- **Candidates should be able to :**
  - Describe the **properties of ultrasound**.
  - Describe the **piezoelectric effect**.
  - Explain how **ultrasound transducers** emit and receive high-frequency sound.
  - Describe the **principles of ultrasound scanning**.
  - Describe the differences between **A-scan** and **B-scan**.
  - Calculate the **acoustic impedance (Z)** using the equation :

$$Z = \rho c$$

  - Calculate the **fraction of reflected intensity (I_r)** using the equation :

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

  - Describe the importance of **impedance matching**.
  - Explain why a **gel is required for effective ultrasound imaging techniques**.

ULTRASOUND

ULTRASOUND is any sound wave having a frequency greater than the upper frequency limit of human hearing (20 kHz).

- In medical imaging the **ultrasound frequency range is 2 to 10 MHz**.
- The **speed of ultrasound** depends on the substance through which it travels. The table opposite gives ultrasound speeds in some common medical imaging substances.

SUBSTANCE	Ultrasound speed/m s^{-1}
air	330
bone	2700 - 4100
muscle	1545 - 1630
soft tissue	1460 - 1615
fat	1450
blood	1570

- At the **high frequencies** used in medical imaging, the **ultrasound wavelength** will be **very small** and this means that smaller details can be detected in a scan.

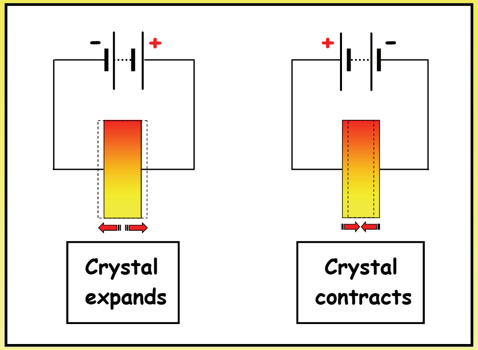
e.g. for ultrasound of **f = 5 MHz** travelling through muscle tissue, the **wavelength (λ)** is given by :

$$\lambda = \frac{v}{f} = \frac{1500}{5 \times 10^6} = \mathbf{3 \times 10^{-4}\ m \ \text{or}\ 0.3\ mm}$$

THE PIEZOELECTRIC EFFECT

- Ultrasonic waves are emitted from a crystal transducer.

- When a p.d. is applied across such a crystal, it **expands** along one axis and when the p.d. is reversed, the crystal **contracts** as shown in the diagram opposite.



- The reverse is also true. If pressure is applied to the crystal, a small p.d. develops across it.

This is the **PIEZOELECTRIC EFFECT**.

> The property of certain crystalline or ceramic materials to develop a p.d. when deformed by the application of pressure and to deform when a p.d. is applied to them. This effect provides a means of converting electrical into sound energy and it is used in the ultrasound transducer to produce ultrasound waves for medical imaging.

THE ULTRASOUND TRANSDUCER

- An **ultrasound transducer** is a device for emitting and detecting ultrasound. The key component of the transducer is the piezoelectric crystal which works on the principle of the **piezoelectric effect**. The same transducer is used to **transmit** ultrasound and to **detect** the reflected ultrasound waves.

  - When an **alternating voltage** (of frequency = the resonant frequency of the crystal) is applied to the crystal, it is set into **resonant vibration of the same frequency as that of the alternating voltage**. The crystal vibrations produce ultrasound waves which are transmitted into the substance the transducer is in contact with.

PRINCIPLES OF ULTRASOUND SCANNING

- Ultrasound scanning makes use of echoes. The ultrasound waves from a transducer are reflected at the boundary between one substance and another.

  The boundary at which the reflection occurs might be that between the air and the skin, or tissue and liquid, or tissue and bone.

