same as the frequency of the ac

mention of piezoelectric effect/crystal

[3 marks]

c.i. Z_{muscle} = 1.71 x 10^6 «kgm^{-2} s^{-1}»

[1 mark]

c.ii. «$\frac{I_2}{I_1} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$» = 4.3 x 10^{-3}

I_2 = «0.012 x (4.3 x 10^{-3}) =» 5.1 x 10^{-5} «W cm^{-2}»

Allow ECF from (c)(i).

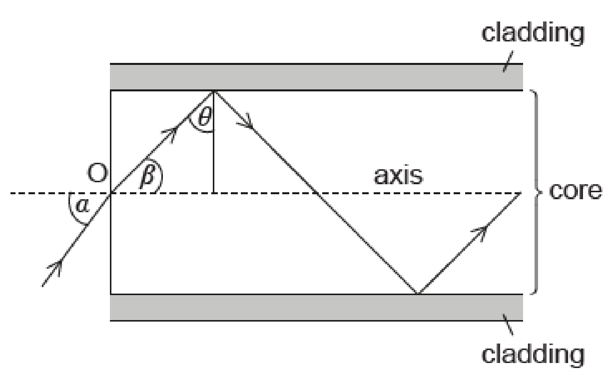
Allow ECF from MP1 to MP2.

[2 marks]

Examiners report

a. [N/A]
b. [N/A]
c.i. [N/A]
c.ii. [N/A]

Some optic fibres consist of a core surrounded by cladding as shown in the diagram.



a. Calculate the maximum angle β for light to travel through the fibre. [3]

Refractive index of core = 1.50
Refractive index of cladding = 1.48

b. Outline how the combination of core and cladding reduces the overall dispersion in the optic fibres. [3]

Markscheme

a. realization that θ min is the critical angle

θ = «$\sin^{-1}\frac{1.48}{1.5}$ =» 80.6 «°»

Accept 1.4 rad

β = «90 – 80.6 =» 9.4 «°»

Accept 0.16 rad

b. because the critical angle is nearly 90°

then only rays that are «almost» parallel to the fibre pass down it

so pulse broadening is reduced

OWTTE

Examiners report

a. [N/A]
b. [N/A]

The table shows the speed of ultrasound and the acoustic impedance for different media.

	speed of ultrasound / $m\,s^{-1}$	acoustic impedance / $kg\,m^{-2}\,s^{-1}$
air	3.33×10^2	4.30×10^2
gel	1.48×10^3	1.48×10^6
skin	1.73×10^3	1.99×10^6

The fraction F of the intensity of an ultrasound wave reflected at the boundary between two media having acoustic impedances Z_1 and Z_2 is given by F = $\frac{(Z_1-Z_2)^2}{(Z_1+Z_2)^2}$.

a. Outline how ultrasound is generated for medical imaging. [2]

b. Describe **one** advantage and **one** disadvantage of using high frequencies ultrasound over low frequencies ultra sound for medical imaging. [2]

Advantage: ....

....

Disadvantage: ....

....

c. Suggest **one** reason why doctors use ultrasound rather than X-rays to monitor the development of a fetus. [1]

d.i. Calculate the density of skin. [1]

d.ii. Explain, with appropriate calculations, why a gel is used between the transducer and the skin. [4]

Markscheme

a. crystal vibration /piezo-electric effect

caused by an alternating potential difference is applied across a crystal

[2 marks]

b. ***ADVANTAGES***

the wavelength must be less than the size of the object being imaged to avoid diffraction effects

the frequency must be high to ensure several full wavelengths in the pulse

DISADVANTAGES

the depth of the organ being imaged must be considered (no more than 200 wavelengths)

attenuation increases at higher frequencies

[1] *for advantages,* ***[1]*** *for disadvantages.*

[2 marks]

c. X-rays are an ionizing radiation and so might cause harm to the developing fetus.

OR

there are no known harmful effects when using ultrasound

Ignore “moving images by ultrasound”.

[1 mark]

d.i. $\rho = \frac{1.99\times10^6}{1.73\times10^3} = 1.15\times10^3$ «kgm^{-3}»

[1 mark]

d.ii. $F = \frac{(1.99\times10^6-4.3\times10^2)^2}{(1.99\times10^6+4.3\times10^2)^2} = 1.0$

$F = \frac{(1.48\times10^6-1.99\times10^6)^2}{(1.48\times10^6+1.99\times10^6)^2} = 0.02$

almost 100% of the ultrasound will be reflected from the air-skin surface ***OR*** almost none is transmitted

whereas only 2% will be reflected from the gel-skin surface and so a much greater proportion is transmitted

Need to explain that more is transmitted through gel-skin surface for MP4.

[4 marks]

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d.i. [N/A]
d.ii. [N/A]

This question is about nuclear magnetic resonance (NMR).

In nuclear magnetic resonance imaging, the patient is placed in a large uniform magnetic field. In addition, the part of the patient under investigation is subject to a weaker non-uniform (gradient) field.

Explain the role of these two fields in the imaging process.

Markscheme

strong field causes protons (in the body) to precess/align with the field;

gradient magnetic field applied so that magnetic field at every point in the body is different;

radio frequency radiation directed at the body excites protons (to a higher energy state);

frequency emitted (by de-exciting protons) depends on magnetic field;

frequency determines point of emission (since different parts of the body correspond to different frequency);

intensity of radiation/relaxation times depend on type of tissue (so that contrast can be achieved);

Examiners report

In nuclear magnetic resonance (NMR) imaging radio frequency electromagnetic radiation is detected by the imaging sensors. Discuss the origin of this radiation.

Markscheme

«strong» magnetic field aligns proton «spins»

an RF signal is applied to excite protons
OR
change spin up to spin down state

protons de-excite/return to lower energy state
OR
proton relaxation occurs

with emission of RF radiation «that is detected»

OWTTE

Treat any mention of the following as neutral as they are not strictly relevant to the question:
gradient field, Larmor frequency, precession, resonance, 3-D image

[3 marks]

Examiners report

[N/A]

This question is about transmission of digital signals in an optic fibre.

The input power to a single optic fibre X is 25 mW. The signal needs to be amplified when the power has been attenuated to 4.0 ×10^{-19} W. The attenuation loss in the optic fibre is 1.8 dB km^{-1}.

Calculate the maximum distance between amplifiers in the system.

Markscheme

$\frac{I}{I_0} = 101\text{g}\left[\frac{25\times10^{-3}}{4\times10^{-19}}\right] (= 168);$

$\frac{168}{1.8};$

93 km;

Examiners report

This question is about X-rays.

(i) X-rays travelling in a medium experience attenuation. State what is meant by attenuation.

(ii) Show that the half-value thickness $x_{\frac{1}{2}}$ is related to the attenuation coefficient μ by

$$\mu x_{\frac{1}{2}} = 1\text{n}2$$

(iii) Estimate the fraction of the incident intensity of an X-ray beam that has travelled through 2.0 cm of muscle. The half-value thickness of muscle is 0.73 cm.

Markscheme

(i) the absorption of energy/loss of power from the beam;

(ii) correct substitution $\frac{I_0}{2} = I_0 e^{-\mu x_{\frac{1}{2}}};$
taking natural logs $1\text{n}\frac{1}{2} = -\mu x_{\frac{1}{2}};$
$\left(1\text{n}2 = \mu x_{\frac{1}{2}}\right)$
Answer given, marks are for correct working.

(iii) $\mu = \left(\frac{1\text{n}2}{0.73} =\right) 0.95\text{cm}^{-1};$
$I = \left(I_0 e^{-0.95\times2.0} =\right) 0.15 I_0;$

or

number of half-value thicknesses $= \frac{2}{0.73} = 2.74$;
$I = 0.5^{2.74} = 0.15 I_0$;
*Award **[2]** for a bald correct answer.*

Examiners report

Part (a) contains two standard questions and was well answered. In comparing the processes of computed tomography (CT) and conventional X-ray imaging many candidates did well. Common problems included not mentioning the fact that CT images are taken at all angles during rotation and that CT involves a far greater absorbed dose.

This question is about nuclear magnetic resonance (NMR) imaging.

a. Outline the physical principles of NMR imaging. [5]

b. State **two** advantages of NMR imaging over computed tomography (CT) imaging. [2]

1.

2.

Markscheme

a. a magnetic field is applied (*eg* to a patient);

protons/H nuclei (in patient) have spin/magnetic moment;

which align with the field / have different energy levels;

a radio frequency (RF) field (at resonant/Larmor frequency) is turned on;

which changes the spin orientation/energy levels;

the protons/nuclei then emit an RF pulse (as they de-excite);

which is detected to determine the position of the proton/nuclei;

b. no exposure to harmful radiation;

better quality image;

Examiners report

a. Both parts of this question were answered very well. It is clear that previous questions on NMR imaging have reaped benefits as now the majority can list most of the main physical principles involved.

b. Both parts of this question were answered very well. It is clear that previous questions on NMR imaging have reaped benefits as now the majority can list most of the main physical principles involved.

This question is about the use of ultrasound.

a.i. Define *acoustic impedance*. [1]

a.ii. State the significance of acoustic impedance in the use of ultrasound techniques. [1]

b. Medical practitioners select the frequency of the ultrasound depending on the diagnosis they are undertaking. Outline the importance of using ultrasound of the appropriate frequency. [3]

Markscheme

a.i. product of the density of a substance and the speed of sound in that substance;

a.ii. if impedance is not matched, large percentage of energy loss at interface;

difference in acoustic impedances necessary for imagery/reflection from organs;

b. attenuation increases with frequency / deeper objects require lower frequencies;

resolution increases with frequency;
balance required between energy loss/attenuation and image quality/resolution;

Examiners report

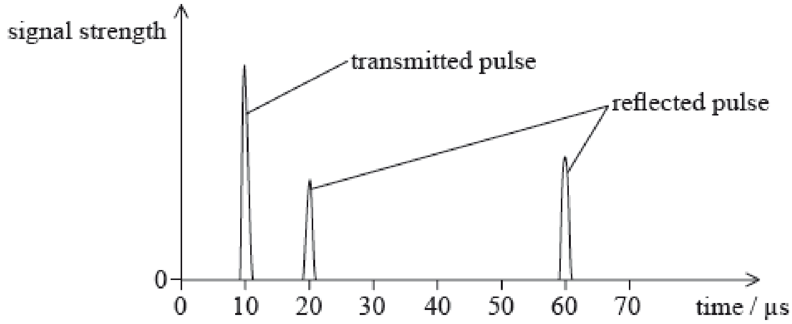
a.i. Often well answered with clear outlying of the frequency appropriateness in different depths of organs displayed.

a.ii. Often well answered with clear outlying of the frequency appropriateness in different depths of organs displayed.

b. Often well answered with clear outlying of the frequency appropriateness in different depths of organs displayed.

