A2 Level Physics

Chapter 21 – Medical Imaging

21.3.2 Using Ultrasound

Worked Examples

Ultrasound

Exam Style Question 1

The quality of ultrasound images in increasing at a phenomenal pace, thanks to advances in computerised imaging techniques. The computer technology is sophisticated enough to monitor and display tiny ultrasound signals from a patient.

The ratio of reflected intensity to incident intensity for ultrasound reflected at a boundary is related to the acoustic impedance Z_1 of the medium on one side of the boundary and the acoustic impedance Z_2 of the medium on the other side of the boundary by the following equation.

$$\frac{reflect\ intensity}{incident\ intensity} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

(a) State two factors that determine the value of the acoustic impedance.

(b) An ultrasound investigation was used to identify a small volume of substance in a patient. It is suspected that this substance is either blood or muscle.

During the ultrasound investigation, an ultrasound pulse of frequency of $3.5 \times 10^6\ Hz$ passed through soft tissue and then into the small volume of unidentified substance. A pulse of ultrasound reflected from the front surface of the volume was detected $26.5\ \mu s$ later. The ratio of the reflected intensity to the incident intensity, for the ultrasound pulse reflected at this boundary was found to be 4.42×10^{-4}. The table below shows data for the acoustic impedances of various materials found in a human body.

medium	acoustic impedance Z/ kg m^{-2} s^{-1}
air	4.29×10^2
blood	1.59×10^6
water	1.50×10^6
brain tissue	1.58×10^6
soft tissue	1.63×10^6
bone	7.78×10^6
muscle	1.70×10^6

(i) Use appropriate data from the table above to identify the unknown medium. You must show your reasoning.

(ii) Calculate the depth at which the ultrasound pulse was reflected if the speed of ultrasound in soft tissue is $1.54\ km\ s^{-1}$.

(iii) Calculate the wavelength of the ultrasound in the soft tissue.

Ultrasound

Exam Style Question 1

(a)State two factors that determine the value of the acoustic impedance.

- Density of medium
- Speed of ultrasound in medium

(b) (i) Use appropriate data from the table above to identify the unknown medium. You must show your reasoning.

Use $\frac{reflect\ intensity}{incident\ intensity} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$

Remember, the boundary at which the reflection occurs might be that between the air and the skin, or tissue and liquid, or tissue and bone. However in this case we just need it from soft tissue to either blood or muscle.

Blood:

$$\frac{I_r}{I_0} = \frac{(1.59 \times 10^{-6} - 1.63 \times 10^{-6})^2}{(1.59 \times 10^{-6} + 1.63 \times 10^{-6})^2}$$

$$\frac{I_r}{I_0} = 1.54 \times 10^{-4}\ (2\ d.p.)$$

Muscle:

$$\frac{I_r}{I_0} = \frac{(1.70 \times 10^{-6} - 1.63 \times 10^{-6})^2}{(1.70 \times 10^{-6} + 1.63 \times 10^{-6})^2}$$

$$\frac{I_r}{I_0} = 4.4 \times 10^{-4}\ (2\ s.f.)$$

So the medium is muscle.

Ultrasound

Exam Style Question 1

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(iii) Calculate the wavelength of the ultrasound in the soft tissue.

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Ultrasound

Exam Style Question 1

(b) (ii) Calculate the depth at which the ultrasound pulse was reflected if the speed of ultrasound in soft tissue is $1.54\ km\ s^{-1}$.

Use $speed = \frac{distance}{time}$ and rearrange for $distance$:

$$distance = speed \times time$$
$$distance = (1.54 \times 10^3\ m\ s^{-1})(26.5 \times 10^{-6}\ s)$$
$$distance = 0.04081\ m$$
$$\therefore depth = \frac{0.04081\ m}{2} = 0.020\ m\ (2\ s.f.)$$

(b) (iii) Calculate the wavelength of the ultrasound in the soft tissue.

Use $v = f\lambda$ and rearrange for λ:

$$\lambda = \frac{v}{f} = \frac{1.54 \times 10^3\ m\ s^{-1}}{3.5 \times 10^6\ Hz}$$
$$\lambda = 4.4 \times 10^{-4}\ m$$

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Ultrasound

Exam Style Question 2

(a) Explain what is meant by Doppler effect.

