A2 Level Physics

Chapter 21 – Medical Imaging

21.3.1 Using Ultrasound

Notes

Ultrasound

Any sound wave with a frequency higher than the upper frequency limit of human hearing (20 000 Hz) is said to be ultrasound.

The ultrasound frequency range in medical imaging is 1 to 15 MHz.

The speed of ultrasound depends on the substance through which it travels.

The speed of ultrasound through air is $330\ ms^{-1}$, through muscle it is between $1545-1630\ ms^{-1}$ and through bone it is between $2700-4100\ ms^{-1}$.

The ultrasound wavelength will be very small at the high frequencies used in medical imaging, which means that smaller details can be seen in a scan (i.e. a higher resolution is obtained).

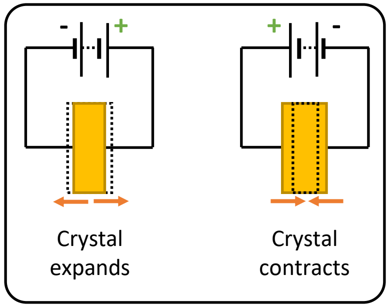
e.g. when an ultrasound of frequency $f=4\ MHz$ travels through muscle tissue (ultrasound speed = $1500\ ms^{-1}$), the wavelength (λ) is given by:

$$\lambda=\frac{v}{f}=\frac{1500}{4\times10^{6}}=3.75\times10^{-4}m\ or\ 0.4mm$$

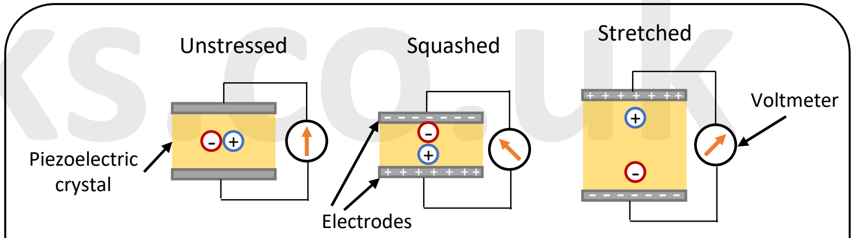
The Piezoelectric Effect

A crystal transducer produces ultrasonic waves.

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. If the p.d. is alternating, then the crystal vibrates at the same frequency as the alternating p.d.



The opposite is also true. When you apply a pressure (squashed or stretched) to the crystal, a tiny p.d. is produced across it.



When piezoelectric crystals are squeezed or stretched, they create an electric potential difference.

This is the piezoelectric effect.

The piezoelectric effect is defined as:

When some crystalline or ceramic materials are deformed by applying pressure, they produce a p.d. and when a p.d. is applied to them, they deform.

A piezoelectric crystal can be used as an ultrasound receiver, which converts sound waves into alternating voltages, or as a transmitter, which converts alternating voltages back into sound waves.

Ultrasound Transducer

A device that emits and detects ultrasound is known as an ultrasound transducer. The piezoelectric crystal is the key component of the transducer and works on the principle of the piezoelectric effect. The same transducer is used to transmit ultrasound and to detect the reflected ultrasound waves.

An alternating voltage (of frequency = the resonant frequency of the crystal) is applied to the crystal, to set it into resonant vibration of the same frequency as that of the alternating voltage. Ultrasound waves are produced by the vibrating crystal and are transmitted into the substance with which the transducer is in contact with.

Principles of Ultrasound Scanning

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

The boundary where the reflection occurs could be between the air and the skin, or between the tissue and the liquid, or between the tissue and the bone.

The basic ultrasound system uses the *pulse echo technique**, which is represented by the equation:

$$s = vt$$

Where:

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

v = ultrasound speed in the substance,

t = the time it takes for the ultrasound to travel to and from the boundary.

s can be calculated if the v is known and the time interval t between the emitted and reflected pulses is measured.