This question is about ultrasound.

An ultrasound pulse is transmitted into the body of a patient. The pulse is partially reflected at a fat–muscle boundary and then, deeper in the body, at a muscle–bone boundary. The graph shows the variation with time of the signal strength at the transducer.



Muscle has density $1.08 \times 10^3\ \mathrm{kg\,m^{-3}}$ and acoustic impedance $1.70 \times 10^6\ \mathrm{kg\,m^{-2}s^{-1}}$.

a. Define *acoustic impedance* [1]

b. (i) Calculate the speed of ultrasound in muscle. [4]

(ii) Determine the thickness of the muscle layer in the patient.

c. State **one** advantage and **one** disadvantage of using ultrasound of frequency 1 MHz, rather than 3 MHz, in medical diagnosis. [2]

Advantage:

Disadvantage:

Markscheme

a. product of density of the substance and the speed of <u>sound</u> in that substance;

b. (i) $c = \left(\frac{1.70 \times 10^6}{1.08 \times 10^3} =\right)\ 1570\ (\mathrm{m\,s^{-1}})$;

(ii) read-off to yield time of $40 \times 10^{-6}\ (\mathrm{s})$;

travel time $= 20 \times 10^{-6}\ (\mathrm{s})$;

thickness $= \left(1570 \times \frac{40 \times 10^{-6}}{2} =\right)\ 3.1\ (\mathrm{cm})$ ***or*** 3.2 (cm);

Award ***[3]*** *for a bald correct answer.*

Award ***[2 max]*** *for answer of 6.2 (cm) or 6.3 (cm).*

c. *advantage*: greater penetration / less attenuation / can scan organs at greater depth;

disadvantage: less resolution / image has less detail / image less sharp;

Examiners report

a. (a) was an easy mark, but many were not specific about the values relating to a particular medium.

b. (b)(i) was another easy mark but the calculation of muscle thickness in (ii) was error prone. Many candidates forgot to halve the time difference between the reflected pulses. ECF marking was often required.

c. (c) was done reasonably well, but with quite a few getting the advantages and disadvantages confused.

This question is about medical imaging using X-rays.

The table shows the attenuation coefficient μ (mu) for different parts of the body.

μ_{air}	$0\ cm^{-1}$
μ_{muscle}	$0.180\ cm^{-1}$
μ_{blood}	$0.178\ cm^{-1}$
μ_{bone}	$0.48\ cm^{-1}$

An X-ray scan is taken of a patient to examine the flow of blood through their arm. X-rays of intensity I are incident on an equal thickness of blood and muscle. The intensity of the X-rays is measured after passing through the blood and muscle respectively.

a.i. Define *attenuation coefficient*. [1]

a.ii. Calculate the half-value thickness for blood. [2]

b.i. Calculate the ratio $\frac{I_{\text{blood}}}{I_{\text{muscle}}}$ for 1 cm of tissue. [2]

b.ii. Suggest why an X-ray scan does not allow for the differentiation between muscle and blood. [2]

c. A contrast medium containing iodine is injected into the patient. This increases the attenuation coefficient of blood so that the difference between the intensities of blood and muscle is greater than 2%. The blood can now be observed on an X-ray scan. Determine the minimum increase in μ_{blood} that will enable a sharper contrast to be observed between an equal thickness of muscle and blood. [3]

d. X-rays are a form of ionizing radiation. To reduce the danger to a patient, the intensity of X-rays are kept to a minimum. Describe how enhancement allows for low intensity X-rays to be used. [2]

Markscheme

a.i. probability of a single photon being absorbed in 1 m of the material / reference to $I = I_{\text{o}}\text{e}^{-\mu x}$ with symbols defined;

a.ii. $x_{\frac{1}{2}} = \frac{\ln 2}{\mu}$;

$= 3.89\text{ cm};$

b.i. $\frac{I_{\text{blood}}}{I_{\text{muscle}}} = \frac{I_0 e^{-\mu_{\text{blood}} x}}{I_0 e^{-\mu_{\text{muscle}} x}} = \frac{e^{-0.178x}}{e^{-0.180x}};$

$e^{0.002} = 1.002;$

b.ii. the difference between the intensities is only around 0.2%/less than that (2%) required to provide sufficient contrast between the muscle and the blood;

this is too small to provide a clear difference on the X-ray film;

c. ratio needs to be 0.98 to show a sharp contrast;

$e^{(0.180 - \mu_{\text{blood}})} = 0.98;$

so $\mu_{\text{blood}} = 0.2$ / increase of around 0.02;

d. low intensity X-rays would not provide sufficient contrast between neighbouring tissues;

enhancement shows a clearer difference in the image;

Examiners report

a.i. In (a) the definition of physical quantities was better than in previous years.

a.ii. In (a) the definition of physical quantities was better than in previous years.

b.i. In (b)(i), the majority of candidates calculated the ratio of blood/muscle intensities.

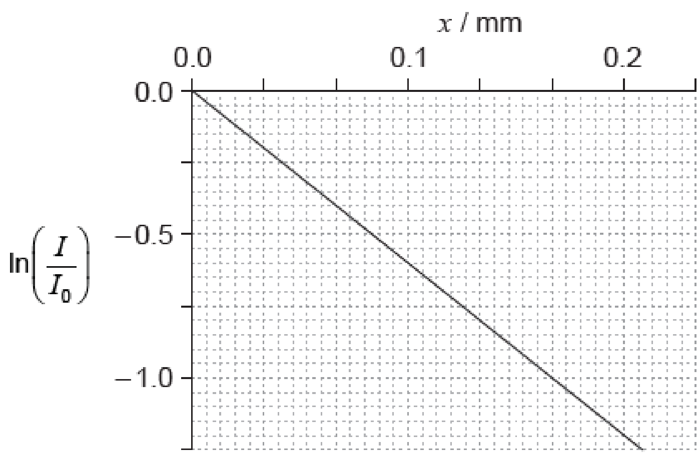
b.ii. In (b)(ii) some candidates did not read the question and answered in terms of blood instead of bone, but better candidates realised that muscle/bone resolution for X-rays is properly and widely used in medical imaging.

c. In (c) the better candidates applied knowledge in a quite complex situation.

d. In (d), the better candidates wrote clear answers. Only some candidates described the mechanism of enhancement instead of the role of it.

An X-ray beam of intensity I_0 is incident on lead. After travelling a distance *x* through the lead the intensity of the beam is reduced to *I*.

The graph shows the variation of $\ln\left(\frac{I}{I_0}\right)$ with *x*.



a. Show that the attenuation coefficient of lead is 60 cm^{-1}. [2]

b. A technician operates an X-ray machine that takes 100 images each day. Estimate the width of the lead screen that is required so that the total exposure of the technician in 250 working days is equal to the exposure that the technician would receive from one X-ray exposure without the lead screen. [2]

Markscheme

a. evidence of finding the gradient

μ = «– gradient =» 59.9 «cm^{-1}»

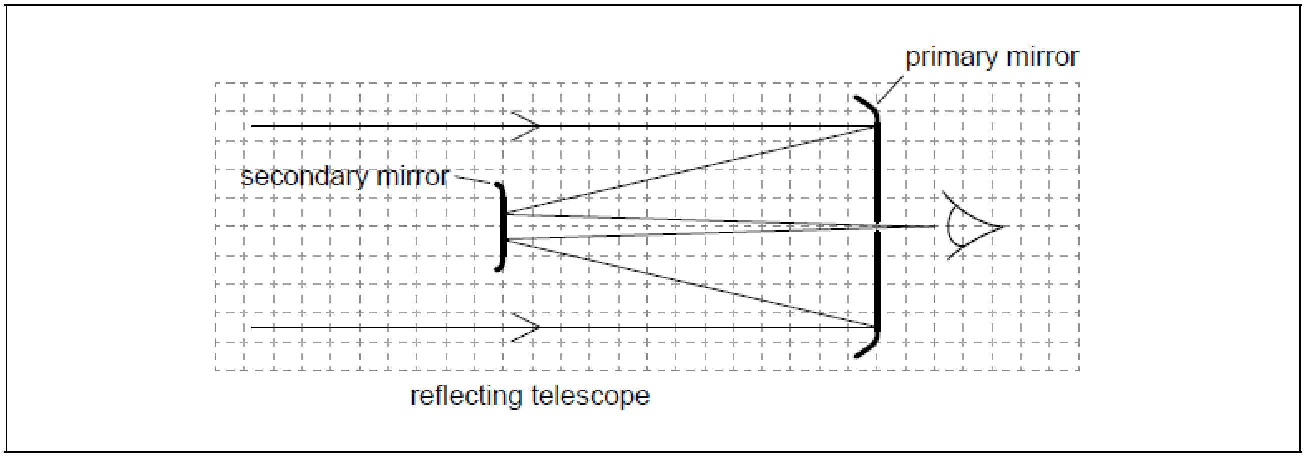
b. $I = \frac{I_0}{25000}$

«ln25000 = μx» x = 0.17 «*cm*» ***or*** 1.7 «mm»

Examiners report

a. [N/A]
b. [N/A]

The diagram represents a simple optical astronomical reflecting telescope with the path of some light rays shown.



It is proposed to build an array of radio telescopes such that the maximum distance between them is 3800 km. The array will operate at a wavelength of 2.1 cm.

Comment on whether it is possible to build an optical telescope operating at 580 nm that is to have the same resolution as the array.