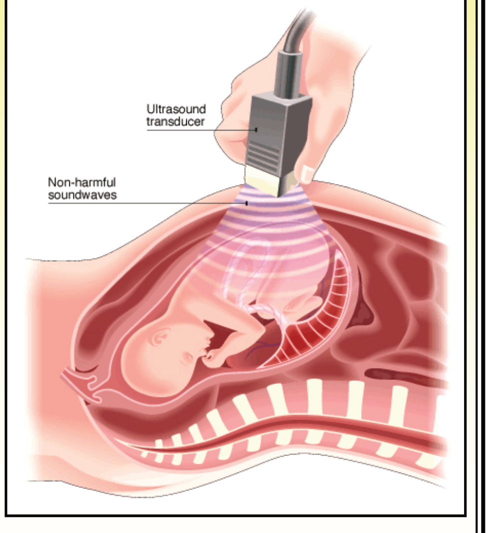
- The basic ultrasound system works on a pulse echo technique using the equation :

$$s = vt$$

s = distance from the transducer to the boundary and back.

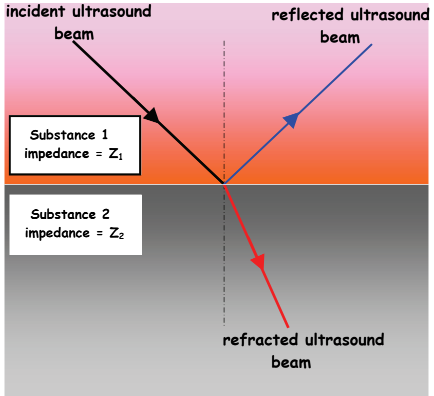
v = speed of ultrasound in the substance.

t = time for the ultrasound to travel to the boundary and back.



If **v** is known and the time interval **t** between the emitted pulse and the reflected pulse can be measured, then **s** can be calculated.

- When an ultrasound wave is incident on the boundary between two different substances, some of the ultrasound will be **reflected** and some will be **refracted**.



The amount of refraction depends on the **acoustic impedance (Z)** of each of the substances and this is given by :

$$Z = \rho v$$

acoustic impedance ($kg\ m^{-2}\ s^{-1}$)
substance density ($kg\ m^{-3}$)
speed of ultrasound in substance ($m\ s^{-1}$)

- The greater the **difference in acoustic impedance (Z)** between the two substances, the greater is the amount of ultrasound **reflected** at the boundary.

It can be shown that for **normal** incidence, the ratio of the **reflected intensity (I_r)** to the **incident intensity (I_0)** is given by :

$$\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

Z_1 = acoustic impedance of substance 1.
Z_2 = acoustic impedance of substance 2.

- The **density (ρ)** and acoustic **impedance (Z)** for some common substances in medical imaging are given in the table shown below :

substance	Density (ρ)/kg m^{-3}	Acoustic impedance (Z)/kg m^{-2} s^{-1}
air	1.3	400
bone	1300 - 1900	7.8×10^6
muscle	1000	1.7×10^6
soft tissue	1000	1.6×10^6
fat	1000	1.4×10^6
blood	1000	1.6×10^6

- Using the equation for I_r/I_0 and the values for **acoustic impedance (Z)** shown above, we can deduce the following :

  - For an **air-fat** boundary : $\frac{I_r}{I_0} = \frac{(1.4 \times 10^6 - 400)^2}{(1.4 \times 10^6 + 400)^2} = 0.99$

    Which means that **99%** of the ultrasound intensity incident at an **air-fat** boundary is **reflected** and **only 1%** is **transmitted**.

  - For an **fat-muscle** boundary : $\frac{I_r}{I_0} = \frac{(1.7 \times 10^6 - 1.4 \times 10^6)^2}{(1.7 \times 10^6 + 1.4 \times 10^6)^2} = 0.01$

    Which means that **only 1%** of the ultrasound intensity incident at a **fat-muscle** boundary is **reflected** and **99%** is **transmitted**.

IMPEDANCE (OR ACOUSTIC) MATCHING

- The acoustic impedance (Z) of air is **400 kg m^{-2} s^{-1}** and that of human skin is **1.7 x 10^{6} kg m^{-2} s^{-1}**, so if an ultrasound transducer were to be placed directly on to the patient's skin, **$I_r/I_0 \approx 0.999$**.

  Thus **99.9%** of the incident ultrasound intensity would be **reflected** and only **0.1%** would actually be **transmitted** into the body. Imaging the internal structures of the patient's body would then be impossible.

