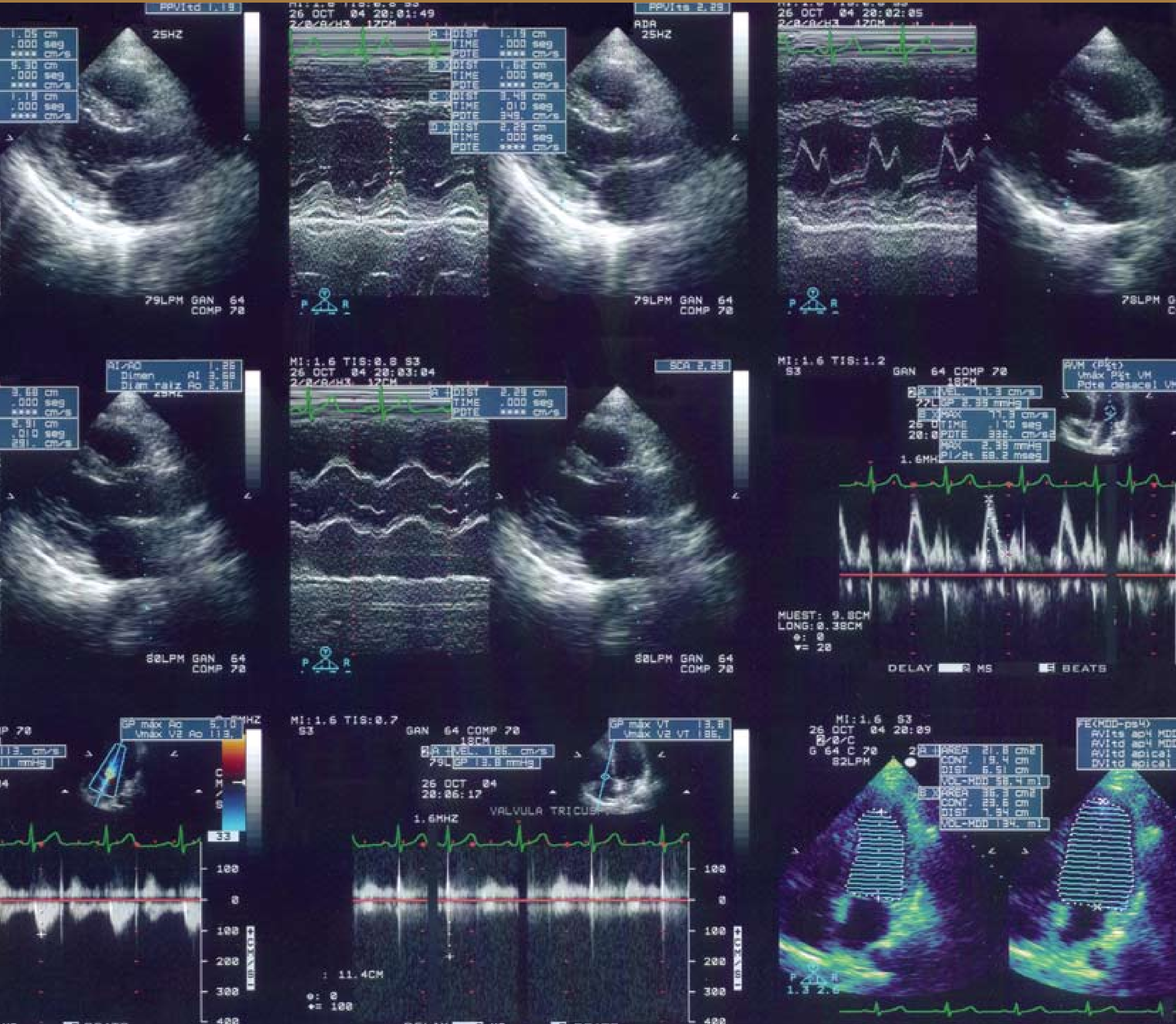
MEDICAL PHYSICS

Mind map



CHAPTER 18

Ultrasound

The properties of ultrasound waves can be used as diagnostic tools

Introduction

The option module Medical Physics focuses on the designs and physics principles behind various imaging methods used in clinical medicine. These image methods are: ultrasound; X-rays and computer axial tomography (CAT or CT); endoscopies; nuclear medicine and positron emission tomography (PET); and magnetic resonance imaging (MRI).

In a hospital setting, an ultrasound can be done with a portable device or in the radiology department. X-ray and CT are the most commonly performed scans in the radiology department. Endoscopies, depending on the type, are used by different departments in the hospital. For instance, colonoscopies (see Chapter 19) are performed by gastroenterology departments, whereas arthroscopies (see Chapter 20) are performed by orthopaedic (bone) surgeons. MRIs are only available in the radiology department of large hospitals or private hospitals as they are very expensive.

The advantages and disadvantages of the clinical use of these scans as well as their cost-effectiveness will be evaluated throughout this module. By studying this module, you should be able to appreciate the choices of certain scans for particular reasons, both in terms of their accuracy and cost-effectiveness.

This chapter discusses the physical principles behind ultrasound as well as its clinical uses.

18.1 Sound waves

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Simulation: Sound harmonics

Sound waves are energy that propagates through a medium, which causes the particles of the medium to vibrate back and forth along the direction of the propagation. For this reason, they are classified as **mechanical waves**, since they require a medium to travel through. The nature of the vibration of the particles makes sound waves **longitudinal waves**.

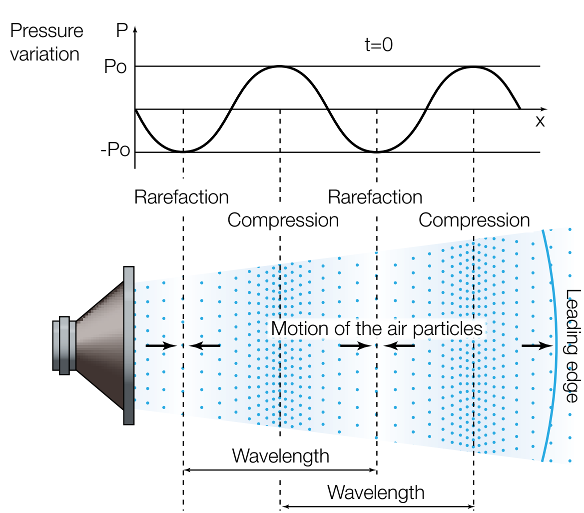

Figure 18.1 A sound wave; note the compression, rarefaction and wavelength

NOTE: For a longitudinal wave, particles vibrate back and forth, in contrast to a transverse wave, where particles vibrate up and down perpendicularly to the direction of the wave propagation.

A representation of a sound wave is shown in Figure 18.1. Note the regions where particles are closer together, which are known as **compressions** and regions where particles are further apart, known as **rarefactions**. Also, the distance between two consecutive compressions or rarefactions is equal and is termed the **wavelength**.

18.2 Ultrasound

■ *Identify the differences between ultrasound and sound in normal hearing range*

The human ear can hear sound between the frequencies of 20 to 20 000 Hz. The frequency of the sound waves corresponds to their pitch: a low frequency corresponds to a low pitch and a high frequency corresponds to a high pitch. Ultrasound, on the other hand, is sound waves that have higher frequencies than the upper limit of the human hearing range, that is, they have frequencies greater than 20 000 Hz. Nevertheless, ultrasound actually exists in nature. It is produced by animals such as dolphins and bats as a part of their navigation systems.

For clinical uses, ultrasound waves are produced artificially, via the piezoelectric effect, which is discussed in the next section. The ultrasound produced for clinical uses usually has a specific frequency determined by the nature of the body parts being scanned. Generally a higher frequency produces a better resolution but a lower frequency increases the penetration. It is logical then that for a superficial organ, such as the skin or muscle, the sound waves do not need to penetrate far. These may be scanned with a high frequency (say 10 MHz) in order to produce better quality images. Scanning a deep body organ, such as the liver, will require more penetrative ultrasound waves, and hence a lower frequency (say 1 MHz). The trade-off in this case will be a lower resolution for the images produced.

NOTE: The intensity or the loudness of a sound wave is determined by its amplitude.

18.3 Piezoelectric materials and the piezoelectric effect

■ *Describe the piezoelectric effect and the effect of using an alternating potential difference with a piezoelectric crystal*

The piezoelectric effect forms the basis for the production and detection of ultrasound waves.

Definition

The **piezoelectric effect** is the phenomenon where mechanical vibrations of a substance are converted into electric signals and vice versa.