Markscheme

«use of $\frac{1.22\lambda}{d}$ to get» resolution of 6.7 × 10^{-9} «rad»

$\frac{5.8\times10^{-7}}{6.7\times10^{-9}}$ = 87 «m»

some reference to difficulty in making optical mirrors/lenses of this size

Allow $\frac{5.8\times10^{-7}}{5.5\times10^{-9}}$ *= 105 «m»*

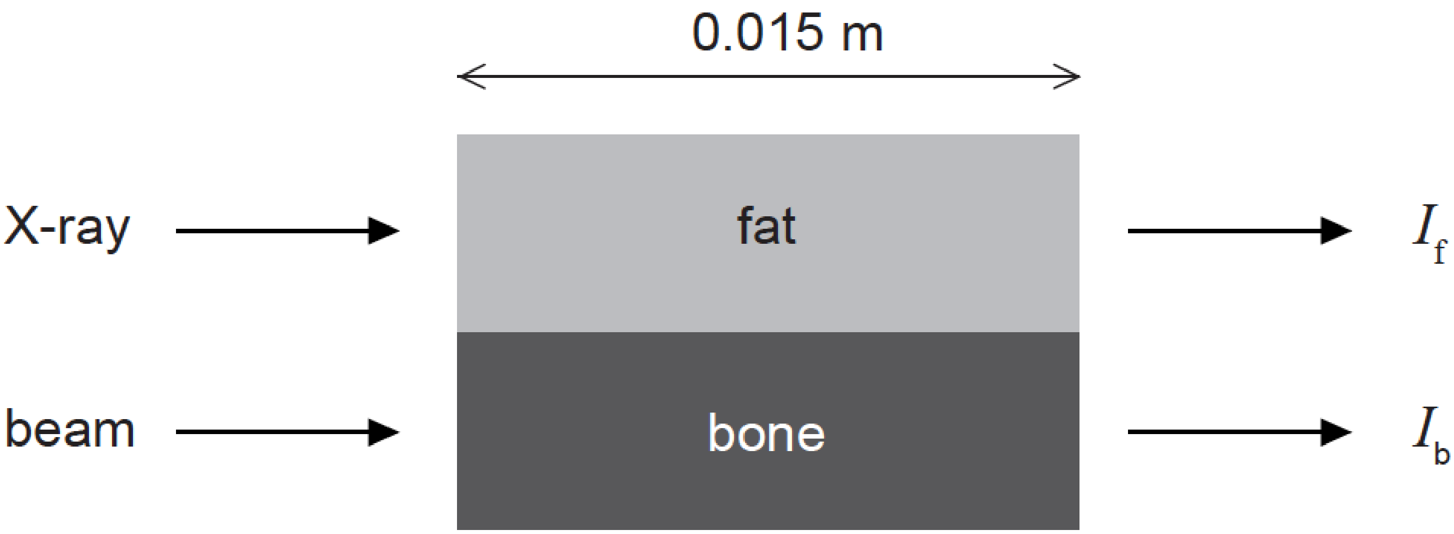
[3 marks]

Examiners report

[N/A]

This question is about X-rays.

a. Two parallel beams of monochromatic X-rays of the same intensity are incident on equal thicknesses of bone and fat in a patient. [3]



The attenuation coefficient for fat is 180m^{-1} and the attenuation coefficient for bone is 345m^{-1}. The thickness of both materials is 0.0150m.

Calculate $\frac{I_b}{I_f}$ where I_b is the intensity of the beam leaving the bone and I_f is the intensity of the beam leaving the fat.

b. Explain how fluorescent emitters are used to enhance the image formed on a photographic X-ray plate. [3]

Markscheme

a. $\frac{I_b}{I_f} = \frac{e^{-\mu_b x}}{e^{-\mu_f x}}$;

$=e^{-0.0150\times165}$;

0.0842;

*Award **[3]** for a bald correct answer.*

b. fluorescent emitters are placed each side of the photographic plate;

X-rays cause emission of (visible) light from the fluorescent material that causes (additional) plate exposure;

better contrast because many X-rays pass through plate without interaction / photographic plate is more sensitive to visible light than to X-rays;

Examiners report

a. [N/A]
b. [N/A]

This question is about X-rays.

a. Define the *attenuation coefficient* as applied to a beam of X-rays travelling through a medium. [2]

b. Derive the relationship between the attenuation coefficient μ and the half-value thickness $x_{\frac{1}{2}}$. [2]

c. Aluminium is often used to filter out the low energy X-rays in a beam of X-rays. The following data are available for a particular X-ray beam. [3]

X-ray energy / keV	half-value thickness of aluminium / mm
15	0.70
30	3.5

Assuming equal initial intensities, determine, after the X-ray beam has passed through an aluminium sheet 6.0 mm thick, the following ratio.

$$\frac{\text{intensityof15keVX} - \text{rays}}{\text{intensityof30keVX} - \text{rays}}$$

d. Outline why X-rays are not suitable to image an organ such as the liver. [2]

Markscheme

a. the intensity of the beam *I* falls by a constant amount d*I* through each distance d*x* travelled such that;

$\frac{dI}{I} = -\mu \mathrm{d}x$ where μ is the attenuation coefficient;

or

$I=I_0e^{-\mu x}$ where I_0 is the intensity of the beam as it enters the medium;
I is the intensity after the beam has travelled a distance *x* in the medium and *μ* is the attenuation coefficient;

or

the probability per unit length;
that a photon will be absorbed;

b. $I = \frac{I_0}{2} = I_0 e^{-\mu x_{\frac{1}{2}}}$ so $e^{-\mu x_{\frac{1}{2}}} = \frac{1}{2}$;

$\mu = \frac{\ln 2}{x_{\frac{1}{2}}}$;

c. *μ* for 15keV = $\left(\frac{\ln 2}{0.7} =\right) 1.0\text{mm}^{-1}$ and *μ* for 30keV = $\left(\frac{\ln 2}{3.5} =\right) 0.20\text{mm}^{-1}$;
$\left(\frac{\text{intensityof15(keV)X}-\text{rays}}{\text{intensityof30(keV)X}-\text{rays}}\right) = \frac{I_0 e^{-1.0\times6.0}}{I_0 e^{-0.2\times6.0}}$;
$=8.2\times10^{-3}$;

Allow similar approach using half value thickness directly in the exponent, without intermediate calculation of μ, to find ratio.

Without the same rounding error this gives 8.6×10^{-3}.

Award ***[3]*** *for a bald correct answer between 8.0 and* 8.6×10^{-3}.

d. the attenuation coefficient of the liver and of the surrounding tissue for the X-rays have approximately the same value;

so no contrast can be obtained between liver and surrounding tissue / liver cannot be distinguished from surrounding tissue;

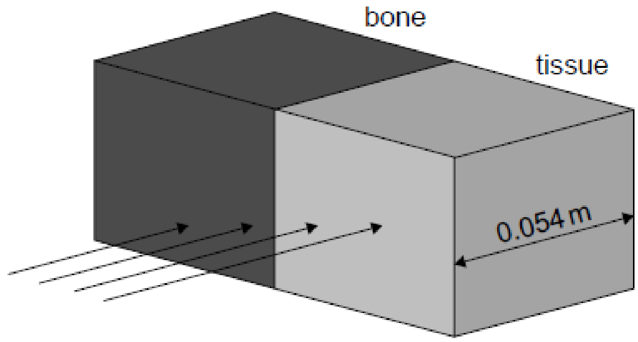
Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]

In the context of nuclear magnetic resonance (NMR) imaging explain the role of

a. Outline why the fracture in a broken bone can be seen in a medical X-ray image. [2]

b. The diagram shows X-rays incident on tissue and bone. [3]



The thicknesses of bone and tissue are both 0.054 m.

The intensity of X-rays transmitted through bone is I_b and the intensity transmitted through tissue is I_t.

The following data are available.

Mass absorption coefficient for bone = mass absorption coefficient for tissue = $1.2 \times 10^{-2}\ m^2\ kg^{-1}$
Density of bone = $1.9 \times 103\ kg\ m^{-3}$
Density of tissue = $1.1 \times 103\ kg\ m^{-3}$

Calculate the ratio $\frac{I_b}{I_t}$.

c.i. the large uniform magnetic field applied to the patient. [1]

c.ii. the radio-frequency signal emitted towards the patient. [2]

c.iii the non-uniform magnetic field applied to the patient. [2]

Markscheme

a. bone and tissue absorb different amounts of X-rays

OR

bone and tissue have different attenuation coefficients

so boundaries and fractures are delineated in an image

[2 marks]

b. $\frac{I_{bone}}{I_{tissue}} = \frac{I_0 e^{-\mu_b x}}{I_0 e^{-\mu_t x}} = e^{-(\mu_b - \mu_t)x}$

$$\frac{I_{\text{bone}}}{I_{\text{tissue}}} = \mathrm{e}^{-1.2\times10^{-2}\times(1.9-1.1)\times10^{3}\times5.4\times10^{-2}}$$

$$\frac{I_{\text{bone}}}{I_{\text{tissue}}} = 0.60$$

[3 marks]

c.i. to split the energy level of protons in the body

OR

to cause protons in the body to align with the field / precess at Larmor frequency

[1 mark]

c.ii. to force/excite protons that are in the spin up/parallel state

into a transition to the spin down/antiparallel state

[2 marks]

c.iii. the emitted radio frequency signal has a frequency that depends on the magnetic field

with a gradient field different parts of the body have different frequencies and so can be identified

[2 marks]

Examiners report

a. [N/A]
b. [N/A]
c.i. [N/A]
c.ii. [N/A]
c.iii. [N/A]

This question is about medical imaging.

The intensity of a parallel X-ray beam is reduced to 50% of its initial intensity when it passes through bone of thickness 1.2 cm. Determine the thickness of bone needed to reduce the intensity of the same X-ray beam to 15% of its initial value.