*The pulse-echo technique is used with ultrasound waves for imagining of objects, most notably for medical imaging. The fact that waves are reflected when they meet boundaries between different materials is the basis for this approach.

Principles of Ultrasound Scanning

Acoustic Impedance

When an ultrasound wave hits the boundary between two different substances, some of the ultrasound is reflected and the rest is refracted.

The acoustic impedance (Z) of each of the substances determines the amount of refraction, and can be calculated using the equation:

$$Z = \rho v$$

Where:

Z = acoustic impendence in $kg\, m^{-2}s^{-1}$,

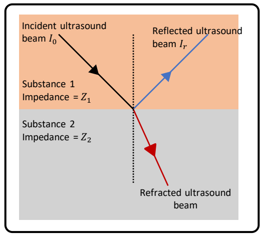
ρ = the density of the substance in $kg\, m^{-3}$,

v = ultrasound speed in substance in ms^{-1}.

The amount of ultrasound reflected at the boundary increases as the difference in acoustic impedance (Z) between the two substances increases.

The ratio of the reflected intensity (I_r) to the incident intensity (I_0) for a normal incidence can be calculated as follows:

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



Where:

I_r = intensity of reflected wave in Wm^{-2},

I_0 = intensity of incident wave in Wm^{-2},

Z_1 = acoustic impedance of first material in $kgm^{-2}s^{-1}$,

Z_2 = acoustic impedance of second material in $kgm^{-2}s^{-1}$.

Principles of Ultrasound Scanning

If the difference in impedance between the two substances is large, then most of the energy is reflected (the intensity of the reflected wave I_r will be high). There is no reflection if the impedance of the two materials is the same.

For example:

The table below shows the density (ρ) and acoustic impedance (Z) of several substances used in medical imaging:

Substance	Density $(\rho)/kgm^{-3}$	Acoustic impedance $(Z)/kgm^{-2}s^{-1}$
Air	1.3	400
Muscle	1000	1.7×10^6
Fat	1000	1.4×10^6

Using the equation for $\frac{I_r}{I_0}$ and the values for acoustic impedance (Z) shown above, we can deduce the following:

For an air-fat boundary: $\frac{I_r}{I_0} = \frac{(1.4\times10^6-400)^2}{(1.4\times10^6+400)^2} = 0.99$

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

For a fat-muscle boundary: $\frac{I_r}{I_0} = \frac{(1.7\times10^6-1.4\times10^6)^2}{(1.7\times10^6+1.4\times10^6)^2} = 0.01$

This means that just 1% of the ultrasound intensity incident at a fat-muscle boundary is reflected, while the remaining 99% is transmitted.

Impedance (or Acoustic) Matching

Since, the acoustic impedance (Z) of air is $400kgm^{-2}s^{-1}$ and the acoustic impedance of human skin is $1.7 \times 10^6\ kgm^{-2}s^{-1}$, if an ultrasound transducer is to be placed directly on to the patient's skin, $\frac{I_r}{I_0} \approx 0.999$.

As a result, 99.9% of the incident ultrasound intensity would be reflected, with only 0.1% being transmitted into the body. It would then be impossible to image the patient's internal structures.

Therefore a special gel is applied between the patient's skin and the transducer to ensure that most of the ultrasound is transmitted into the patient. Since the gel's acoustic impedance is nearly identical to that of the skin, very little ultrasound is reflected, allowing for effective imaging of internal structures.