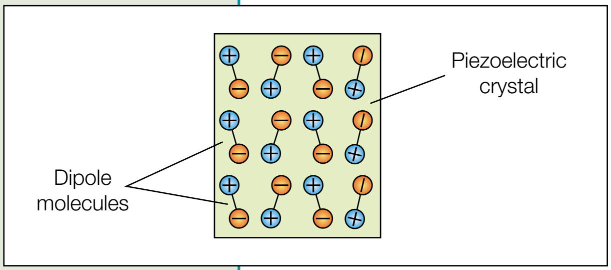

Figure 18.2 (a) A piezoelectric material in its 'normal' state

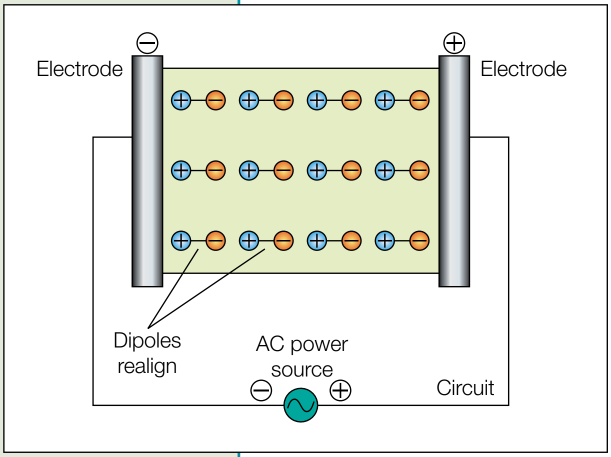

Figure 18.2 (b) A piezoelectric material when placed inside an electric field (when a potential difference is applied)

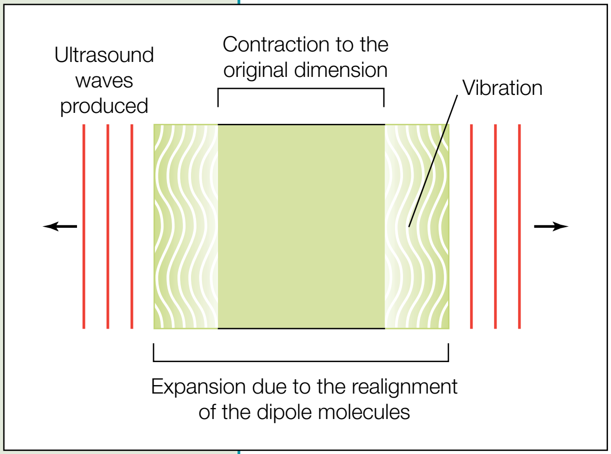

Figure 18.2 (c) The vibration of the piezoelectric material produces ultrasound waves

Piezoelectric materials (crystals) are materials that are able to demonstrate the piezoelectric effect. Some common piezoelectric crystals include quartz and barium titanate.

Piezoelectric crystals are made up of dipole molecules arranged in a lattice form.

NOTE: Dipole molecules are molecules that have a positive pole at one end and a negative pole at the other.

Normally the arrangement of the dipole molecules is such that the piezoelectric crystals would not express any net polarity. This is shown in Figure 18.2 (a). When a piezoelectric crystal is subjected to a potential difference (electric field), its dipole molecules will realign and the new orientation of these molecules will change the dimension of the crystal. In this case, as shown in Figure 18.2 (b), the crystal will expand. If alternating voltage—a voltage that swings from a positive maximum to zero, to a negative maximum then repeats (a sine wave)—is used, then the piezoelectric crystal will continue to alter its dimension, between expansion and contraction to its original dimension (when the AC voltage swings to zero). This results in vibrations that in turn vibrate the air to produce sound. See Figure 18.2 (c). Not surprisingly, the frequency of the vibration of this piezoelectric crystal, which is determined by the frequency of AC supply, will determine the frequency of the sound waves produced. When the frequency of the AC supply is sufficiently high, ultrasound waves are produced. Also, by adjusting the frequency of the AC supply, ultrasound with specific frequencies maybe produced.

The same piezoelectric crystal can also be used to convert ultrasound waves to electric signals. When an ultrasound wave strikes the crystal, it causes the crystal to resonate.

NOTE: To resonate in this case is to vibrate at the same frequency as the ultrasound wave.

The vibration of the crystal results in a dimension change, which is accompanied by an realignment of the dipole molecules. This realignment allows the crystal to express a net polarity; hence, an electric field or potential difference is created. This will cause a current to flow if there is a complete circuit connected to the piezoelectric crystal. (This is essentially the reverse of that shown in Figure 18.2b.) Because vibrations will cause a constantly changing alignment of the dipole molecules, a changing current that reflects the pattern of the vibration (hence the sound wave) will be produced.

Transducers

A transducer unit is a functional unit that produces and detects ultrasound. One or more transducer units may be contained by a single ultrasound probe, one that is held by the clinician to conduct an ultrasound scan. Each transducer unit contains a piezoelectric crystal, and in most transducer units, the same piezoelectric crystal is used to both produce and receive ultrasound.

18.4 The basic principle behind ultrasound imaging

An ultrasound machine

Ultrasound scans are widely used in clinical medicine to produce images of body organs. The details of the designs and functional principles of an ultrasound machine can be quite complicated. However, these can be simplified by considering the schematic drawing shown in Figure 18.3.

To summarise the sequence of events:

1. Ultrasound waves are produced by the piezoelectric crystal that is embedded inside the transducer (probe) (as discussed).
2. Ultrasound waves penetrate through the body wall, with a small portion of the waves being reflected.
3. Ultrasound waves hit the first wall of the target organ. Some of the wave energy is reflected while some goes through.
4. Ultrasound waves reach the other wall of the organ and behave the same as in step 3.
5. Those reflected waves (echoes) from 3 and 4 again penetrate the body wall.
6. The returning ultrasound waves are picked up by the transducer and are converted into electrical signals by the embedded piezoelectric crystal. These signals are then fed through a computer to construct the images of the scanned organ.

(Note that the numbers shown in the diagram correspond to the numbers used in the text.)

The reflection and penetration of the ultrasound waves as well as the image formation process by the computer are explained in detail later in this chapter.

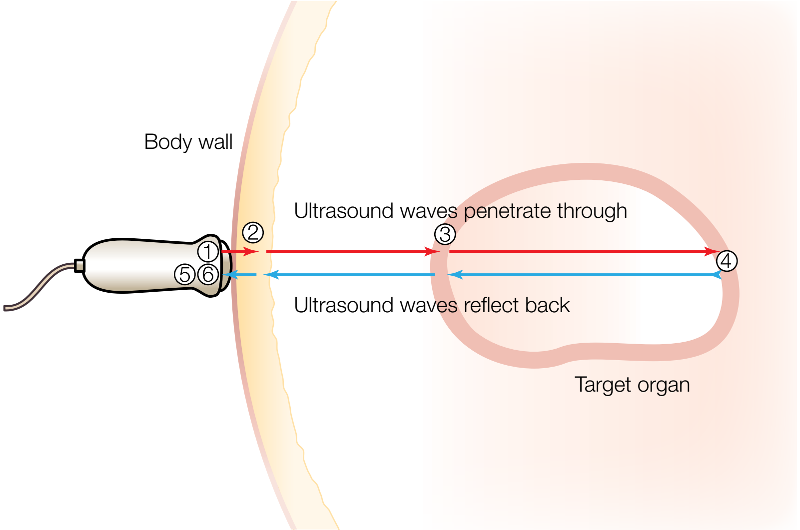

Figure 18.3 Performing an ultrasound scan of a body organ

18.5 A closer look at the reflection and the penetration of ultrasound waves

- ***Define acoustic impedance: $Z = \rho v$ and identify that different materials have different acoustic impedances***
- ***Describe how the principles of acoustic impedance and reflection and refraction are applied to ultrasound***
- ***Define the ratio of reflected to initial intensity as:***

$$\frac{I_r}{I_o} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

- ***Identify that the greater the difference in acoustic impedance between two materials, the greater is the reflected proportion of the incident pulse***

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Worked example 20

- ***Solve problems and analyse information to calculate the acoustic impedance of a range of materials, including bone, muscle, soft tissue, fat, blood and air and explain the types of tissues that ultrasound can be used to examine***
- ***Solve problems and analyse information using: $Z = \rho v$ and***

$$\frac{I_r}{I_o} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

It has been mentioned that every time ultrasound waves meet the boundary between two media, such as when they reach the body wall, or the target organ, some of the wave energy is reflected while some penetrates. Although it is the reflected waves that are analysed to form images, the penetrated waves are also important, as they allow the ultrasound to reach deeper body organs that are beyond the first boundary.

So an obvious question is, what determines the amount of reflection and penetration of the ultrasound waves as they hit the boundary? After studying this section, it will be apparent that the relative amount of reflected and penetrated ultrasound waves depends on the difference between the acoustic impedances of the two media that the waves are propagating through.

Acoustic impedance

Definition

Acoustic impedance of a material refers to the ease with which a sound wave can pass through.

The higher the acoustic impedance, the more difficult it is for the sound wave to pass through. Mathematically the acoustic impedance of a material can be represented by the equation:

$$Z = \rho v$$

Where:

Z = the acoustic impedance of the material, measured in kg m^{-2} s^{-1} or rayls

ρ = the density of the material measured in kilograms per metre cube (kg m^{-3})

v = the velocity or speed of the sound wave when travelling through this material, measured in m s^{-1}

Example 1

When an ultrasound wave travels through muscle tissues, it has a speed of 1.57×10^3 m s^{-1}. Knowing that the muscle tissues have a density of 1.06×10^3 kg m^{-3}, calculate the acoustic impedance of the muscle tissues.

Solution

$$\begin{aligned} Z &= \rho v \\ &= (1.06 \times 10^3) \times (1.57 \times 10^3) \\ &= 1.66 \times 10^6 \text{ kg m}^{-2}\text{ s}^{-1} \text{ (rayls)} \end{aligned}$$

Table 18.1 lists the density of some common types of tissue found in a human body as well as the speed of the sound as it travels through the tissue. Try to calculate the acoustic impedance for each of the tissue types.

Table 18.1

Tissue/material	Density (kg m^{-3})	Speed of the sound (m s^{-1})
Air	1.25	330
Water	1.00×10^3	1.54×10^3
Bone	1.75×10^3	3.72×10^3
Muscle	1.06×10^3	1.57×10^3
Fat	953	1.48×10^3
Blood	1.00×10^3	1.56×10^3
Brain	1.04×10^3	1.52×10^3
Liver	1.07×10^3	1.55×10^3

Reflection and penetration

Acoustic impedance by itself does not determine the reflection or penetration of the sound waves. Rather, it is the difference in the acoustic impedance encountered as the sound waves enter from one medium to another. More precisely, the proportion of sound waves that will be reflected back when they hit the boundary between any two media can be mathematically determined using the equation:

$$\frac{I_r}{I_o} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

Where:

I_r = the intensity of the reflected sound waves

I_o = the original intensity of the sound waves

$\frac{I_r}{I_o}$ represents the proportion of the sound waves being reflected and can be expressed as a percentage if necessary. Also because I_r and I_o are expressed as either a ratio or a percentage, they do not have any specific units as long as they are measured using the same units.