Markscheme

$\mu = \frac{\ln 2}{1.2}\ \left(= 0.58\ \text{cm}^{-1}\right)$;

$0.15 = \mathrm{e}^{-0.58x}$;

$x = 3.3\ (\text{cm})$;

*Award **[3]** for a bald correct answer.*

Watch for valid working in metres.

or

$(0.5)^n = 0.15$ (where *n* is number of half value thicknesses travelled);

so $n = 2.74$;

$x = (2.74 \times 1.2\ \text{cm} =)\ 3.3\ (\text{cm})$;

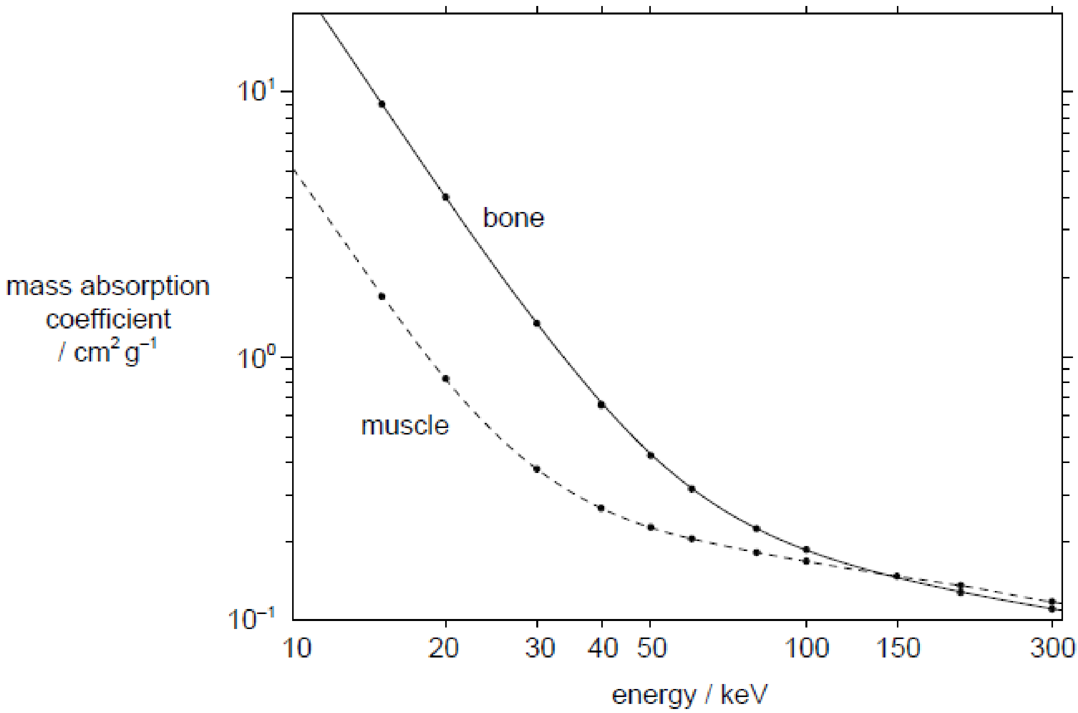
*Award **[3]** for a bald correct answer.*

Examiners report

In (c) there were two popular methods used and many correct answers. Mistakes included using 0.65 instead of 0.35 and logarithmic errors.

The linear attenuation coefficient μ of a material is affected by the energy of the X-ray beam and by the density ρ of the material. The mass absorption coefficient is equal to $\frac{\mu}{\rho}$ to take into account the density of the material.

The graph shows the variation of mass absorption coefficient with energy of the X-ray beam for both muscle and bone.



a. Show that the attenuation coefficient for bone of density 1800 kg m^{-3}, for X-rays of 20 keV, is about 7 cm^{-1}. [2]

b. The density of muscle is 1200 kg m^{-3}. Calculate the ratio of intensities to compare, for a beam of 20 keV, the attenuation produced by 1 cm of bone and 1 cm of muscle. [3]

c. Suggest why more energetic beams of about 150 keV would be unsuitable for imaging a bone–muscle section of a body. [1]

Markscheme

a. reads value on graph at 20 keV as 4 «cm^2 g^{-1}»

«4 cm^2 g^{-1} × 1800 kg m^{-3} × $\frac{1000}{1000000}$ = » 7.2 «cm^{-1}»

Ensure that the calculation has right POT conversion.

Answer must be to at least two significant figures.

b. ***ALTERNATIVE 1***

(finds intensity ratios for muscle and bone separately)

Watch for ECF

for muscle: obtains $\mu = 0.96 \text{ cm}^{-1}$

Allow answers in the range of 0.90 to 1.02 cm^{-1}.

$\frac{I}{I_0} = e^{-\mu x}$ so for muscle 0.38

Allow answers in the range of 0.36 to 0.41.

Allow answers in dB. Muscle -4dB, Bone -30 or -31dB

for bone: $\frac{I}{I_0} = 7.5 \times 10^{-4}$ «if μ = 7.2 is used»

OR

9.1×10^{-4} «if μ=7 is used»

ALTERNATIVE 2
for muscle: obtains $\mu = 0.96 \text{ cm}^{-1}$
Allow answers in the range of 0.90 to 1.02 cm^{-1}.

$$\frac{I_{\text{MUSCLE}}}{I_{\text{BONE}}} = \frac{e^{-0.96}}{e^{-7.2}}$$

Frequently the POT will be incorrect for MP1. Allow ECF from MP1 to MP2.
Allow +/- 26 or 27dB
Award ***[2 max]*** *if μ=960 as they will get* $\frac{I_{\text{MUSCLE}}}{I_{\text{BONE}}} = 0$.

ratio is about 500 «513»
Allow range 395 to 546
If 7 used, ratio is about 420, if 7.2 is used, ratio is about 510
Allow answer I_{BONE}/I_{MUSCLE} *from a range 0.0017 to 0.0026.*

c. similar absorption so poor contrast

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is about ultrasound scanning.

a. Outline how ultrasound is generated for medical diagnostic purposes. [2]

b. When ultrasound of intensity I_0 travels in a medium of acoustic impedance Z_1 and is incident on a medium of acoustic impedance Z_2, the intensity I_R that is reflected at the interface is given by the following equation. [5]

$$I_R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 I_0$$

The following data are available.

	Speed of sound / $m\,s^{-1}$	Density / $kg\,m^{-3}$
air	330	1.3
skin	1500	1000

Use the data to deduce why a layer of gel must be used between a transducer and the patient's skin in medical ultrasound imaging.

c. In medical scanning, practitioners have the option of using A-scans or B-scans. Distinguish, with reference to the techniques used to produce the scans, between an A-scan and a B-scan. [3]

Markscheme

a. use of piezoelectric crystal / quartz;

crystal changes shape/vibrates when an alternating electric field is applied to it;

crystal dimensions are cut to achieve resonance at required frequency;

b. (acoustic impedance of air =) 330 × 1.3 = (=430 ($kgm^{-2}\,s^{-1}$));

(acoustic impedance of skin =) 1500 × 1000 = (=1.5×10^6($kgm^{-2}\,s^{-1}$));

$\frac{I_R}{I_0} \approx 1/0.999$;

little/no transmission (because the reflected intensity is approximately equal to the incident intensity);

gel (has similar impedance to skin and so) is required as it excludes air from the interface (so transmission occurs);

Accept first two marking points if implied in the third marking point.

c. A-scan is a "graph" of returned intensity against time but B-scan is a 2-D image of section through patient;

A-scan: ultrasound probe is fixed in position;

B-scan: operator moves ultrasound generator and computer records echo returns;

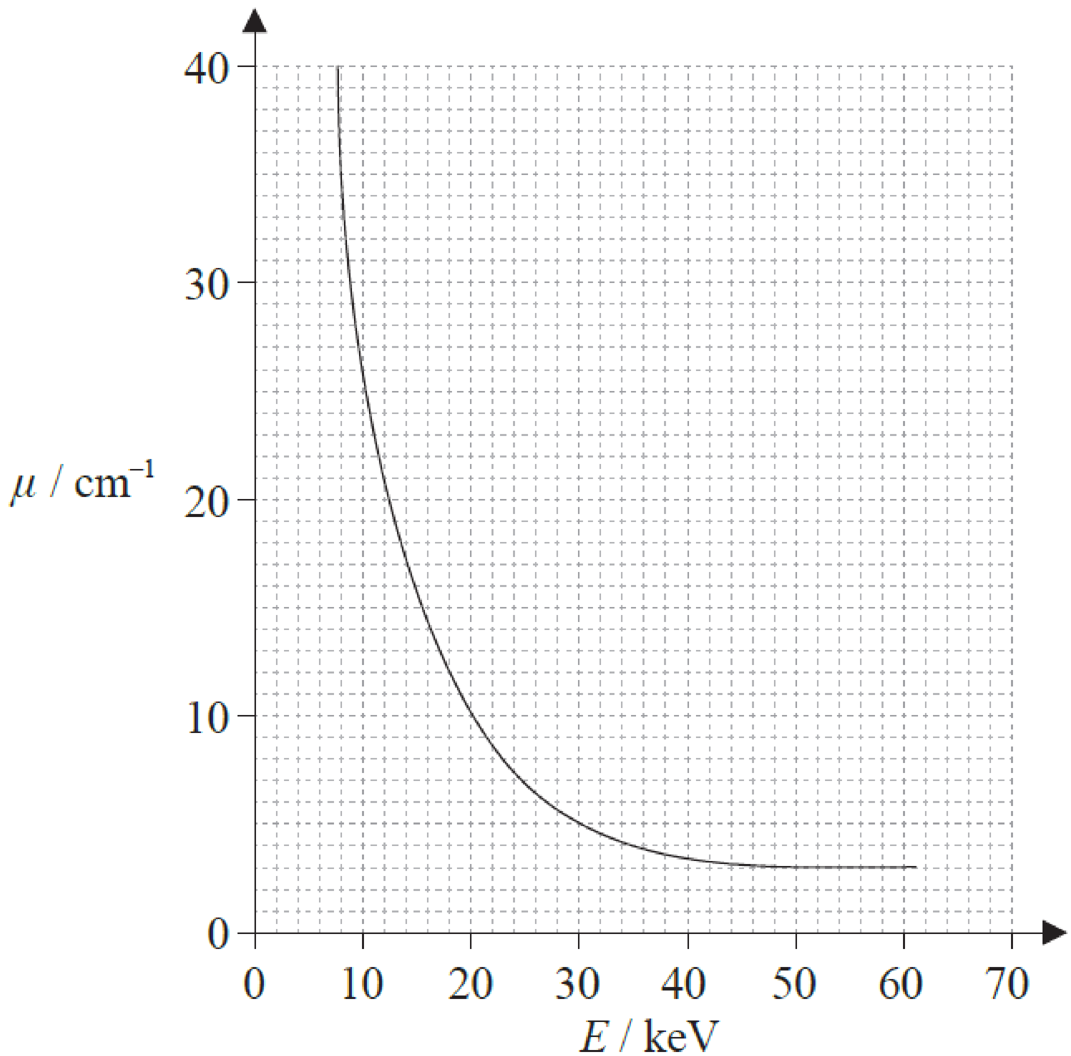
Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is about X-rays.

a. Define *attenuation coefficient.* [1]

b. The graph shows how the attenuation coefficient μ of muscle varies with photon energy E. [5]



In X-ray imaging, photons of energy less than 20 ke V are filtered out of the beam.

(i) Explain, with reference to the graph, why this does not significantly affect the quality of the X-ray image produced.