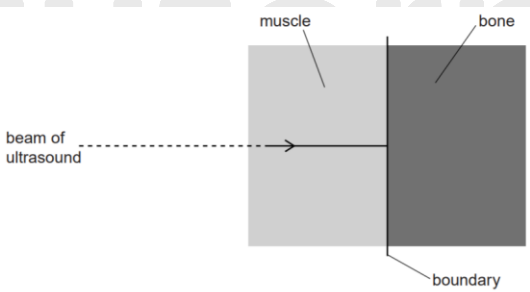
(b) Describe how high-frequency ultrasound can be used to determine the speed of blood through the arteries of a patient.

(c) A patient is scanned using ultrasound of frequency 2.4 MHz. The speed of ultrasound in the blood is 1.57 $km\ s^{-1}$. The acoustic impedance of blood is $1.66 \times 10^6\ kg\ m^{-2}\ s^{-1}$. Calculate

(i) the density of blood

(ii) the wavelength of ultrasound in the blood.

(d) Fig. 9.1 shows a beam of ultrasound incident at right angles to the boundary between muscle and bone.



The acoustic impedance of bone is 4 *times* that of muscle.

Calculate the percentage of ultrasound intensity transmitted into the bone.

(e) During an ultrasound scan it is important that most of the ultrasound from the transducer is transmitted into the patient. Describe and explain how this is achieved.

Ultrasound

Exam Style Question 2

(a)Explain what is meant by Doppler effect.

An increase (or decrease) in the frequency of sound, light, or other waves as the source and observer move towards (or away from) each other.

(b) Describe how high-frequency ultrasound can be used to determine the speed of blood through the arteries of a patient.

1) Ultrasound transducer emits and detects ultrasound.
2) The transducer is placed at an angle to the artery.
3) Ultrasound is reflected by the blood cells.
4) The change in frequency/wavelength of the reflected ultrasound is related to speed of blood.

(c) Calculate

(i) the density of blood,

Use $Z = \rho c$ and rearrange for ρ:

$$\rho = \frac{Z}{c} = \frac{1.66 \times 10^6\ kg\ m^{-2}\ s^{-1}}{1.57 \times 10^3\ m\ s^{-1}}$$
$$\rho = 1060\ kg\ m^{-3}\ (4\ s.f.)$$

(ii) the wavelength of ultrasound in the blood.

Use $v = f\lambda$ and rearrange for λ:

$$\lambda = \frac{v}{f} = \frac{(1.57 \times 10^3\ m\ s^{-1})}{(2.4 \times 10^6\ Hz)}$$
$$\lambda = 6.5 \times 10^{-4}\ m\ (2\ s.f.)$$

Ultrasound

Exam Style Question 2

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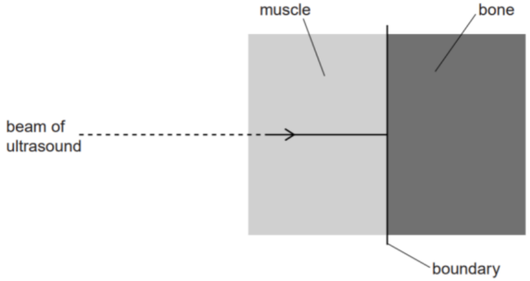

The acoustic impedance of bone is 4 $times$ that of muscle.

Calculate the percentage of ultrasound intensity transmitted into the bone.

(e) During an ultrasound scan it is important that most of the ultrasound from the transducer is transmitted into the patient. Describe and explain how this is achieved.

Ultrasound

Exam Style Question 2

(d) Calculate the percentage of ultrasound intensity transmitted into the bone.

Use $fraction\ of\ intensity\ reflected = \frac{(Z_2-Z_1)^2}{(Z_2+Z_1)^2}$

$$= \frac{(4-1)^2}{(4+1)^2} = \frac{3^2}{5^2} = 0.36$$

Therefore the percentage of ultrasound intensity transmitted into the bone is:

$$intensity = 1 - 0.36 = 0.64 = 64\%$$

(e) During an ultrasound scan it is important that most of the ultrasound from the transducer is transmitted into the patient. Describe and explain how this is achieved.