  In order to ensure that most of the ultrasound is transmitted into the patient, a **special gel** is smeared between the patient's skin and the transducer. **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 effective imaging of internal structures.

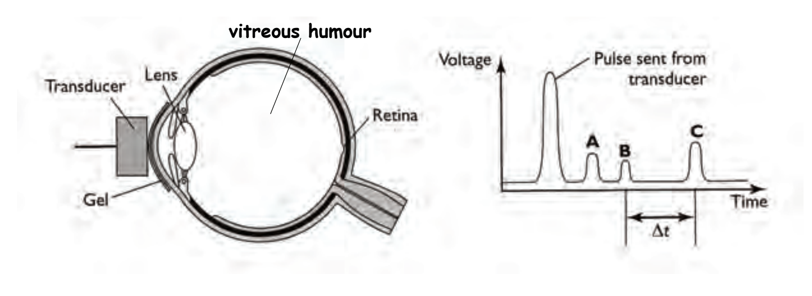
  It should also be noted that using ultrasound, little can be seen beyond the lungs or any other gas-filled cavities.

  In order for the bladder to be examined using ultrasound, it needs to be full.

The process by which the acoustic impedances of the two substances on either side of a boundary are made nearly equal in order to ensure effective ultrasound transmission is called **impedance(or acoustic) matching**.

A-SCANS AND B-SCANS

- An **A-SCAN** gives an image of voltage peaks on a cathode-ray oscilloscope screen from which the internal dimensions of cysts and organs can be determined.
  The ultrasound transducer sends pulses into the patient and detects the reflections from various boundaries within an organ.



The simplified diagram above shows an A-scan of the human eye.
The reflected pulses **A** and **B** are from the front and back of the eye lens.
Pulse **C** is produced by the ultrasound reflection from the retina.

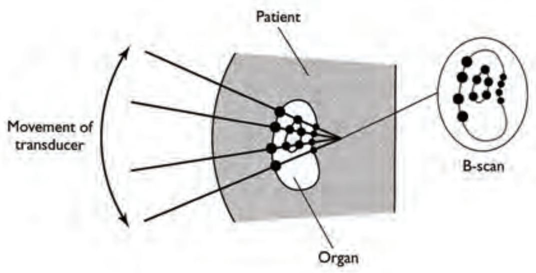
Time, **Δt** = the time taken for the ultrasound to travel from the back of the eye lens to the retina and back again.

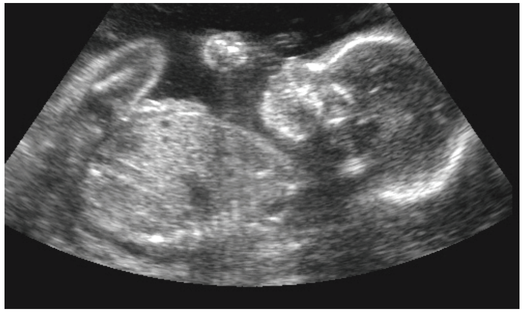
Since the speed **(v)** of the ultrasound in the vitreous humour is known, the lens to retina length **(d)** can be calculated using the equation :

$$2d = v\Delta t$$

If the speed of ultrasound in the vitreous humour of the eye is **1060 m s^{-1}**, and it is found that the time taken for a pulse to travel from the lens to the retina and back is **40 μs**, calculate the length of the eyeball.

- **B-SCANS** are composed of many A-scans and produce a detailed 2-dimensional image of the inside of a patient. **Pre-natal (fetal)** scans are the most common example of a B-scan.





- The transducer is swept to and fro over the part of the patient's body under investigation (in the case of a pregnant woman, the abdomen) and a computer determines the position and orientation of the transducer. Each reflected pulse is analysed and the depth and nature of the reflecting boundary is determined.

  The B-scan image is built up from the superimposition of a large collection of A-scans. Since this takes several seconds, any movements within the organ being scanned will degrade the quality of the image obtained. For example a B-scan of a pulsating heart would yield a blurred and virtually useless image. This is why fetal scans are usually quite blurry.

- **PRACTICE QUESTIONS**

1 At a frequency of **1 MHz** the intensity of any ultrasound falls by **50%** in **70 mm** of soft tissue. Deduce the **percentage reduction in intensity** of **1 MHz** ultrasound after travelling **280 mm** through soft tissue.