(ii) State the advantage to the patient of filtering out the low energy photons from the X-ray beam.

(iii) Calculate the fraction of the intensity transmitted through 3.0 mm of muscle for X-rays of energy 50 ke V.

Markscheme

a. the probability per unit length that a particular X-ray photon will be absorbed;

or

$I = I_0 e^{-\mu x}$; (*with symbols defined)*

b. (i) the attenuation coefficient is large which means that these low energy photons will be mostly absorbed (by muscles);

and so will not contribute to the imaging process;

(ii) the patient avoids unnecessary harmful radiation;

(iii) the linear attenuation coefficient is μ=3.0 cm^{-1} =0.30 (mm^{-1}) (from graph);
and so fraction of intensity transmitted is $e^{-0.30 \times 3.0}$=0.41

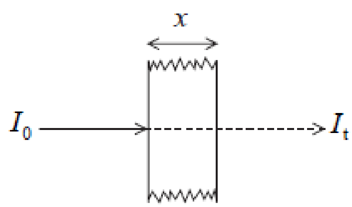
Examiners report

a. (a) Very few could define attenuation coefficient. Far too many candidates tried to define it in terms of half value thickness. If a defining equation is stated marks are only awarded if the meaning of every symbol is given.

b. (b)(i) proved difficult for a candidate who did not realize that almost all of the low energy X-rays would be attenuated inside the body and so would never even reach the sensor. Even so they could answer (b)(ii) well in terms of less exposure to harmful X-rays. Arithmetic errors in (b)(iii) were common unless they were fortunate enough to work in cm. There were very few who did. An attenuation coefficient of 3 cm^{-1} was often mistakenly converted to 30 mm^{-1} .

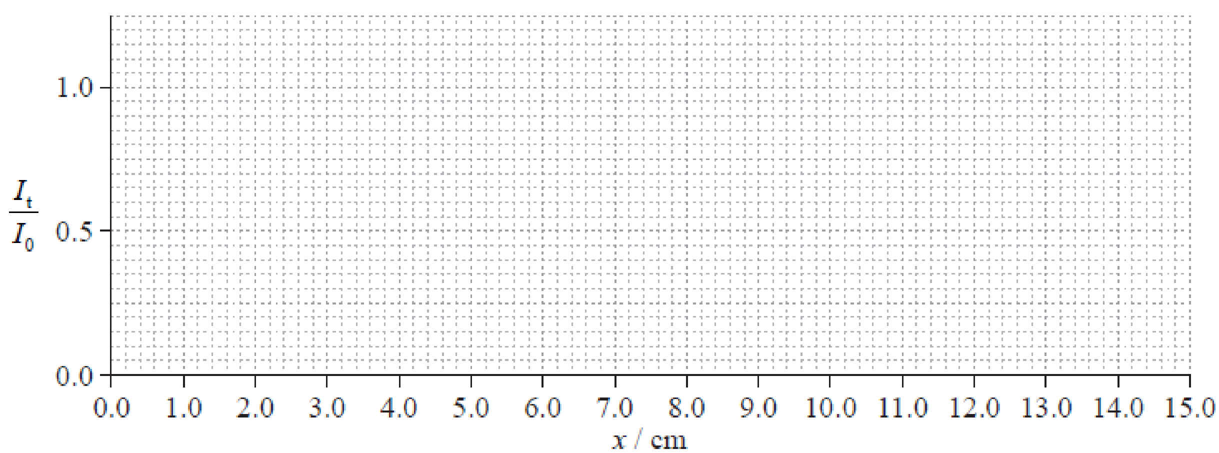
This question is about X-ray absorption.

A parallel beam of X-rays is incident on a section of tissue of thickness *x*. The constant incident intensity is I_0 and the transmitted intensity is I_t.



a. The half-value thickness of the tissue is 4.0 cm. [2]

On the axes below, sketch a graph to show the variation with tissue thickness *x* of $\frac{I_t}{I_0}$.



b. Calculate the attenuation coefficient of X-rays for this tissue. [2]

c. For a different type of tissue, the ratio $\frac{I_t}{I_0}$ is smaller for the same thickness *x* of material. [2]

Compare the attenuation coefficient of this tissue with that of the tissue in (b).

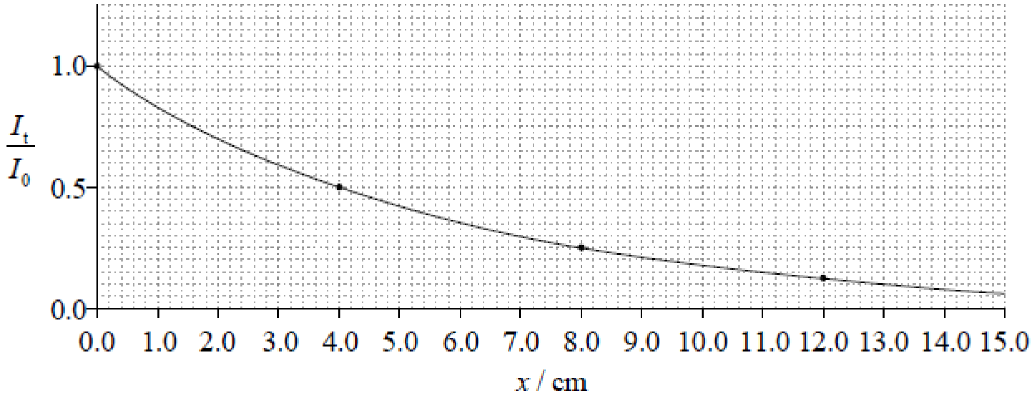
d. Barium has an attenuation coefficient that is much larger than that for human tissue. [3]

Explain why a patient is asked to drink a liquid barium meal to help produce an X-ray image of the digestive system.

Markscheme

a. smooth curved decay line beginning at $\frac{I_t}{I_0} = 1$ when x=0;

passing through other three points as shown;



b. $\mu = \frac{\ln 2}{4}$;

0.17cm^{-1};

Watch for alternative correct answers such as 17m^{-1}.

c. $e^{-\mu x}$ smaller/$e^{\mu x}$ is larger;

μ larger;

or

it has a shorter half value thickness;
and so μ larger;

d. stomach tissue has similar attenuation coefficient to nearby tissue (so does not show up on X-ray);

barium absorbs X-rays well (and lines the stomach after drinking);

barium allows stomach walls to show as contrast;

Examiners report

a.

b.

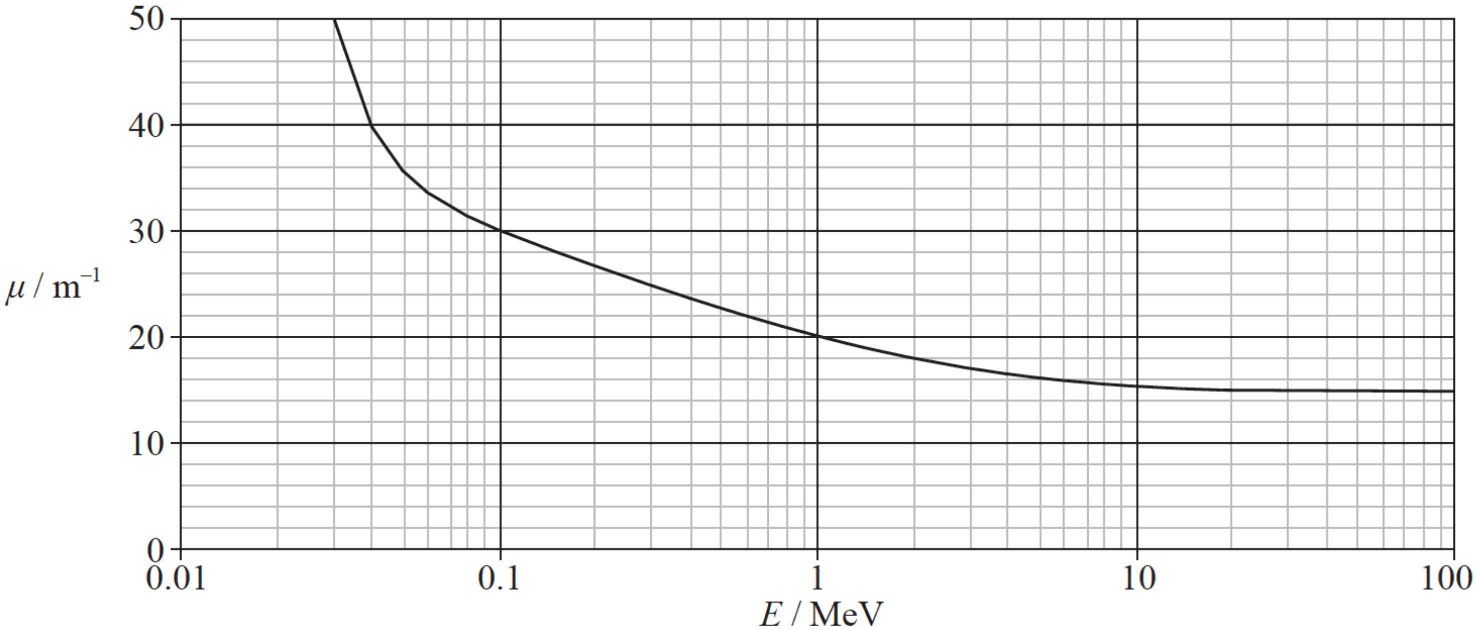
c.

d.

This question is about X-rays.

a. Define *attenuation coefficient*. [1]

b. The graph below shows the variation of attenuation coefficient μ with photon energy E for X-rays in an absorbing medium. [6]



A beam of X-rays is incident on a sample of the medium with intensity I_0. Using the graph,

(i) determine how far X-rays with energy equal to 0.1MeV travel inside the sample before their intensity reduces to $0.1I_0$.
(ii) predict whether X-rays of energy 10MeV are more penetrating than X-rays of energy 0.1MeV in this medium.

Markscheme

a. probability of a single photon being absorbed in 1m of the material / reference to $I = I_0 e^{-\mu x}$ with symbols defined;

b. at 0.1MeV, μ=30(m^{-1});

$0.1 = e^{-30x}$;

$x = \frac{\ln 0.1}{-30}$;

x=0.077(m);

(ii) (at 10MeV,) μ is smaller (than at 0.1MeV);
so (10MeV X-rays are) more penetrating;
Award second mark only if first mark has been awarded.