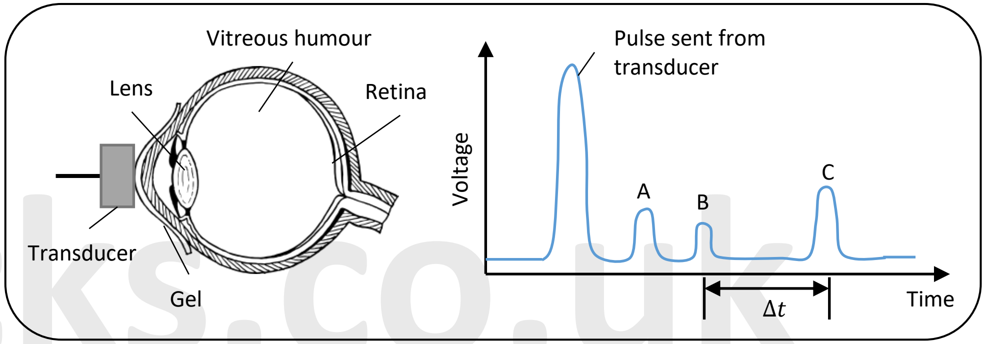
It's also worth noting that ultrasound can't detect much beyond the lungs or other gas-filled cavities.

A-scans and B-scans

An A-scan and a B-scan are two different types of ultrasound scanning.

The A-scan

The amplitude scan (A-scan) sends a pulse of ultrasound to the body and at the same time an electron beam travels across a cathode ray oscilloscope (CRO) screen. A spike appears on the oscilloscope every time the transducer receives a pulse. The time taken is shown on the x-axis, while signal strength is shown on the y-axis.



The duration between the spikes can be used to determine the thickness and depths at which the ultrasound reflected (for example, the diameter of a baby's head). How much ultrasound is reflected is indicated by the signal strength.

An A-scan of the human eye is shown in the simplified diagram above. The reflected pulses A and B are from the front and back of the eye lens. The ultrasound reflected from the retina generates pulse C.

Time, Δt = is the amount of time it takes an ultrasound to travel from the back of the eye lens to the retina and back.

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:

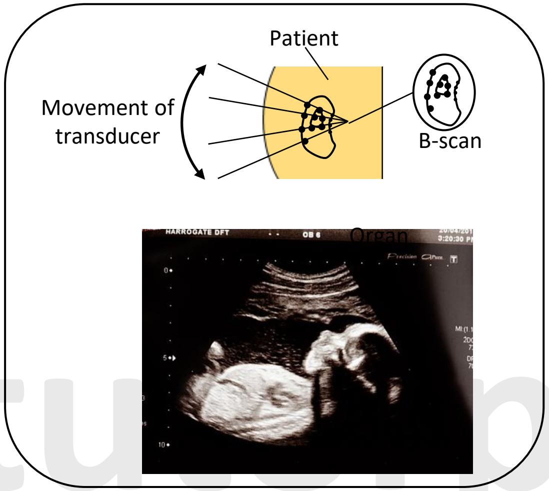
$$2d = v\Delta t$$

This method does not produce an image, but it does allow for the measuring of dimensions.

A-scans and B-scans

The B-scan

A brightness scan (B-scan) is made up of several A-scans that produce 2D or 3D images of the inside of a patient. The most common type of B-scan is a prenatal (foetal) scan.



The transducer is moved back and forth on the part of the patient's body that is being examined, and the position and orientation of the transducer are determined by a computer. The greater the reflection, the brighter that region will appear on screen. Each reflected pulse is analysed to determine the depth and nature of the reflecting boundary.

Note:

The B-scan image is produced from the superimposition of a large collection of A-scans. This means any movements within the organ being scanned will decrease the quality of the image obtained. A B-scan of a pulsing heart, for example, would produce a blurry and unusable image. This is why most foetal scans are blurry.

Advantages and Disadvantages

Advantages

- It's useful for imaging soft tissues because you can get real-time images — X-ray fluoroscopy can do this, but it comes with a high dosage of ionising radiation.
- Unlike X-ray imaging, ultrasound imaging has no known risks, side effects and exposure to ionising radiation.
- Unlike MRI scanners, which cost millions of pounds, ultrasound instruments are cheap and portable.
- The scan takes about 10 to 15 minutes, and the patient can move around during it.