Gel is used between transducer and skin. The acoustic impedance of gel is similar to that for skin hence less reflection at the skin.

Ultrasound

Exam Style Question 3

(a) Describe the principles of ultrasound scanning.

(b) Explain the difference between an ultrasound A-scan and B-scan.

Ultrasound

Exam Style Question 3

(a) Describe the principles of ultrasound scanning.

1) A piezoelectric crystal / transducer is used to send pulses of ultrasound into the patient.
2) Ultrasound is reflected at the boundary of tissue.
3) The intensity of the reflected signal depends on the acoustic impedances at the boundary.
4) The time of delay is used to determine the depth/thickness.

(b) Explain the difference between an ultrasound A-scan and B-scan.

- A-scan is one directional whereas B-scan involves different directions.
- B-scan consist of many A-scans.
- B-scan produces 2-D or 3-D image.

Ultrasound

Exam Style Question 4

(a) Describe the piezoelectric effect.

(b) Describe how ultrasound scanning is used to obtain diagnostic information about internal structures of a body. In your description include the differences between an A-scan and a B-scan.

(c) Fig. 7.1 shows the speed of ultrasound, density and acoustic impedance for muscle and bone.

material	speed of ultrasound / $m\,s^{-1}$	density / $kg\,m^{-3}$	acoustic impedance / $10^6\,kg\,m^{-2}\,s^{-1}$
muscle	1590	1080	1.72
bone	4080	1750	7.14

Fig. 7.1

(i) Show that the unit for acoustic impedance is $kg\ m^{-2}\ s^{-1}$.

(ii) An ultrasound pulse is incident at right angles to the boundary between bone and muscle. Calculate the fraction of reflected intensity of the ultrasound.

(iii) What is meant by acoustic impedance matching ? Explain why a gel is used to produce an effective ultrasound image.

(iv) The frequency of the ultrasound in the muscle is 1.2 MHz. Calculate the wavelength of the ultrasound in millimetres (mm).

(v) Suggest why it is desirable to have ultrasound of short wavelength for a scan..

Ultrasound

Exam Style Question 4

(a)Describe the piezoelectric effect.
The application of a p.d. across a material causes an expansion or contraction or vibration.

(b) Describe how ultrasound scanning is used to obtain diagnostic information about internal structures of a body.

- Pulses of ultrasound sent into the body.
- Ultrasound is reflected at boundary of tissue.
- Time of delay used to determine depth/thickness.
- The reflected signal intensity is used to identify the tissue.

(c) (i) Show that the unit for acoustic impedance is $kg\ m^{-2}\ s^{-1}$.

$$acoustic\ impedance = density\ (kg\ m^{-3}) \times speed\ (m\ s^{-1})$$
$$kg\ m^{-3} \times m\ s^{-1} = kg\ m^{-2}\ s^{-1}$$

(c) (ii) An ultrasound pulse is incident at right angles to the boundary between bone and muscle. Calculate the fraction of reflected intensity of the ultrasound.

Use $fraction\ of\ intensity\ reflected = \frac{(Z_2-Z_1)^2}{(Z_2+Z_1)^2}$

$$fraction = \frac{(7.14-1.72)^2}{(7.14-1.72)^2} = 0.37\ (2\ d.p.)$$

(c) (iii) What is meant by acoustic impedance matching ? Explain why a gel is used to produce an effective ultrasound image.
Acoustic impedances of media are similar/identical.
The acoustic impedance of the gel is almost the same as that of the skin and since $Z_2 \approx Z_1$, very little ultrasound will be reflected and this ensures maximum transmission of ultrasound into the body.

Ultrasound

Exam Style Question 4

(a) Describe the piezoelectric effect.

(b) Describe how ultrasound scanning is used to obtain diagnostic information about internal structures of a body. In your description include the differences between an A-scan and a B-scan.

(c) Fig. 7.1 shows the speed of ultrasound, density and acoustic impedance for muscle and bone.

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(i) Show that the unit for acoustic impedance is $kg\ m^{-2}\ s^{-1}$.

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(iv) The frequency of the ultrasound in the muscle is 1.2 MHz. Calculate the wavelength of the ultrasound in millimetres (mm).

(v) Suggest why it is desirable to have ultrasound of short wavelength for a scan..