Examiners report

a. Candidates do not use precise enough wording in definitions, as seen in answers to (a).

b. In (b), the majority of candidates had no problem with the determination of attenuation coefficient from the graph and used it in the calculation of the result.

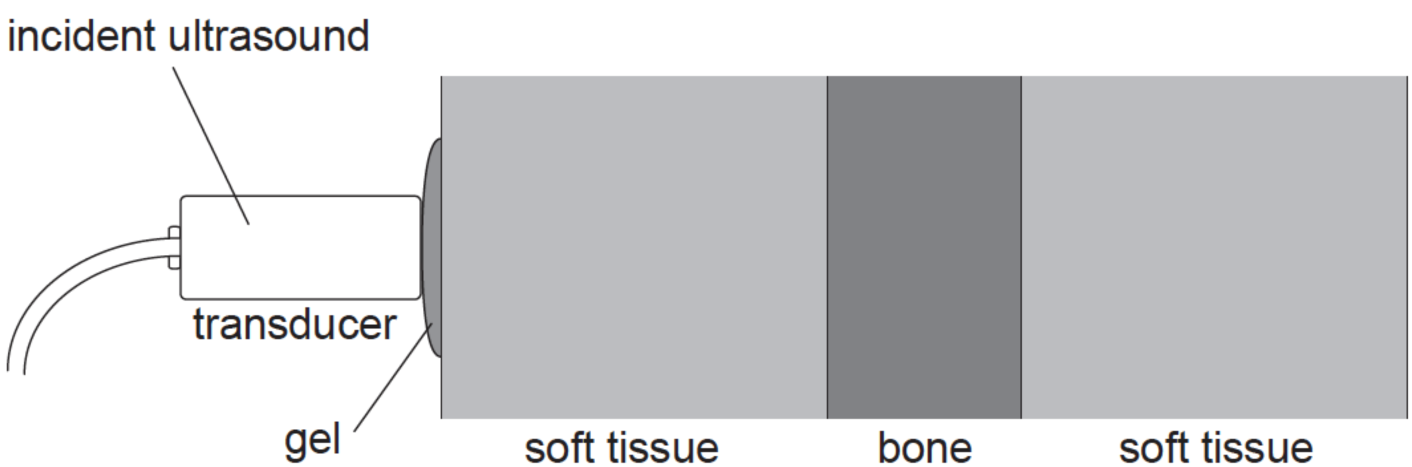
This question is about ultrasound.

a. Define *acoustic impedance* of a medium. [1]

b. The acoustic impedances for various media are shown in the table. [6]

Medium	Acoustic impedance / $kg\,m^{-2}\,s^{-1}$
soft tissue	1.6×10^{6}
gel	1.6×10^{6}
bone	6.1×10^{6}

Ultrasound is incident normally on a layer of soft tissue. Gel is placed between the skin and the transducer.



The fraction of the intensity of ultrasound that is reflected (reflection coefficient) at the boundary of two media of impedances Z_1 and Z_2 is given by the following equation.

$$\left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

(i) Suggest why the gel allows the ultrasound to enter the soft tissue without any reflection.

(ii) Calculate the reflection coefficient at the soft tissue–bone boundary.

(iii) The soft tissue between the skin and the bone absorbs 60% of the intensity of ultrasound travelling through it. The intensity of ultrasound leaving the transducer is I_0. Determine, in terms of I_0, the intensity of the ultrasound that is reflected back into the transducer from the bone.

Markscheme

a. the product of the speed of sound and the density of the medium/substance;

Accept as an equation with symbols defined.

b. (i) *The data is on the previous page and most candidates do not realize it is to be used here. So two alternative MS are given which try to be fair to all candidates.*

the impedance of gel and soft tissue are the same;
so the equation gives a reflection coefficient (OWTTE) of zero;

or *(knowledge based answer)*

gel replaces air which would cause unwanted reflection / air has a lower impedance than soft tissue;
the impedance of gel and soft tissue are the same/similar so reflection is reduced;

Do not reward bald "reflection will be less/reduced" for the second marking points as this is given in the question.
Do not accept "density" instead of impedance.

(ii) $\left(\left[\frac{6.1\times10^6-1.6\times10^6}{6.1\times10^6+1.6\times10^6}\right]^2\right) = 0.34;$

(iii) intensity reaching bone is $0.40I_0$;
intensity reflected from bone is $0.34\times0.40I_0$; { *(allow ECF from first marking point)*
intensity reaching transducer is $(0.40\times0.34\times0.40I_0)=0.054I_0$;

*Award **[2 max]** for an answer of 0.16 I_0 **or** 0.12 I_0.*

*Award **[3]** for a bald correct answer.*

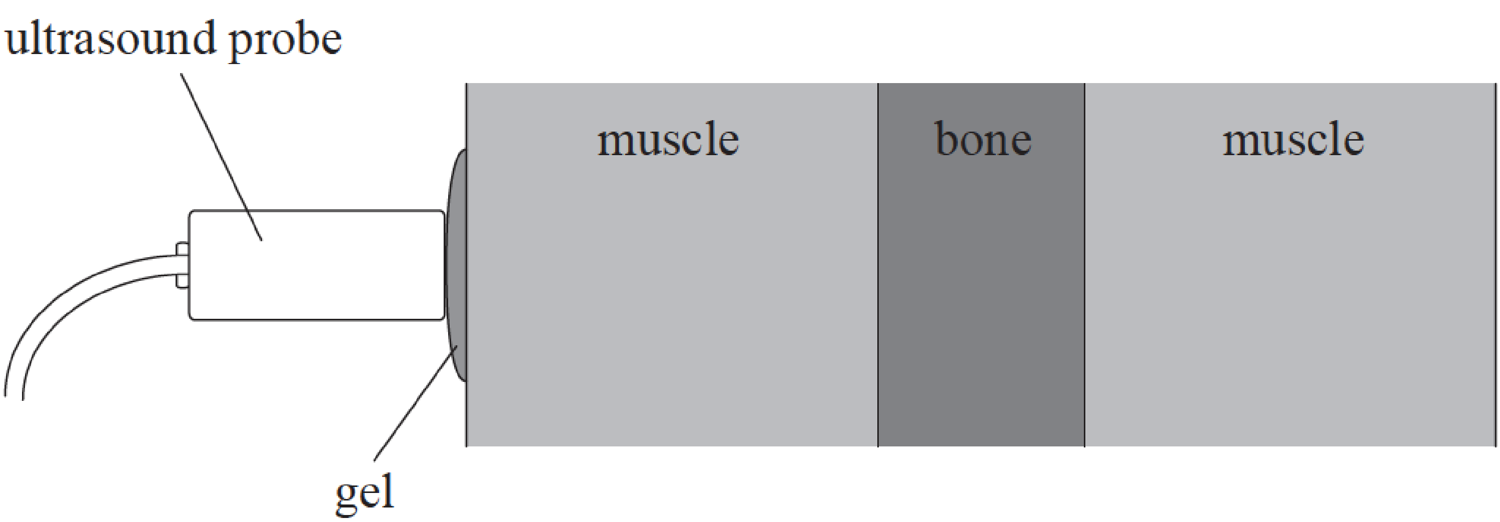
Examiners report

a. Part (a) was an easy mark, although the speed of light was mentioned too often.

b. In (b)(i) many candidates ignored the data and answered using existing knowledge. The reflection coefficient was usually correctly calculated in (b)(ii). Part (b)(iii) was poorly answered. Most candidates did not take the time to analyse what was happening. Two attenuations and one reflection, so I = 0.4 × 0.34 × 0.4Io for 3 marks — but very few correct answers were seen.

This question is about ultrasound.

The diagram shows part of a cross-section through the leg of a patient who is undergoing an ultrasound scan.



Data for the speed *c* of ultrasound in different media are shown below, together with values for the acoustic impedance *Z*.

	c / m s^{-1}	Z / kg m^{-2} s^{-1}
air	3.3×10^{2}	4.3×10^{2}
gel	1.5×10^{3}	1.5×10^{6}
muscle	1.5×10^{3}	1.4×10^{6}
bone	4.1×10^{3}	7.8×10^{6}

a. Use the data from the table to calculate a value for the density of bone. [2]

b. The fraction F of the intensity of an ultrasound wave reflected at the boundary between two media having acoustic impedances Z_1 and Z_2 is given by the following equation. [4]

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

Determine the fraction F for the boundary between

(i) air and muscle.

(ii) gel and muscle.

c. Use your answers in (b) to explain the need for a gel on the patient's skin. [2]

Markscheme

a. use of $Z=\rho c$;

$7.8\times10^{6}=\rho\times4.1\times10^{3}$

$\rho=1900\text{kgm}^{-3}$;

b. (i) $F=\frac{(1.4\times10^{6}-4.3\times10^{2})^2}{(1.4\times10^{6}+4.3\times10^{2})^2}$;

$F\approx1$;

(ii) $F=\frac{(1.5\times10^{6}-1.4\times10^{6})^2}{(1.5\times10^{6}+1.4\times10^{6})^2}$;

$F=0.0012$;

c. for air-muscle boundary, very little ultrasound is transmitted;