Disadvantages

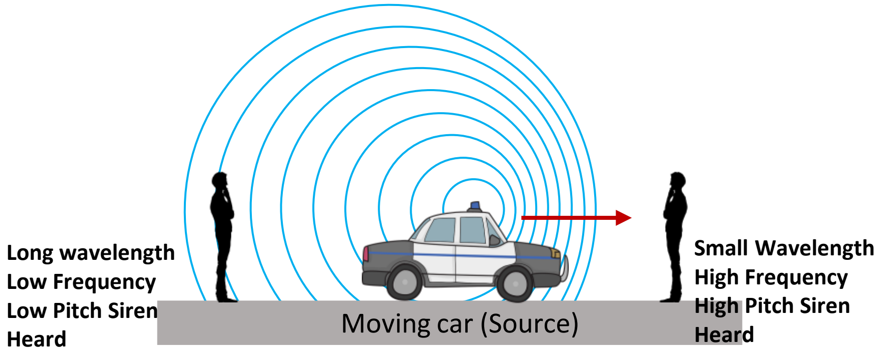
- The resolution is low, therefore you won't be able to see fine detail.
- Due to a mismatch in impedance, ultrasound cannot flow through air gaps in the body and so cannot provide images from behind the lungs.
- Since ultrasound cannot penetrate bone, it cannot identify fractures or scan the brain.

• Difference between A-scan and B-scan

1) B-scan consists of multiple A-scans.
2) B-scan produces 2D or 3D images.
3) A-scan is one directional, but B-scan involves different directions of angles.

Doppler Effect in Ultrasound

When there is a relative velocity between a wave source and an observer/detector, the wavelength or frequency of the wave changes, and this is known as the doppler effect.



The doppler effect can be used in medical applications, such as:

1) Measuring the speed of blood flow

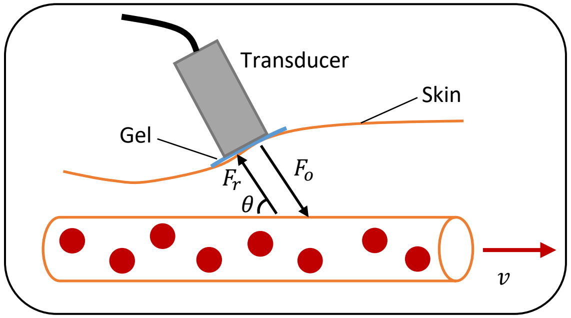
An ultrasound transducer is a device for emitting and detecting sound waves with a frequency greater than 20 kHz.

When an ultrasound transducer is held close to a major blood artery, the iron-rich blood cells reflect the ultrasound.

According to the Doppler effect, reflected ultrasound has a slightly higher frequency for blood flowing towards the transducer and a slightly lower frequency for blood flowing away from the transducer.

Doppler Effect in Ultrasound

The speed at which blood flows is directly proportional to the change in ultrasound frequency (Δf). Therefore the speed at which blood flows can be determined from Δf.



The equation linking the frequency of emitted and reflected waves to the speed of blood travelling at v is:

$$\frac{\Delta f}{f} = \frac{2v\ cos\theta}{c_{ultrasound}}$$

Where:

Δf = change in ultrasound frequency (the doppler shift in frequency),

f = original frequency of the ultrasound,

v = speed of blood travelling,

$c_{ultrasound}$ = speed of ultrasound in the tissue,

θ = the incident angle of the ultrasound beam with respect to the moving object.

In the case of a foetus, the direction of blood flow via the heart is important. Blood can flow backwards in some parts of the pumping cycle or by-pass particular parts of the body if there is a heart-valve problem. This type of condition can be diagnosed with Doppler ultrasound.

Doppler Effect in Ultrasound

2) Determining Heartbeat Rate

An ultrasound transducer is placed on the patient’s chest, directly above the heart. The heart's surface approaches and recedes from the transducer as it beats.

The heartbeat rate can then be calculated using the increase and decrease in the frequency of the detected ultrasound.

Please see ’21.3.2 Using Ultrasound worked examples’ pack for exam style questions.

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