Ultrasound

Exam Style Question 4

(c) (iv) The frequency of the ultrasound in the muscle is $1.2\ MHz$. Calculate the wavelength of the ultrasound in millimetres (mm).

Use $v = f\lambda$ and rearrange for λ:

$$\lambda = \frac{v}{f} = \frac{1590\ m\ s^{-1}}{1.2 \times 10^6\ Hz}$$

$$\lambda = 1.325 \times 10^{-3}\ m = 1.33\ mm\ (2\ d.p.)$$

(c) (v) Suggest why it is desirable to have ultrasound of short wavelength for a scan.

Small wavelength means great resolution and so finer detail can be seen.

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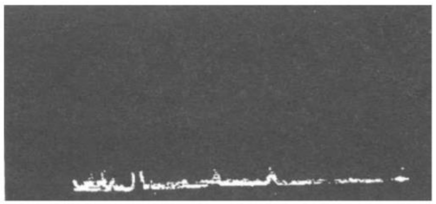
Ultrasound

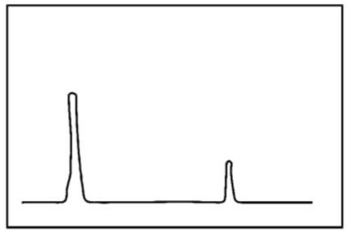
Exam Style Question 5

An ultrasound A-scan is a test that is commonly carried out to check that a fetus is developing correctly and growing at the expected rate. A typical use would be to monitor the growth of a baby's head.

The photograph on the left and the simplified diagram on the right show a scan of the baby's head.



Trace seen on monitor



Simplified diagram of trace

(i) What quantity is represented by the horizontal axis of the trace?

(ii) Explain briefly how the two peaks of the trace are formed

(iii) Explain briefly how the trace could be used to obtain a measurement of the size of the baby's head.

If ultrasound is used to image a moving object such as the heart, a Doppler shift is observed.

(iv) Explain what is meant by the term Doppler shift.

Ultrasound

Exam Style Question 5

(i) What quantity is represented by the horizontal axis of the trace?
Time

(ii) Explain briefly how the two peaks of the trace are formed.

Reflection occurs at boundary between head and surrounding fluid. 1st reflection occurs when entering head and the 2nd reflection occurs on leaving. Therefore you get two peaks.

(iii) Explain briefly how the trace could be used to obtain a measurement of the size of the baby's head.

If you know the speed of ultrasound in head, distance can be calculated using:

$$distance = ultrasound\ speed \times time$$

$$width\ of\ head = \frac{distance}{2}$$

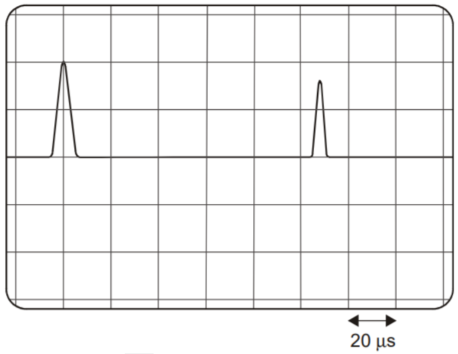
(iv) Explain what is meant by the term Doppler shift.

A change in frequency caused by relative movement between transducer and object.

Ultrasound

Exam Style Question 6

The diagram below shows a trace on a cathode-ray oscilloscope (CRO) of an ultrasound reflection from the front edge and rear edge of a foetal head.



The CRO timebase is set to 20 $\mu s\ cm^{-1}$. The speed of ultrasound in the foetal head is $1.5 \times\ 10^3\ m\ s^{-1}$.

(i) Calculate the size of the foetal head.

(ii) State and explain what would be seen on the CRO screen if gel had not been applied between the ultrasound transducer and the skin of the mother.

Ultrasound

Exam Style Question 6

(i) Calculate the size of the foetal head.