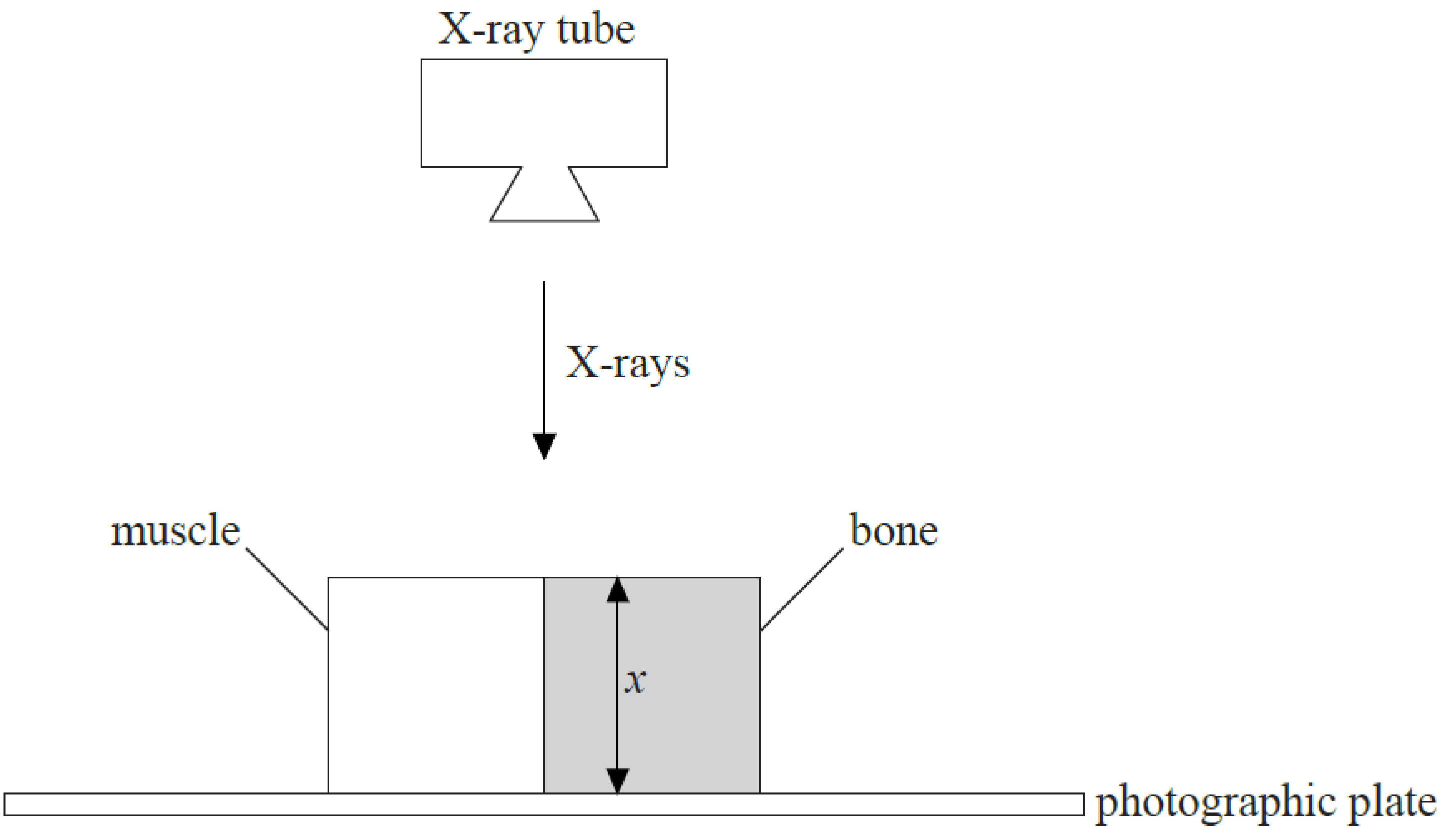
gel permits almost complete transmission;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is about the use of X-rays and ultrasound in medical imaging.

a. The diagram below shows X-rays being used to scan a sample of bone and muscle. [7]



(i) Outline how the arrangement differentiates between bone and muscle.

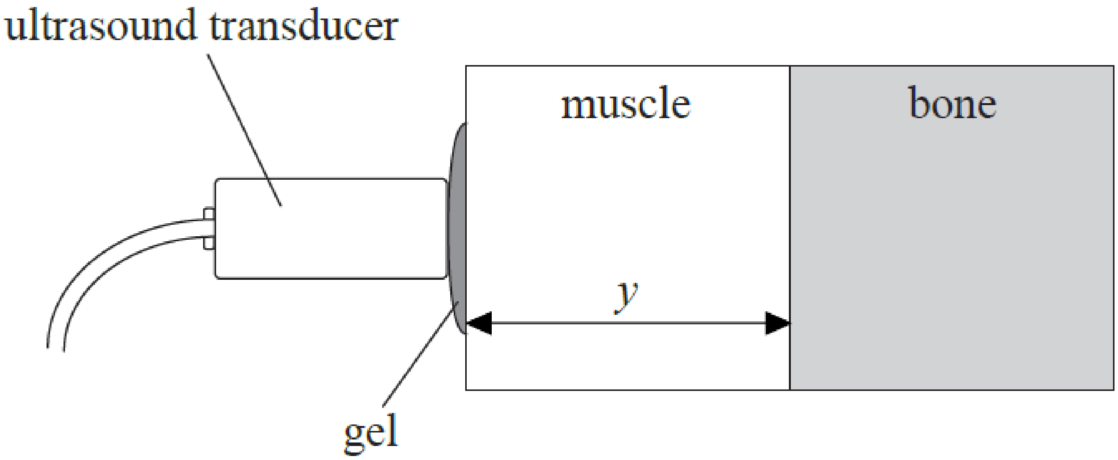
(ii) Use the data below to determine the ratio $\frac{I_b}{I_m}$ where I_b and I_m are the intensity of X-rays reaching the photographic plate through the bone and the muscle, respectively.

Thickness x of sample = 10.0 cm
Linear attenuation coefficient of bone μ_b = 0.53 cm^{-1}
Linear attenuation coefficient of muscle μ_m = 0.30 cm^{-1}

(iii) The half-value thickness of a material increases as the energy of the radiation increases.

Discuss, with reference to penetration and effect on tissue, why using low energy X-rays in medical imaging is highly desirable but is rare in practice.

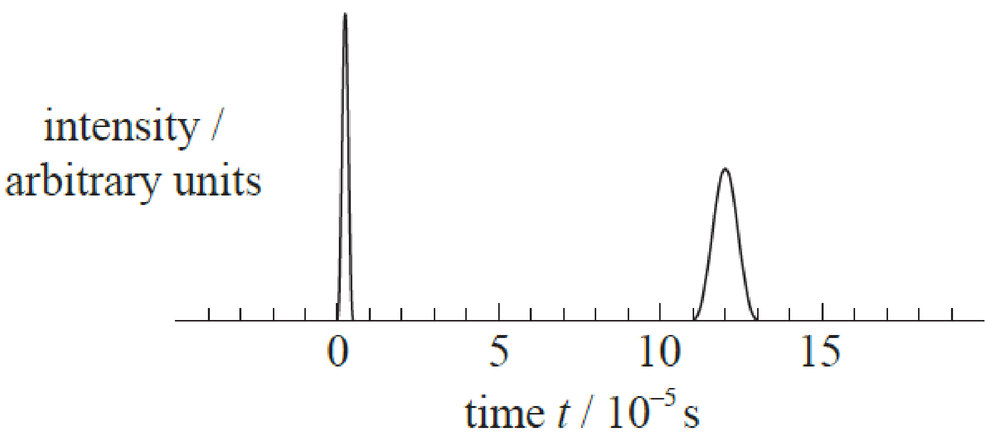
b. The same sample is now investigated with an ultrasound A-scan from the side as shown. [4]



(i) State **one** advantage of ultrasound over X-ray imaging.

(ii) State why gel is needed at the transducer-muscle boundary.

(iii) A short pulse is directed from the transducer into the sample at time $t = 0$.
The graph shows how the intensity of the reflected signal from the muscle-bone boundary varies as a function of time. The speed of sound in muscle is 1.6×10^3 m s^{-1}.



Calculate the thickness y of the sample of muscle.

Markscheme

a. (i) X-rays are absorbed more by bone as it is denser / X-rays are transmitted more by muscle as it is less dense;

denser material/bone leads to less exposure / less dense material/muscle leads to more exposure (on the photographic plate);

(ii) $I_b=I_0e^{-0.53\times10}=0.0050\times I_0$;
$I_m=I_0e^{-0.30\times10}=0.0498\times I_0$;
$\frac{I_b}{I_m}=\frac{0.0050\times I_0}{0.0498\times I_0}=0.10$;

(iii) low energy X-rays cause less damage to tissue;
but do not penetrate as deeply;

b. (i) no exposure to radiation / *OWTTE;*

(ii) for impedance matching / *OWTTE;*

(iii) $y=\frac{vt}{2}$;
$y=\frac{1600\times10\times10^{-5}}{2}=0.096\,(\text{m})\,(=9.6\text{cm})$;

Examiners report

a. (a)(i) Many candidates had the idea of the difference between muscle and bone, but not all mentioned density or exposure on the plate. There were many mistakes in algebra in (a)(ii), especially with the exponent. Many candidates got confused with units, changing the thickness to m but not changing the attenuation coefficient to m^{-1}. (a)(iii) was well answered by most candidates.

b. (b)(i) and (b)(ii) were well answered though answers to (b)(ii) were not always precise. (b)(iii) was very poorly answered. This was surprising as it was basically reading a value from a graph and applying the equation speed = distance / time. Many candidates misread the graph value and many forgot to divide by two to take into account travel and return time.

This question is about ultrasonic imaging.

The table gives the velocity of sound in, and the densities of, the materials.

	Velocity of sound / $m\,s^{-1}$	Density / $kg\,m^{-3}$	Acoustic impedance
Air	330	1.3	
Gel	1420	980	
Muscle tissue	1580	1080	

(i) State the SI unit for acoustic impedance.

(ii) Calculate the acoustic impedance for each material and write your answers in the table above.