Z_1 is the acoustic impedance of medium 1 and Z_2 is the acoustic impedance of medium 2. Again, both Z_1 and Z_2 are measured in kg m^{-2} s^{-1} or rayls.

Important things to note for the above equation:

- When applying this equation to any two media, it does not matter which medium is treated as 'medium 1' and which is treated as 'medium 2'. This is because $Z_2 + Z_1$ is the same as $Z_1 + Z_2$ and the square of $Z_2 - Z_1$ is the same as that of $Z_1 - Z_2$.
- To work out the proportion of the penetrated sound waves, it would simply be $1 - \frac{I_r}{I_o}$.
- The bigger the difference between Z_1 and Z_2, the larger the proportion of the sound waves reflected and the smaller the proportion that will penetrate. The reverse is also true. This can be illustrated in Figure 18.4 (a) and (b).
- When Z_1 and Z_2 are equal, there will be no reflection of the sound waves.

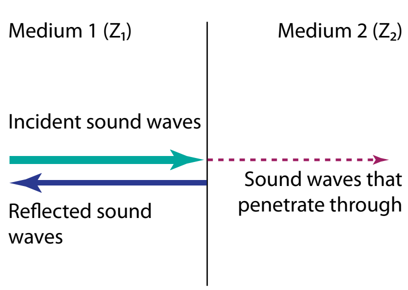


Figure 18.4 (a) When there is a big difference between Z_1 and Z_2, more sound waves will be reflected and a smaller proportion will pass through the boundary

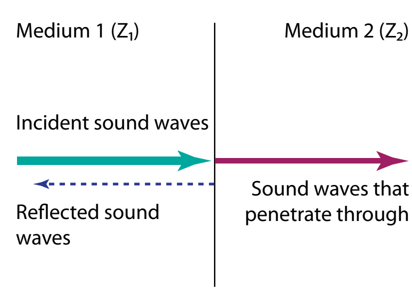


Figure 18.4 (b) When the difference between Z_1 and Z_2 is small, a greater proportion of the sound waves will penetrate and fewer will be reflected

Example 1

Determine the percentage of ultrasound waves that will be reflected when they reach the junction between air and fat tissues.

Solution

$$\frac{I_r}{I_o} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

Z_1 = acoustic impedance of air = 1.25×330

Z_2 = acoustic impedance of fat tissues = $953 \times (1.48 \times 10^3)$

$$\frac{I_r}{I_o} = \frac{[(953 \times 1.48 \times 10^3) - (1.25 \times 330)]^2}{[(953 \times 1.48 \times 10^3) + (1.25 \times 330)]^2}$$

$= 0.999$

$= 99.9\%$

The clinical significance of this particular example is that when performing an ultrasound scan, even if the transducer is pushed tightly against the skin, a small air gap will still exist between the transducer and the skin (for the purpose of this discussion, assume the skin tissue is made up of fat). The existence of the air–fat junction means that 99.9% of the ultrasound waves produced will be reflected at the skin surface and only 0.1% of the waves will be transmitted. This small amount of ultrasound will not be adequate in forming images of deep organs.

To eliminate the air gap, gels with similar acoustic impedance to skin (fat tissues) are used. When the transducer with gel applied is pushed against the skin, the absence of an air gap, as well as a small difference in the acoustic impedance of the gel and the skin, will result in a minimal reflection at the skin surface. Consequently, most of the ultrasound wave energy will penetrate to scan the deep organs.

Example 2

Calculate the percentage of the ultrasound waves that are reflected at the junction between the skull bone and the brain. Calculate the percentage of the ultrasound waves that will reach the brain.

Solution

$$\frac{I_r}{I_o} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

Z_1 = acoustic impedance of bone = $(1.75 \times 10^3) \times (3.72 \times 10^3)$

Z_2 = acoustic impedance of brain = $(1.04 \times 10^3) \times (1.52 \times 10^3)$

$$\frac{I_r}{I_o} = \frac{[(1.04 \times 10^3 \times 1.52 \times 10^3) - (1.75 \times 10^3 \times 3.72 \times 10^3)]^2}{[(1.04 \times 10^3 \times 1.52 \times 10^3) + (1.75 \times 10^3 \times 3.72 \times 10^3)]^2}$$

$= 0.371$

$= 37.1\%$

Therefore the percentage of the ultrasound that will penetrate through to the brain:

$$= 1 - \frac{I_r}{I_o}$$

$= 1 - 0.371$

$= 0.629$

$= 62.9\%$

The clinical significance of this example is that when trying to visualise the brain with ultrasound, at the junction between the skull bone and the brain, 37.1% (or even more, given the fact the skull bone has a higher density than the value provided in Table 18.1) of the ultrasound waves are reflected. On returning towards the transducer, another 37.1% is reflected. The consequence of this is that only a small portion of the ultrasound waves will be received by the detector for image formation. Hence ultrasound scans produce poor images of the brain. Furthermore, this concept can be extended to all body organs that are covered by bones, for instance, the lungs, which are covered by the ribcage. As an ultrasonographer would say, 'The bone casts shadows over the soft tissue organs.'

18.6 Different types of ultrasound scans

■ ***Describe the situations in which A-scans, B-scans and sector scans would be used and the reasons for the use of each***

So far, the production of the ultrasound waves and the rules that determine their reflection and penetration have been described. This section will discuss how the reflected ultrasound waves from a target organ can be analysed by the computer system to form images.

In summary, different types of images can be formed by decoding the received ultrasound waves in different ways. These include A-scans and B-scans, with the B-scans forming the basis for linear scans and sector scans.

A-scan (amplitude scan)

In an A-scan, the reflected ultrasound waves are displayed using wave amplitudes (hence amplitude scan), which are plotted as a function of time. A typical A-scan image is shown in Figure 18.5.

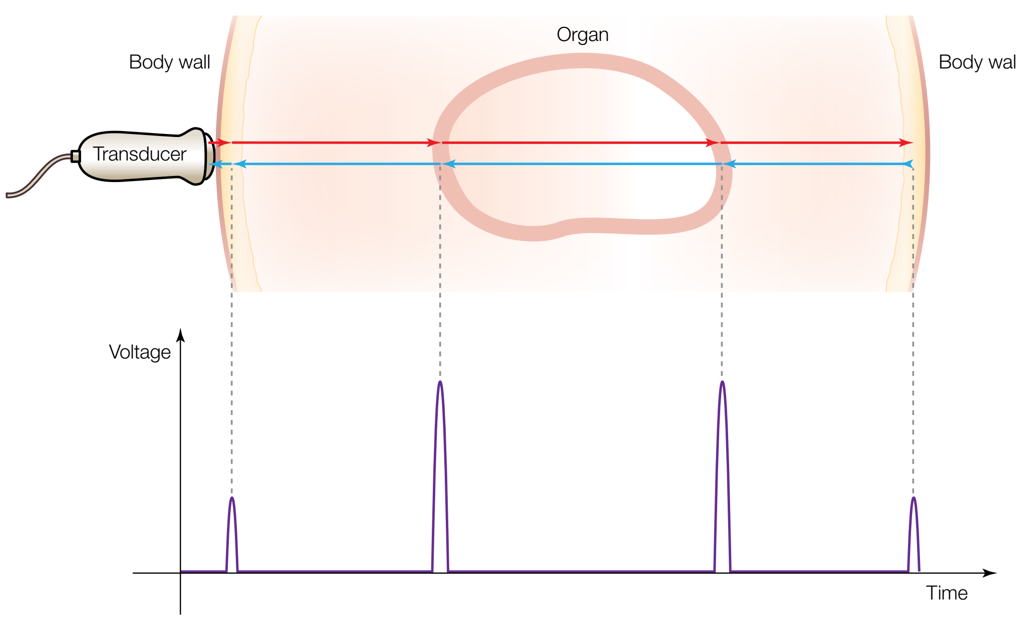


Figure 18.5 An A-scan image of a body organ

In an A-scan the amplitude of the peaks will provide information about the nature of the organ, whereas the position of the peaks will provide information about the location and dimension of the target organ.

As shown in Figure 18.5, as the ultrasound wave hits the near side body wall, a small portion of it reflects. The detector (the piezoelectric material inside the transducer) receives it and converts it into an electrical signal, which is displayed by the computer as a small peak. The ultrasound wave then reaches the near surface of the target organ. Assuming there is more of the ultrasound wave reflected at this interface, a larger peak will be displayed. A similar process will take place when the ultrasound wave reaches the far surface of the organ and the opposite body wall. Essentially, the amount of reflected ultrasound wave—which depends on the type of organ being scanned (some organs produce more reflection than others due to a larger acoustic impedance difference)—will determine the displayed amplitudes. The distance between the peaks is related to the delay between each subsequent reflected ultrasound wave and this depends on the distance between each of the interfaces. Thus the distances between the peaks are a good estimate of the dimension as well as the position of the organ.

Because the images formed by A-scans are two-dimensional and are difficult to interpret, A-scans are not commonly used clinically. A-scans are occasionally used to measure the internal dimensions of the eyes, for instance, the distance from the lens of the eye to the retina, which can be shortened when there is a tumour growing on the retina.

Simple atlas of the eye

NOTE: The distance between the wave peaks relates to the dimension of the target organ.

NOTE: A-scan is also known as A-mode.