The first peak is the time it takes for ultrasound reflection from the front edge of a foetal head and the second peak is for the rear edge of a foetal head. The difference between the two is the time taken for ultrasound reflection from the front edge to the rear edge of a foetal head.
To calculate this time count the squares between the two peaks and times it by 20 μs.

$$No. of\ squares\ between\ the\ peaks = 5.4\ cm$$
$$\therefore time = 5.4\ cm \times 20 \times 10^{-6}\ s\ cm^{-1}$$
$$time = 1.08 \times 10^{-4}\ s$$

So, the time taken for the ultrasound to get from the front edge to the rear edge is $1.08 \times 10^{-4}\ s$. Now that we have the time and the speed of the ultrasound, we can use $distance = speed \times time$ to calculate the size of the foetal head:

$$distance = (1.5 \times 10^3\ m\ s^{-1})(1.08 \times 10^{-4}\ s)$$
$$distance = 0.162\ m$$
$$depth = \frac{0.162\ m}{2} = 0.081\ m$$

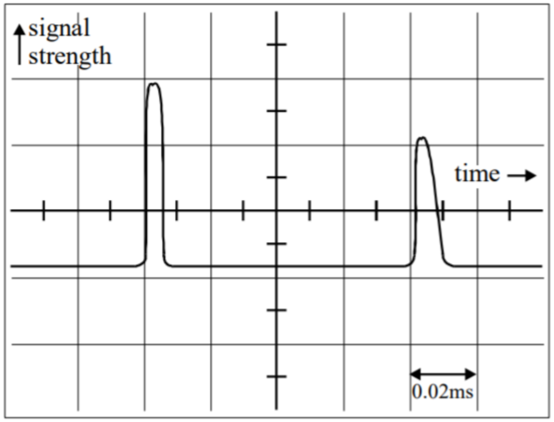
(ii) State and explain what would be seen on the CRO screen if gel had not been applied between the ultrasound transducer and the skin of the mother.

High reflection at the air-skin boundary and therefore little ultrasound enters the body. Therefore, a very large peak is produced right at the start due to the large difference in acoustic impedance and very low subsequent peaks.

Ultrasound

Exam Style Question 7

An ultrasound transducer is used to obtain an A-scan of an internal organ. The A-scan pulses shown on the diagram were identified as coming from the front and rear surfaces of the organ.



(a) Describe the practical process, including details of the use of the transducer and the adjustment of the oscilloscope, required to produce this A-scan.

(b) From the A-scan, estimate

(i) the thickness of the organ if the speed of ultrasound in the tissue is $1500\ m\ s^{-1}$ (the horizontal scale is $0.02\ ms/cm$),

(ii) the duration of the first ultrasound pulse.

(c) Give two reasons why the height of the second pulse is smaller than that of the first pulse.

(d) State one advantage and one disadvantage of ultrasound compared with X-rays in medical imaging.

Ultrasound

Exam Style Question 7

(a)Describe the practical process, including details of the use of the transducer and the adjustment of the oscilloscope, required to produce this A-scan.
Surface of body covered with an oil to improve transmission from ultrasound transducer to body.
Short ultrasound pulses sent into the body and echoes received. These pulses are detected by the transducer from the surface.
The oscilloscope sweep time is synchronised with the ultrasound pulse frequency.

(b) Estimate
(i) the thickness of the organ if the speed of ultrasound in the tissue is $1500\ m\ s^{-1}$ (the horizontal scale is $0.02\ ms/cm$),
Use $distance = speed \times change\ in\ time$

$$\Delta time = 4\ squares(or\ 4\ cm) \times 0.02\ ms/cm = 0.08\ ms$$
$$\therefore distance = 1500\ m\ s^{-1} \times 0.08 \times 10^{-3}\ s = 0.12\ m$$
$$thickness = \frac{0.12\ m}{2} = 0.06\ m$$

(ii) the duration of the first ultrasound pulse.
Duration of the pulse is the horizontal length of the peak of the pulse and how many squares it takes up. In this case it takes up about 0.3 squares.

$$pulse\ duration = 0.3\ cm \times 0.02\frac{ms}{cm} = 0.006\ ms$$

(c) Give two reasons why the height of the second pulse is smaller than that of the first pulse.
- Extra distance in tissue results in more signal absorption.
- Pulse more spread over time.
- Signal is diffracted.

(d) State one advantage and one disadvantage of ultrasound compared with X-rays in medical imaging.
Advantage: Not harmful to living cells or soft tissue.
Disadvantage: Cannot penetrate bone or low resolution.

Please see '21.3.1 Using Ultrasound notes' pack for revision notes.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.

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