2 **(a)** What is the **acoustic impedance** of human bone of density **1800 kg m^{-3}** if ultrasound travels through it at a speed of **3700 m s^{-1}**?

(b) Calculate the **speed** of ultrasound in air, given that its density is **1.3 kg m^{-3}** and its acoustic impedance is **400 kg m^{-2} s^{-1}**.

(c) Blood has an acoustic impedance of **1.6 x 10^{6} kg m^{-2} s^{-1}** and ultrasound travels through it at a speed of **1600 m s^{-1}**. Calculate the **density** of blood.

3 The acoustic impedance of **bone** and **brain tissue** is **6.4 x 10^{6} kg m^{-2} s^{-1}** and **1.6 x 10^{6} kg m^{-2} s^{-1}** respectively.

With the aid of a calculation, explain why an ultrasound scan is **NOT** a sensible procedure for imaging a patient with suspected head/brain injuries.

4 **(a)** Show that the unit of **acoustic impedance** is **kg m^{-2} s^{-1}**.

(b) Explain why the term : $\frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$

has **no units** and why **the terms in brackets need to be squared.**

- **HOMEWORK QUESTIONS**

1 **Fig 1.** below shows a cross-section through an ultrasound transducer.

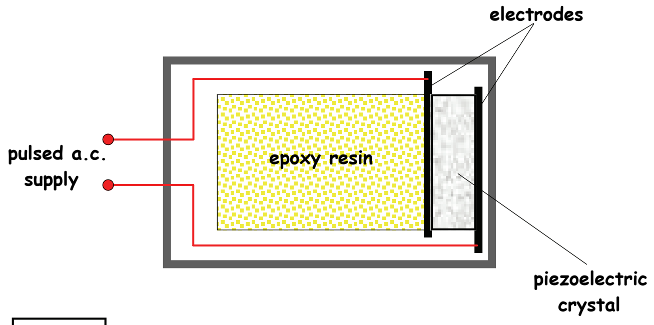


Fig 1.

The piezoelectric crystal is backed by a slab of epoxy resin, and the power supply to the electrodes either side of the crystal is pulsed.

(a) Describe the **generation** and **detection** of ultrasound by a piezoelectric crystal. Explain why the epoxy resin is needed and give reasons for pulsing the ultrasound.

(b)

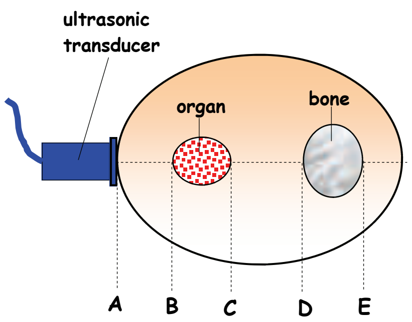


Fig 2.

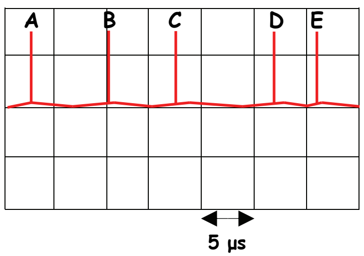


Fig 3.

Fig 2. shows a cross-section through a part of the body. Ultrasound is pulsed through the centre of the section so that it passes first through an organ and then through a bone.

Fig 3. is an oscilloscope trace of the reflected ultrasound signal received from the gel-skin boundary and then from the front and back edges of first the organ and then the bone.

DATA

material	ultrasound speed/m s^{-1}
organ	1600
bone	4100
Soft tissue	1100

(i) Deduce from **Fig 3.** the **time interval in s** during which the Ultrasound travels in the **organ.** The time-base setting on the oscilloscope is **5 μs cm^{-1}**.

(ii) Calculate the **distance in m** travelled by ultrasound through the organ.

(iii) Calculate the **thickness in m** of the organ.

(iv) Calculate the **thickness in m** of the bone.

(c) Explain one example where **ultrasound is used rather than X-rays** for medical imaging.

(OCR A2 Physics - Module 2825 - January 2004)