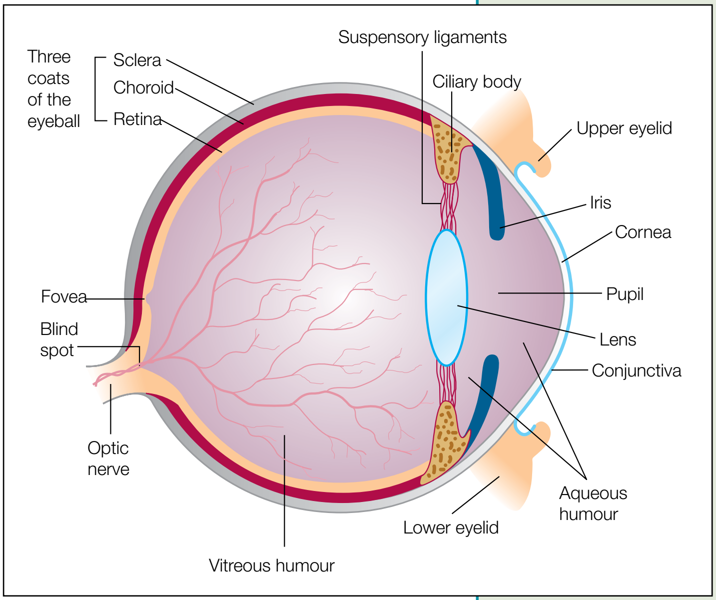
B-scan (brightness scan)

In a B-scan, the reflected ultrasound waves are displayed as fluorescent dots. The more intense the reflection, the brighter the dot; whereas a minimal reflection is displayed as a grey or black dot. The separation of the dots, just like the separation of the peaks in an A-scan, depends on the dimension and position of the target organ. This is summarised in Figure 18.6. Importantly, B-scans form the basis of linear scans and sector scans.

As shown in Figure 18.6 overleaf, the reflected ultrasound wave is displayed using fluorescent dots. The more the reflected wave, the brighter (whiter) the dot; whereas less reflection corresponds to a grey dot.

NOTE: The scale used to measure the brightness of the dots is known as the **grey scale**. The brightest dot correlates to the most intense reflection, whereas non-fluorescence (a dark or black dot) correlates to no reflection. Various levels of greyness exist in between the extremes.

Simple atlas of the eye



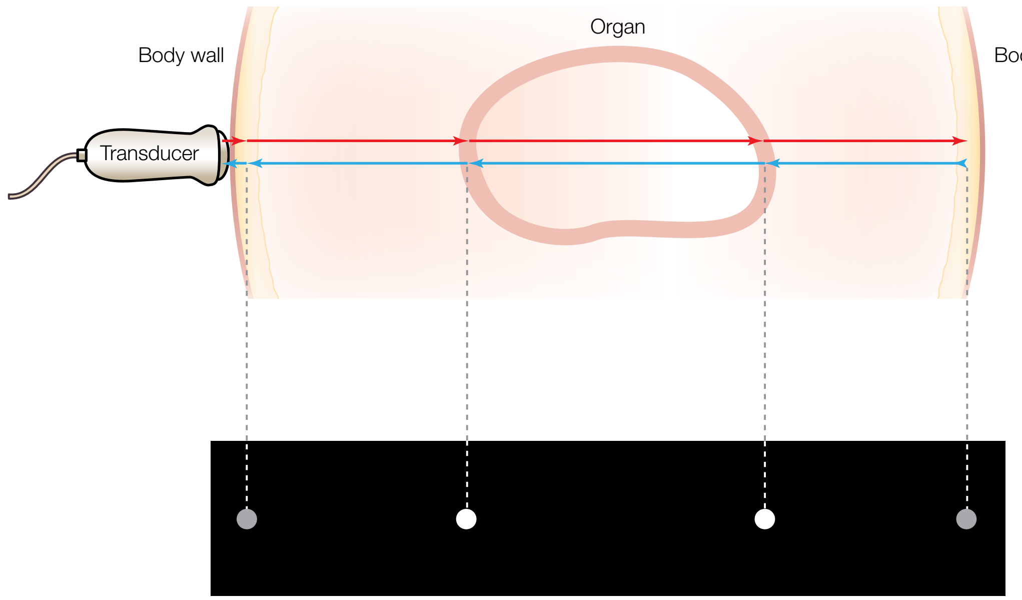


Figure 18.6
A B-scan image of a body organ

NOTE: B-scan is also known as B-mode.

Linear scan and sector scan

As shown in Figure 18.7, if the transducer that is producing the B-scan is moved back and forth, many B-scans will be produced in line with the transducer. These B-scans will be seen to be adjacent to each other, such that a two-dimensional image of the target organ is created.

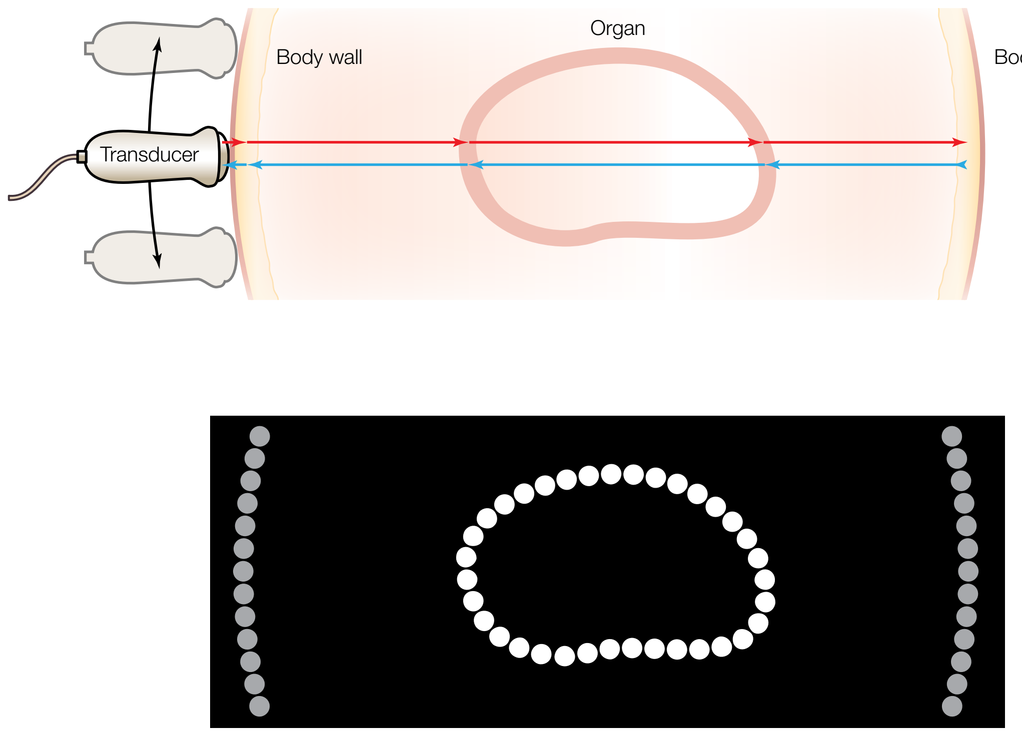


Figure 18.7
A linear scan of a body organ, formed by many B-scans

This can either be done by manually moving a single transducer unit back and forth or by hundreds of adjacently placed transducer units.

Fortunately, producing ultrasound images by manually moving the transducer unit is an old technology. Steady manual movement is technically difficult and the images formed in this way are often poor in quality. In modern clinical practice, it is more frequent to scan with an array of the transducer units (10s to 100s of units placed side by side) so that hundreds of B-scans are produced adjacent to each other without manually moving the transducer units. This improves the quality of the images formed and lengthens the longevity of the probe.

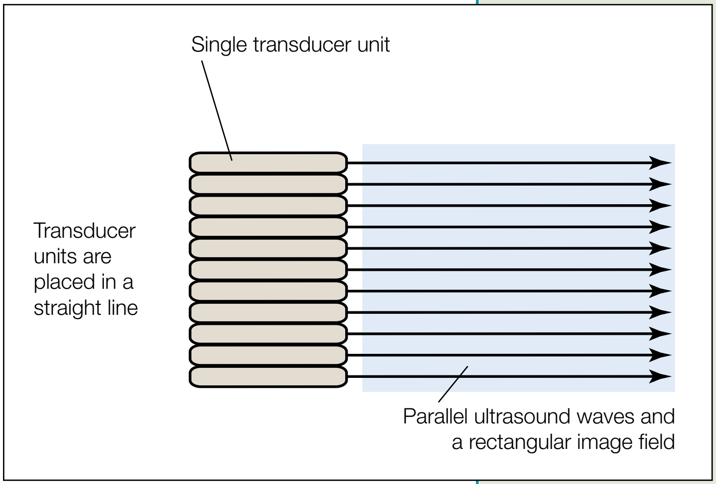


Figure 18.8 (a) A linear array or linear scan: the transducer units inside the probe are placed in a straight line

If the transducer units are placed side by side in a straight line, then the ultrasound waves will be emitted parallel to each other. This will produce a rectangular image with its width equal to the width of the array of the transducer units. This is known as a **linear array** or **linear scan** and is shown in Figure 18.8 (a). (The image it produces is like the one shown in Figure 18.7.) If however, the transducer units are placed next to each other in a convex fashion, then the emitted ultrasound waves will be spread out, so that a sector-shaped image will be produced. This is known as a **curved array** or **sector scan**, and is shown in Figure 18.8 (b).