Markscheme

(i) $kgm^{-2}s^{-1}$;

(ii)

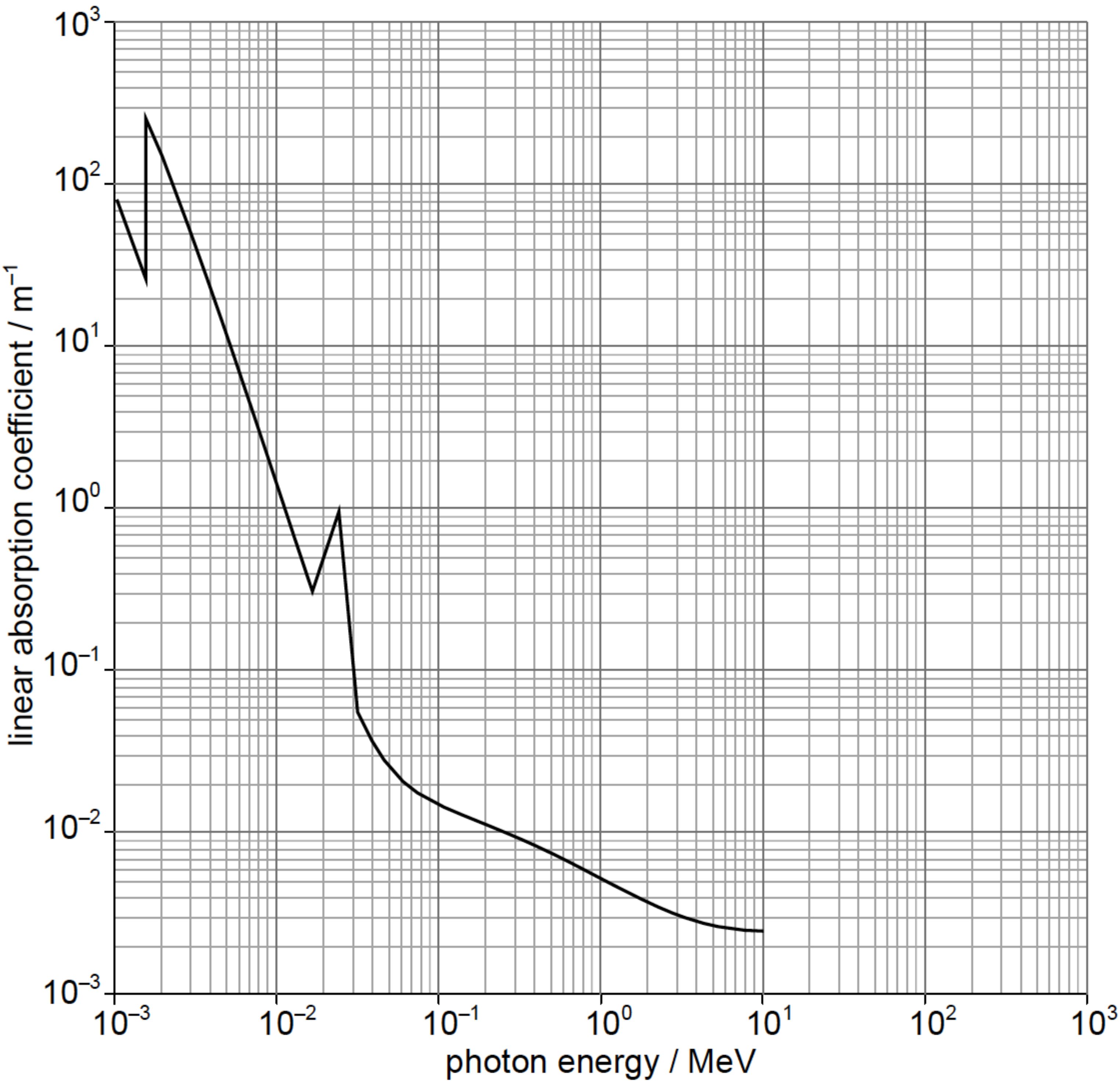
	Velocity of sound/ms^{-1}	Density/kg m^{-3}	Acoustic impedance/kg $m^{-2}s^{-1}$
Air	*330*	*1.3*	4.3×10^{2}
Gel	*1420*	*980*	1.4×10^{6}
Muscle tissue	*1580*	*1080*	1.71×10^{6}

*Award **[2]** for all correct and **[1 max]** for 2 or 1 correct.*

Examiners report

[N/A]

In medical imaging, X-rays can be passed through aluminium before reaching the body. The graph shows the variation of the linear absorption coefficient of aluminium for different photon energies.



a. X-rays are incident on an aluminium sheet of thickness 8.0 cm. Calculate the fraction of the incident X-ray intensity that emerges from this sheet for photon energies of [3]

(i) 9.0 MeV.

(ii) 3.0×10^{-3} MeV.

b. With reference to your answers to (a)(i) and (a)(ii), discuss the advantages of using the aluminium sheet. [2]

Markscheme

a. (i) $\mu = 2.7 \times 10^{-3}\left(\pm 0.3 \times 10^{-3}\right)$

So $\frac{I}{I_O} = \ll e^{-\mu x} = e^{-\left(2.7 \times 10^{-3} \times 8 \times 10^{-2}\right)} \gg = 0.9999 \approx 1.0$

(ii) $\ll \mu = 50 \text{togive} \gg \frac{I}{I_O} = 1.8 \times 10^{-2}$

b. low energy radiation removed but not high energy radiation

radiation has narrower range of energies

only necessary radiation reaches the patient making it safer

Examiners report

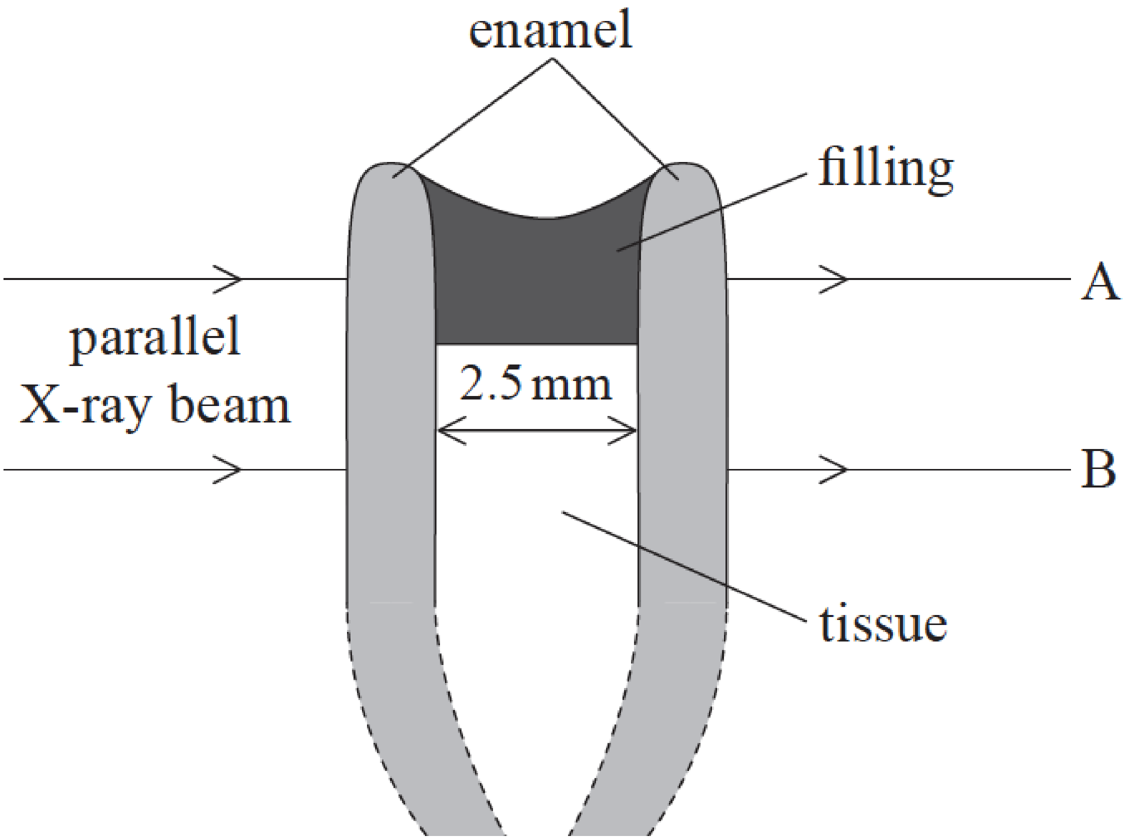
a. [N/A]

b. [N/A]

This question is about medical imaging.

a. Define *attenuation coefficient*. [2]

b. X-rays are used in dentistry to reveal decay inside teeth. In a research study, a tooth is partially filled with a new glass-based material to replace decayed tissue. X-ray photographs are taken of the tooth. [6]



Attenuation coefficient of filling $= 6.3\,\text{mm}^{-1}$
Attenuation coefficient of enamel $= 0.46\,\text{mm}^{-1}$
Attenuation coefficient of tissue $= 0.30\,\text{mm}^{-1}$
Width of the tissue $= 2.5\,\text{mm}$
Width of the filling $= 2.5\,\text{mm}$

A parallel beam of X-rays is incident on the tooth. X-rays emerging at A have travelled through enamel and filling only, X-rays emerging at B have travelled through enamel and tooth tissue only.

(i) Show that the ratio $\frac{\text{intensityofX}-\text{raysatA}}{\text{intensityofX}-\text{raysatB}}$ is approximately 3×10^{-7}.

(ii) The X-ray exposure time is such as to enable fine detail in the enamel to be revealed by X-rays emerging at B. Suggest, with reference to the ratio in (b)(i), why the contrast at B is much greater than the contrast at A.

c. A complete dental record of all the teeth in a patient's mouth requires about 20 separate X-ray exposures. Image intensifiers are now used in dentistry to allow a single image to be made of all the teeth with one exposure. Outline the advantages of this for the patient. [2]

d. The table shows data about the acoustic impedance of some materials that would be involved in the transmission of ultrasound through a tooth. [2]

Material	Acoustic impedance / relative units
tissue	1.7
decayed tissue	1.6
enamel	7.8
air	4.0×10^{-4}

Without carrying out a calculation, outline **two** reasons why ultrasound is not used to detect the presence of decay inside a tooth.

Markscheme

a. μ in $I=I_0e^{-\mu x}$;

all symbols defined;

or

the probability per unit length/metre;
of a photon being absorbed;

b. (i) $I_A = I_0 e^{[-\mu_e 2x - \mu_f y]}$ ***or*** $I_B = I_0 e^{[-\mu_e 2x - \mu_t y]}$;

$\frac{I_A}{I_B} = \frac{e^{[-\mu_e 2x - \mu_f y]}}{e^{[-\mu_e 2x - \mu_t y]}}$;

$= e^{[-[6.3-0.3]2.5]}$;

$=3.1\times10^{-7}$;

Do not apply a marking penalty if attenuation effect of enamel is ignored, as it is the same for both rays.

Award first and second marking point by implication if only the correct working of the third marking point is shown.

Approximate answer is given in the question, so look for working and at least two significant figures in the final answer (3.059...).

(ii) intensity ratio is very small / intensity for A is much less than at B;
so if the contrast is correct for B, it cannot be correct for A / A will be underexposed so contrast will be poor;

or

compared to B, the much smaller intensity for A is due to the filling;
for A, small changes in enamel attenuation coefficient will be insignificant compared to that of the filling, so contrast is poor;

c. quicker procedure;

less dose overall / safer;

d. acoustic impedance difference between decayed and good tissue is very small so reflection will be weak;

the acoustic impedance of tissue/decayed tissue is much smaller than for enamel so contrast would be poor;

difficult to get ultrasound signal into tooth given mismatch between acoustic impedance of air and enamel;

there will be a strong internal reflection when reflection from tissue is incident on enamel from inside;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]