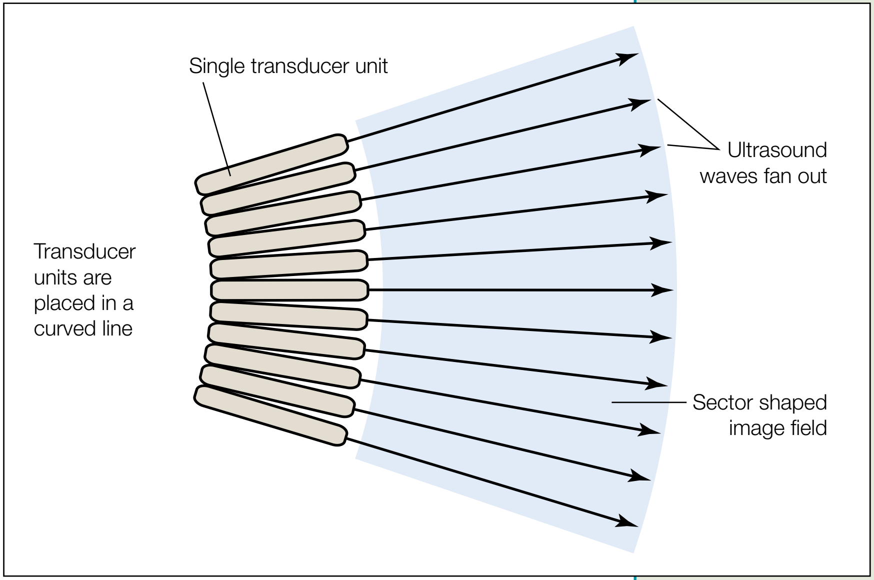


Figure 18.8 (b) A curved array or sector scan: the transducer units are placed in a curved line

Phase scans [Not in syllabus]

Phase can be added to both the linear scan and the sector scan to improve the quality of the images produced. For the sake of simplicity, adding phase to a linear scan is discussed here.

In a linear phased scan, ultrasound waves are sequentially emitted by each of the transducer units with a small delay between each emission. The delays are controlled by the computer and are adjusted when necessary. Consider Figure 18.9, a probe with five transducer units (in reality, there will be over a hundred units); in (a), transducer unit 1 is first to emit an ultrasound wave. After a small delay, unit 2 then emits an ultrasound wave. This is followed by the third, the fourth and the fifth transducer unit. The overall result of this is that the wavefront of the ultrasound produced will have its direction steered to one side of the probe. For the next round of emissions, the delays are decreased; and when the delays are reduced to zero, the ultrasound wavefront will return to the neutral position. This is shown in Figure 18.9 (b). After this, the reverse happens. The delays are restored, however, with transducer unit 5 emitting ultrasound first and unit 1 last. This will cause the wavefront to be steered

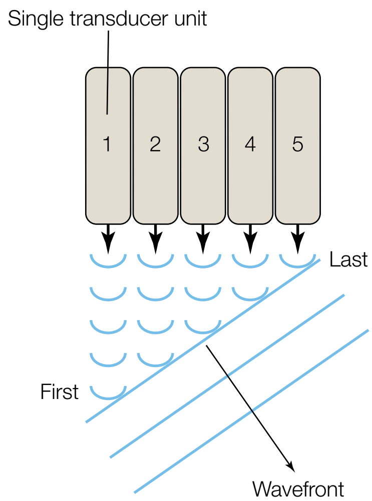


Figure 18.9 (a) Linear phased scan: ultrasound is emitted sequentially from transducer unit 1 to 5; this causes the wavefront to be steered to the right

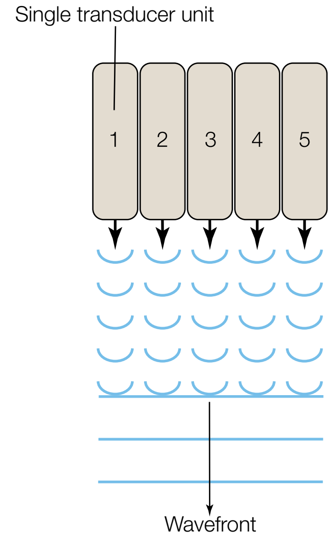


Figure 18.9 (b) Linear phased scan: ultrasound is emitted by the transducer units with no time delay; the wavefront returns to the neutral position

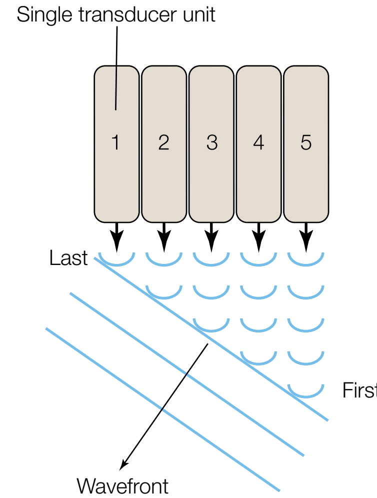


Figure 18.9 (c) Linear phased scan: the sequence is reversed, ultrasound is emitted sequentially from transducer unit 5 through to 1; this causes the wavefront to be steered to the left

to the opposite side. This is shown in Figure 18.9 (c). If the above sequences are repeated rapidly, the emitted ultrasound waves will swipe from side to side, producing a sector shaped image field. For this reason, a linear phased scan is also known as an electronic sector scan (because the sector-shaped image field is produced electronically using phase rather than mechanically using a curved array of transducer units). Similarly, phase can also be added to sector scans to improve the image field.

NOTE: Wavefronts are lines that join together the corresponding points on adjacent waves; usually they are either crests or troughs.

Adding phase to linear scans or sector scans is not just to improve their image field. Adding phase improves the quality of the images produced in other ways. For example, the use of phase enables electronic focusing, so that structures at various depths can be focused electronically such that all can be viewed with clarity. Phase can also generate echoes that will return from the target organ at different angles. The echoes are then analysed to form a compounding image of the target organ, which improves the quality of the image. Electronic focusing and electronic compounding are quite difficult concepts and are not required for this course.

Both the linear scans and the sector scans, with or without phase, are also collectively known as the standard pulse-echo ultrasound in clinical medicine. This is because when performing these scans, a new ultrasound wave is only sent after the echo of the previous wave is received.

Real-time and three-dimensional ultrasound

Both the sector scans and the phase scans produce two-dimensional grey scale images that can be displayed using either a monitor or printed films. One example is shown in Figure 18.10. When the images produced are refreshed at a fast enough rate (say 30 images per second, displayed using a computer monitor), the temporal sequence of the images can then be appreciated so that movements can be visualised (like motion pictures). This is known as **real-time ultrasound imaging**.

In recent years, three-dimensional ultrasound imaging has been developed. A three-dimensional ultrasound image can be produced by computed summation of many adjacent parallel two-dimensional images. Three-dimensional ultrasound images provide more detail about the anatomy of the body parts than two-dimensional images.

Figure 18.10 An ultrasound image of a foetus in the uterus

The clinical uses of ultrasound

SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

12.3A, D
13.1B

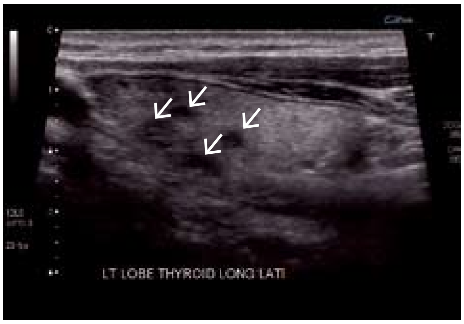
18.7

■ *Gather secondary information to observe at least two ultrasound images of body organs*

Ultrasound scans are used as a diagnostic tool in a variety of medical specialties. Some examples of the body organs or pathologies that can be imaged using (pulse-echo) ultrasound include:

1. Cardiology and vascular surgery—to look at the function and the anatomy of the heart or the blood vessels. This is discussed in the Doppler ultrasound section later in this chapter.
2. Gynaecology—to look for an ectopic pregnancy (pregnancy outside the uterus) or ovarian cysts.
3. Obstetrics—to look for the position and the state of the foetus and guide amniocentesis. Amniocentesis is a technique used to take a fluid sample from the sac around the foetus so that tests can be performed to detect any abnormality of the growing foetus. The insertion of the needle is guided by ultrasound in order to visualise and avoid injuries to the foetus. See Figure 18.10.
4. Endocrinology—to scan the thyroid gland for thyroid cysts or thyroid tumours.

NOTE: The thyroid gland is a gland in front of the voice box, just below the skin. It produces thyroid hormone, which controls the rate of the body's metabolism.



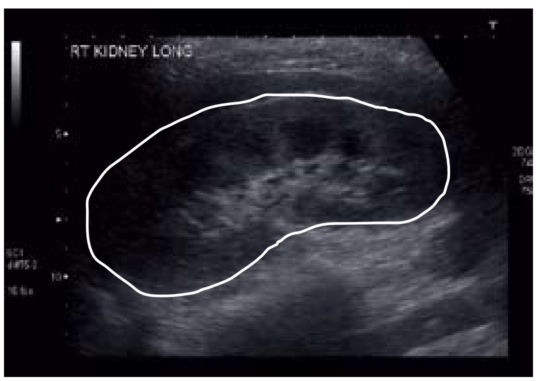
A thyroid gland containing multiple small cysts

5. Gastroenterology—to detect gall bladder stones.

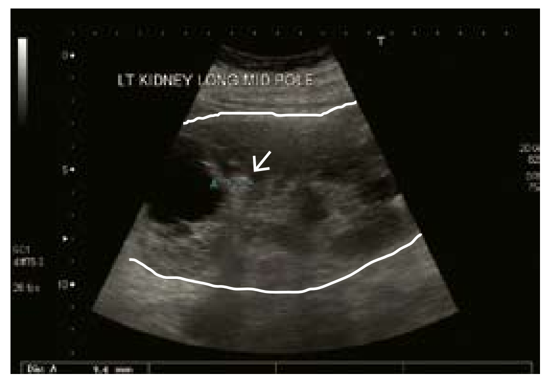
A normal gall bladder

Ultrasound of a gall bladder showing a gallstone

6. Renal—to determine the size of the kidneys and the ureters (ureters are the tubes that connect the kidneys to the bladder) or to detect kidney stones.



A normal kidney



Ultrasound of a kidney showing a kidney stone

7. Ultrasound is very useful for diagnosing soft tissue injuries such tears in muscles and tendons.

Ultrasound scans are particularly useful in detecting cysts, stones or tears in soft tissues. Cysts contain fluids, and fluids (water) have very different acoustic impedance compared to surrounding tissues. Thus at the cyst–tissue boundary, a large portion of the ultrasound waves will be reflected, making the cyst stand out. The same principle applies to stones, which also have very different acoustic impedance compared to the surrounding tissues. Injuries such as tears in the muscles and tendons will result in fluid collections at the torn sites. Just like the cysts, fluids are shown well using ultrasound.

Ultrasound cannot be used to visualise organs beyond any bony tissues, such as the brain, because much of the ultrasound waves will be reflected at the bone–tissue interface. It follows that in order to perform an ultrasound scan of the heart, the probe must be placed in between the ribs to avoid reflection of the ultrasound waves by the ribs.

Extended activity

You are required to gather and observe ultrasound images of body organs. This chapter has provided ultrasound images of a variety of body organs. You may wish to obtain more images. You could ask your GP, and search the internet and medical journals or textbooks. Local hospital ultrasound departments may also be contacted.

Observing the ultrasound images, note and describe the following:

- What features would help you to identify these images as ultrasound images? Describe the colour, resolution and contrast of these images.

- What organs are shown and what pathologies (diseases, problems, etc, if any) are present? Why is ultrasound done for this particular pathology?
- Are ultrasound images easy or difficult to interpret?

The advantages and disadvantages of using ultrasound as diagnostic tool

Advantages

- Ultrasound scans do not use ionising radiation; therefore they are safe and have no side effects. This is particularly important in obstetrics, where the foetus has to be viewed. A foetus is a not-yet-formed human being very susceptible to the ionising radiation used in X-rays and CT scans. Both scans are contraindicated (not recommended) during pregnancy. Ultrasound scans on the other hand have no harmful effect on the growing foetus and are therefore safe to use during pregnancy.
- Ultrasound scans are one of the cheapest forms of medical imaging available.
- Ultrasound scans show soft tissue quite well compared to X-rays and are excellent for detecting cysts and stones.
- Ultrasound machines may be made small and portable. These days, an ultrasound machine can be fashioned with a lap-top design.

Disadvantages

- Certain body parts cannot be scanned using ultrasound. These include organs that are covered by bony tissues, such as the brain and the lungs.
- The resolution of ultrasound scans is low compared to other scan methods. Compare the head of the foetus shown using ultrasound (Figure 18.10) to the CT image of the brain (in Chapter 19)—the ultrasound image is poor in quality.
- Ultrasound scans are performed by ultrasonographers who need to manipulate the probe to acquire the desired images. Therefore the quality of the ultrasound images produced and their interpretation are largely operator dependent.

18.7 Doppler ultrasound

- ***Describe the Doppler effect in sound waves and how it is used in ultrasonics to obtain flow characteristics of blood moving through the heart***

Doppler ultrasound employs the **Doppler effect** to study the movement of blood in the body.

SR

Simulation: the Doppler effect

Definition

The **Doppler effect** is defined as the apparent change in the frequency of sound when the source of the sound is moving relative to its receiver.

NOTE: It is the relative motion between the sound source and receiver that creates the Doppler effect. Between a moving source and a stationary receiver there will be a Doppler shift as there would be between a stationary source and a moving receiver. On the other hand, no Doppler effect will occur if the source and the receiver are both moving at the same speed and in the same direction.

When the source and the receiver are moving away from each other relatively, the frequency of the sound decreases and the wavelength increases.

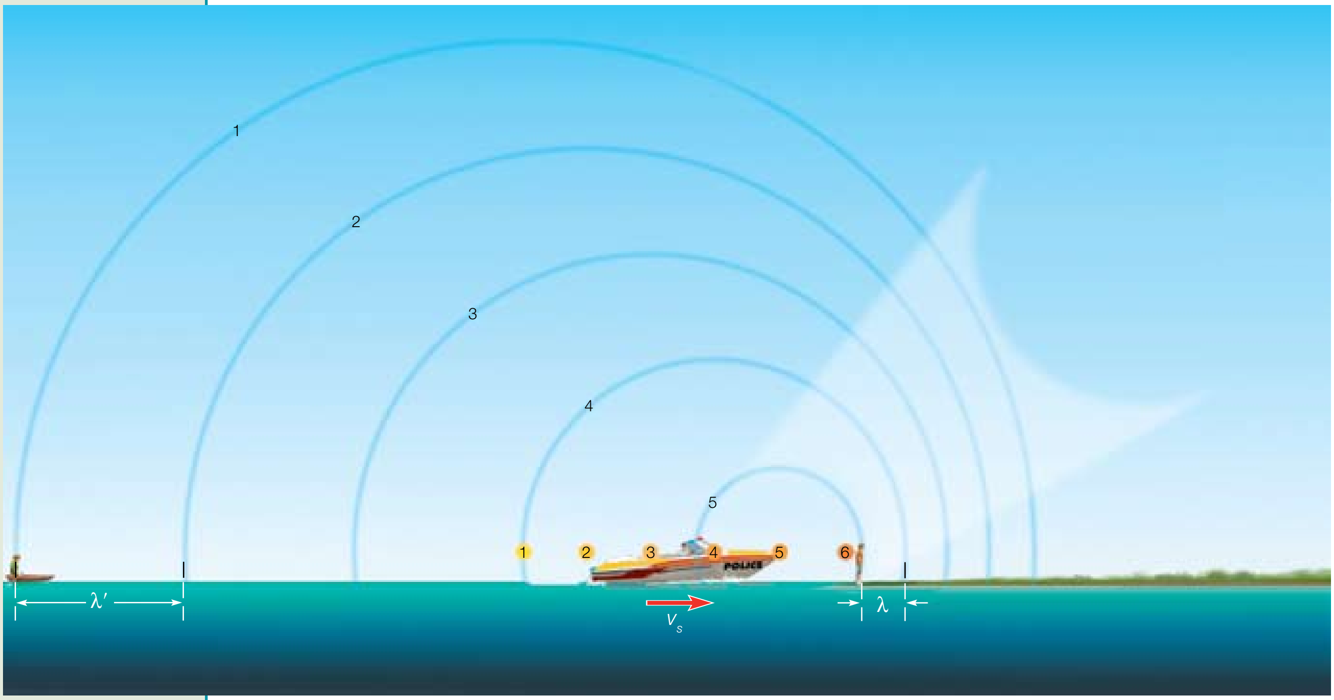
When the source and receiver are moving closer to each other relatively, the frequency of the sound increases and the wavelength decreases.

This is shown in Figure 18.11.

NOTE: In both cases, the speed of sound remains constant.

NOTE: Similar behaviours are observed for electromagnetic radiation and are known as the red shift and blue shift respectively.

Figure 18.11 The Doppler effect: note that λ′ is greater than λ



USEFUL WEBSITE

The Doppler effect:
http://cat.sckans.edu/physics/doppler_effect.htm

How the frequency changes (whether it increases or decreases) is an indication of the relative motion between the sound source and the receiver; whereas the magnitude of the change correlates to the magnitude of the relative velocity between the source and the receiver.

■ *Describe the Doppler effect in sound waves and how it is used in ultrasonics to obtain flow characteristics of blood moving through the heart*

What is the new technology and how does it compare with the old technology?

Doppler ultrasound is a technique that combines the established ultrasound procedures with the Doppler effect when a wave is reflected off a moving target. The ability to combine the two sets of information simultaneously provides information about the speed of blood flow through critical arteries within and near the heart. Abnormal blood flow, including restrictions, blockages, dilations and other conditions can be imaged with Doppler ultrasound.

The additional information gained from an analysis of the frequency shift of the reflected sound wave is used to measure the velocity of the blood flowing through the heart. The physics involved—a combination of improved transducer (using piezoelectric technology) and application of the Doppler effect when analysing the reflected signal—has been critical in the development of this technology.

Older forms of ultrasound technology provided much less detail and no information about the motion of blood within the heart. Other forms of diagnosis, possibly involving radioisotopes, were required to provide information about blood flow in the heart.

Assessment of the impact of advances in physics on the development of this technology

Knowledge of the behaviour of waves, particularly with reference to reflected waves from moving objects, has been essential to the development of Doppler ultrasound techniques. Computing speed and power to interpret the data and produce images in real time also plays a critical role in this medical technology. Microprocessors capable of handling this task have become available at a suitable price and size only in recent years.

Any assessment of the impact of the advances in physics on the development of Doppler ultrasound must take into account how essential these advances are to the technology.

USEFUL WEBSITES

About vascular ultrasound:
http://www.radiologyinfo.org/en/info.cfm?pg=vascularus

Information about piezoelectric transducers and more detail about ultrasound:
http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/piezotransducers.htm

PFA
H3

'Assesses the impact of particular advances in physics on the development of technologies'

TR

PFA scaffold H3
Mapping the PFAs

WWW

18.8 Doppler ultrasound as a diagnostic tool

- ***Describe the Doppler effect in sound waves and how it is used in ultrasonics to obtain flow characteristics of blood moving through the heart***
- ***Outline some cardiac problems that can be detected through the use of the Doppler effect***
- ***Identify data sources and gather information to observe the flow of blood through the heart from a Doppler ultrasound video image***

PFAs

H3

PHYSICS SKILLS

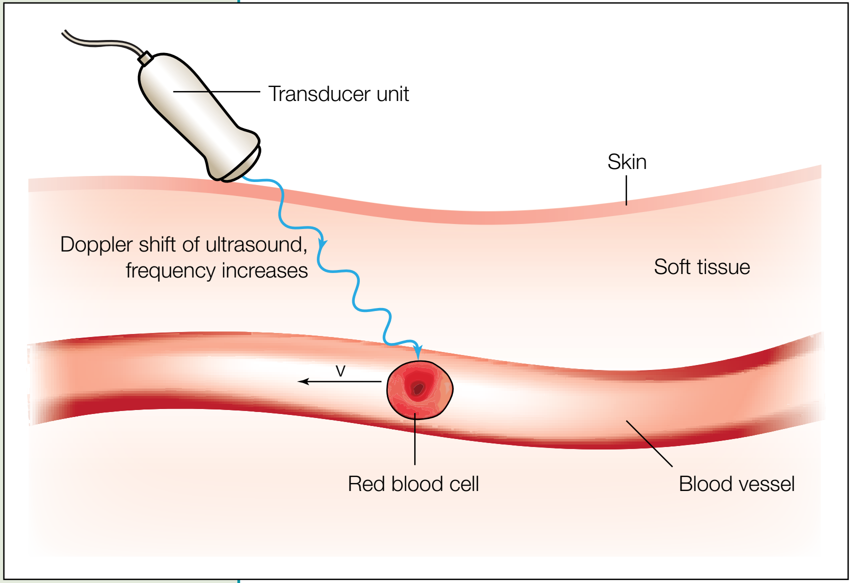
H11.1E
H12.3 A, B

To understand how Doppler ultrasound can be used as an imaging tool to study blood flow, consider the simplified representation shown in Figure 18.12 (a), where an ultrasound wave is emitted by the transducer unit and is directed towards the blood vessel in which a red blood cell is flowing towards the transducer. At this moment, the red blood cell, which can be viewed as the 'receiver', is moving closer towards the sound source. This will result in an increase in the frequency of the ultrasound wave proportional to the speed of the moving red blood cell. After the ultrasound strikes the red blood cell and is reflected off (shown in Figure 18.12b), the red blood cell will act as the 'source', which is again moving closer towards the 'receiver'—the transducer. This will result in a further increase in the wave frequency.

The conclusion drawn for this scenario is that the ultrasound wave, after reaching the red blood cell and then being reflected back to the transducer, will have increased its frequency twice. As a consequence, the detected echo (reflected ultrasound) will have a higher frequency compared to the original wave. This difference enables the computer to calculate the speed at which the red blood cell is moving towards the transducer unit, thereby providing information about the blood flow.

A similar but opposite process will take place in cases where the red blood cell is moving away from the transducer. The frequency of the ultrasound wave will be reduced twice, resulting in a lower frequency of the detected echo. The reduction in frequency will be interpreted by the computer as being the blood flowing away from the transducer unit and the magnitude of the change will be used to calculate this receding speed.

Figure 18.12 (a) Doppler shift of the ultrasound wave as it is travelling towards the red blood cell



Types of Doppler ultrasound and image display

There are two ways in which Doppler ultrasound can be emitted and received to provide information about blood flow. One is to emit and receive the ultrasound continuously, known as the **continuous Doppler mode**. The other is to emit and receive the ultrasound in discrete pulses, similar to the pulse-echo grey scale imaging technique described, known as the **pulse Doppler mode**. The continuous Doppler mode provides information about blood flow either in an audio form or visually as a spectral display (discussed later). The pulse Doppler can provide the information in an audio form, visually as a spectral display as well as two-dimensional, colour-coded images. In modern practice, Doppler ultrasound (mainly the pulse Doppler) is combined with the standard pulse-echo grey scale ultrasound so that the anatomical information and blood flow can be studied simultaneously using real-time images.

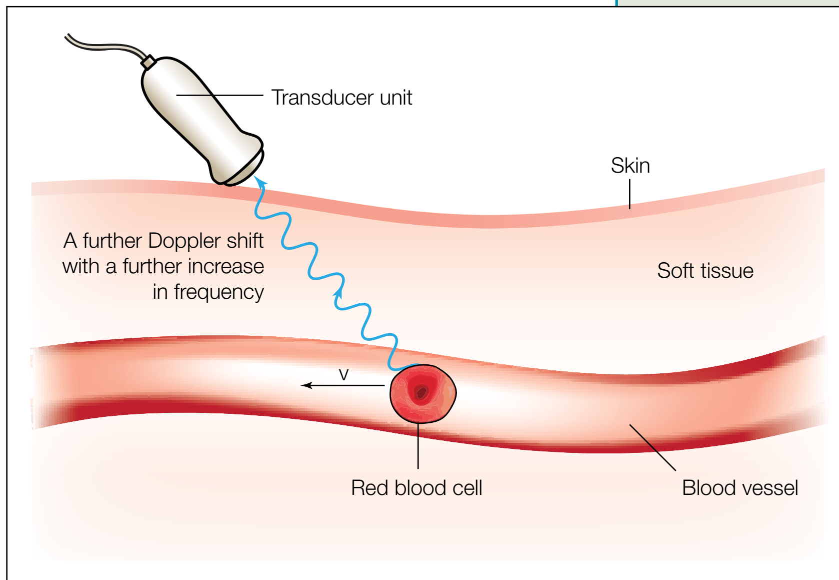
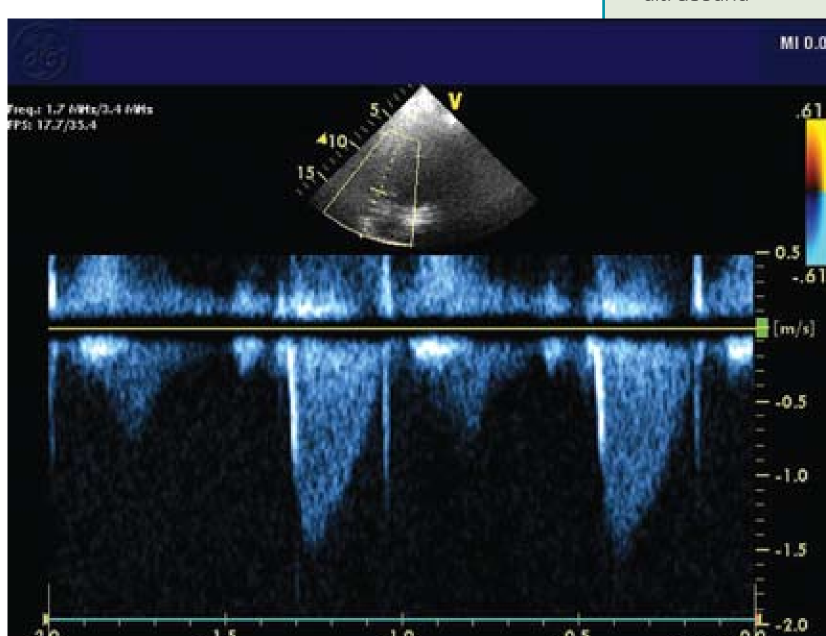


Figure 18.12 (b) Doppler shift of the ultrasound wave as it is being reflected off the red blood cell

The continuous Doppler mode

For the continuous Doppler mode, there are two separate pieces of piezoelectric material within a single probe. One piece of the piezoelectric material sends out a continuous ultrasound wave at a frequency of 2–10 MHz and the other one continuously receives echoes from the moving blood cells. The received echoes will show Doppler shift, the extent of which depends on the speed of the moving blood cells. These echoes are converted into electrical signals, which are electronically subtracted from the electrical signals that generate the original wave. Such a difference is often in the audible frequency range and can be used to drive a loudspeaker. The sound produced can be listened to and the pattern of the blood flow can be evaluated by the clinician. The difference in frequency can also be displayed visually after being processed using a fast Fourier transformation. Such a display is known as a spectral display; it plots the level of Doppler shift (frequency) as a function of time (see Fig. 18.13). A **wall filter** is employed in both cases to filter out the much lower frequency Doppler shift produced by the moving tissues, to minimise interferences.

Figure 18.13 A spectral display of Doppler ultrasound



The downside of the continuous Doppler mode is that it detects all Doppler shifts along the entire scan line (along the entire depth the sound wave can reach). Therefore, when there are many blood vessels close to each other—for instance, an artery and a vein next to each other—they cannot be analysed separately and a lot of false signals will be produced. A similar difficulty will be encountered when an attempt to examine the blood flow through the heart is made.

Clinically, continuous Doppler can be used as an audible device to listen for blood flow through an artery, which can be important when the arterial pulse is impalpable such that clots in the artery are suspected. It may also be used to detect the blood flow through the foetal heart as a way of monitoring a foetus's well-being, in antenatal clinics as well as during labour.

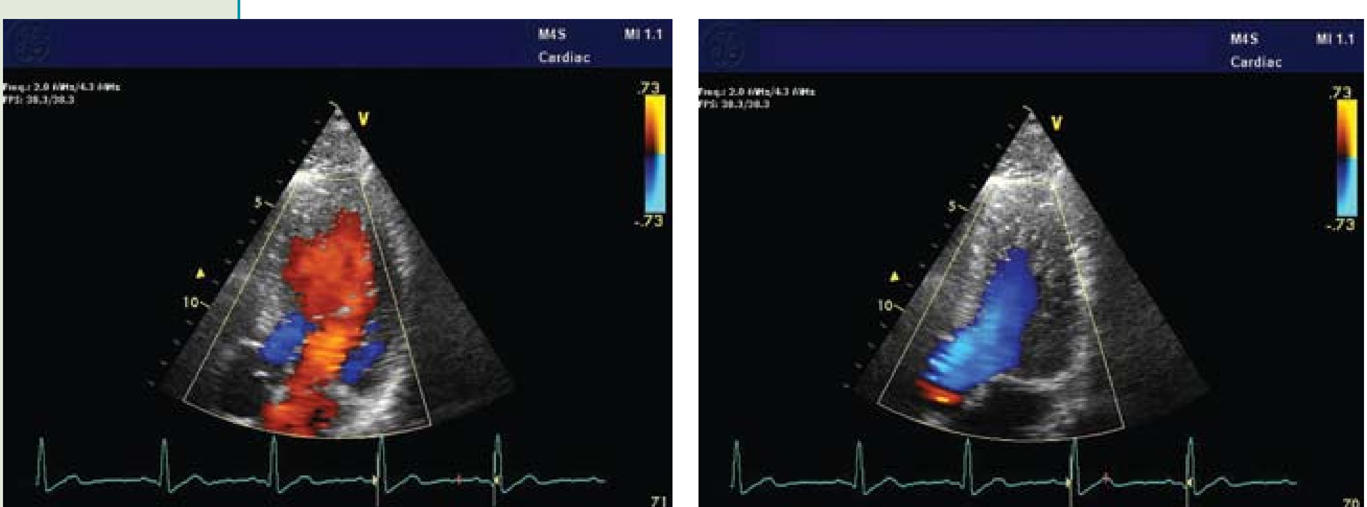
NOTE: Foetal heart sounds, unlike those of adults, are difficult to hear using a stethoscope.

The pulse Doppler mode

For the pulse Doppler mode, ultrasound is sent out as discrete pulses. In other words, one pulse is sent and its echo is detected before the second pulse is sent. The Doppler shift can be analysed in an audio form or using a spectral display, similar to those used by the continuous Doppler mode. Pulse Doppler can also display the Doppler shift using two-dimensional, colour-coded images. Red is used to denote blood flowing towards the transducer unit, whereas blue is used to denote blood flowing away. The redder or bluer the colour, the faster is the flowing velocity of the blood through the blood vessel. The colour Doppler is shown in Figure 18.14.

The main advantage of this mode is its ability to selectively study the blood flow at a single depth (if necessary). This may be the lumen of a single blood vessel or a particular valve within the heart chamber. This is made possible because knowing the speed of the sound wave in a particular tissue, the time of arrival of the echo from a known depth can be determined. Thus any echo arriving outside this time (e.g. echoes from other blood vessels along the scan line) is filtered and will not be displayed. This is known as range gating.

In order to select a correct range gating for the returning echo, the accurate depth, and hence the anatomy, must be known. Therefore pulse Doppler is often made to combine with standard grey scale ultrasound in a scanning device known as the **duplex scan**. The sector or phase scan displays the anatomy of the blood vessel, including its depth, which provides information for the correct selection of the range gating.



(a) **(b)**

Figure 18.14 Colour Doppler: red **(a)** is blood flowing towards the transducer unit, whereas blue **(b)** is blood flowing away

The use of Doppler ultrasound in cardiovascular medicine

Duplex scans are frequently performed in cardiology and are also known as echocardiograms. The standard sector or phase scan displays the anatomy of the heart including its muscle walls and valve architecture. Such information is displayed using a grey scale. At the same time, the Doppler ultrasound provides information about the blood flow through the heart and is often displayed using colour codes. These are shown in Figure 18.15 (a) and (b) respectively. The blood flow may also be listened to or analysed quantitatively using the spectral display. The spectral display enables the analysis of blood flow at a specific location, such as the aortic valve, by selecting a specific range gating based on the anatomy seen on a grey scale display. An example is shown in Figure 18.5 (c). Furthermore, modern duplex scans are capable of refreshing many images (30 or more) per second, such that the movement of the heart as well as the dynamic nature of the blood flow can be seen. As mentioned before, this is known as real-time images (like a video).

Echocardiograms are useful for diagnosing many common cardiac (heart) pathologies. The real-time grey scale images are useful for assessing heart muscle movements, which may be impaired due to scarring from a previous heart attack. The colour Doppler images can detect abnormal blood flow through the heart due to a malfunctioning valve, whether as a result of stenosis (narrowing) or regurgitation (abnormal backward flow of blood through an incompetent valve). Spectral display can measure the pressure gradient across a diseased valve, providing quantitative information about the severity of the valvular stenosis.

Figure 18.15 (a) A grey scale ultrasound image of the heart

Figure 18.15 (b) The grey scale ultrasound image combined with colour Doppler

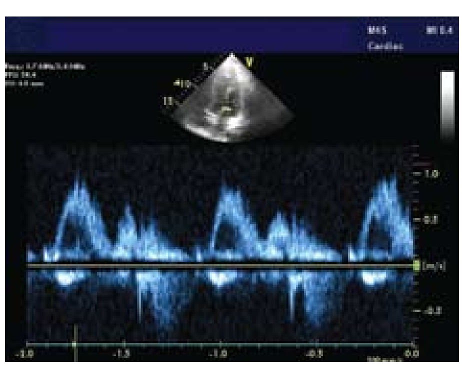
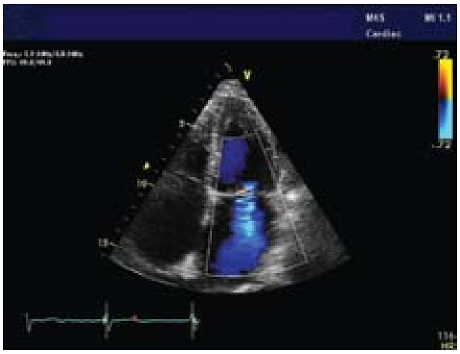


Figure 18.15 (c) A spectral display for analysing blood flowing through a valve



Duplex ultrasound scans (Fig. 18.16) are also frequently used to assess the level of blood flow through an artery and are extremely valuable in assessing the degree of narrowing in the target artery.

Figure 18.16 A duplex scan showing an incompetent mitral valve—mitral valve regurgitation

Ultrasound as a tool for measuring bone density

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H11.1E
H12.3A
H12.4F
H14.1A, B, G, H

■ *Identify data sources, gather, process and analyse information to describe how ultrasound is used to measure bone density*

About a decade ago, it was proposed that ultrasound was able to assess bone density to screen for osteoporosis.

Osteoporosis is a medical condition, usually in elderly people, where there is a gradual loss of bone minerals. This results in brittle bones, which are prone to fractures. Osteoporosis can cause very serious fractures in the elderly with a very high associated mortality rate. Although osteoporosis is not reversible once diagnosed, it is to some extent preventable, so early detection and treatment are important. The detection of osteoporosis relies on an accurate measurement of bone (mineral) density.

When using ultrasound to assess bone density, the patient is asked to place his or her foot into a warm bath. An ultrasound wave is produced by a transducer unit to pass through the heel bone of the foot and is detected on the opposite side. The speed as well as the attenuation of the ultrasound at various frequencies (known as broadband ultrasound attenuation) are calculated by the computer attached to the detector. These values are compared to age-specific mean values so that the quality of the bone can be analysed to detect osteoporosis.

Such an ultrasound bone density scanner is small, and hence can be made mobile. The scanner is also cheap and is available at local pharmacies. The scanner does not use harmful ionising radiation, and therefore is safe. Consequently, it was thought that such a device would be an ideal choice for diagnosing osteoporosis. However, research has shown that the 'density' measured by ultrasound is not clinically useful, for instance, in determining the likelihood of fractures, as measured by the traditional dual energy X-ray absorptiometry (DEXA).

NOTE: DEXA assesses the bone mineral density using X-rays. The device passes low energy X-rays through the vertebra and hip bones. The absorption of the X-rays is measured and from that the bone mineral density is calculated. This method has a very high sensitivity and specificity in diagnosing osteoporosis.

Because of the lack of accuracy, ultrasound bone density scans are becoming less popular in today's medical practice. Patients who are suspected to have osteoporosis based on their risk factors are sent directly to have a DEXA scan. Most doctors see this practice as more economical overall and argue that a small amount of ionising radiation from DEXA will not do significant harm.

CHAPTER REVISION QUESTIONS

1. Using wavefronts, draw a sound wave that contains two wavelengths. Label on the diagram compression, rarefaction and wavelength.
2. (a) What are piezoelectric materials?
   (b) Give two examples of piezoelectric material.
   (c) What are the roles of piezoelectric materials when used in ultrasound scanners?
3. (a) Calculate the percentage of the ultrasound waves that will be reflected when they reach the junction between muscle and fat tissues. You may wish to refer to Table 18.1.
   (b) Calculate the percentage of the ultrasound waves that will pass through the junction between the liver and the fat tissues.
4. What are A-scans? What types of information do A-scans provide?
5. What are B-scans? What is the relation between B-scans and sector scans?
6. Lisa presented to her GP with a lump in the neck. After examining her, the GP decided that such a lump was likely to be related to the thyroid gland. As well as performing some blood tests, the GP ordered an ultrasound scan of the thyroid gland.
   (a) What thyroid problems are best shown using ultrasound and why?
   (b) Give one reason why ultrasound may be potentially better than other imaging methods in this situation.
7. Jane was six months into her pregnancy. Her obstetrician performed an ultrasound scan of her uterus to examine the position of the foetus. Why is ultrasound the investigation of choice for examining a foetus during pregnancy?
8. List two other clinical uses of ultrasound.
9. Define the Doppler effect.
10. What application does the Doppler effect have in clinical medicine?
11. (a) How is ultrasound used in a duplex scan?
    (b) What clinical uses does a duplex scan have?
12. A decade ago, ultrasound was thought to have the ability to measure bone density.
    (a) Describe how ultrasound can be used to measure bone density.
    (b) Why did ultrasound bone density scans lose favour in recent years?

SR Answers to chapter revision questions