Physics of ultrasound

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Abstract

Ultrasound is a form of non-ionizing radiation that uses high-frequency sound waves to image the body. It is a real-time investigation which allows assessment of moving structures and also facilitates measurement of velocity and direction of blood flow within a vessel.

It can be used for a variety of purposes in the intensive care setting, for example to aid central venous catheter insertion and pleural drain insertion. When using this imaging modality it is vital to understand the relevant physical principles and how the images are created.

This article will explain these principles, including the use of Doppler ultrasound and the interpretation of common artefacts.

Keywords Doppler effect; echoes; imaging artefacts; sound attenuation; ultrasound safety; ultrasound waves

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Learning objectives

After reading this article you should be able to:
- describe the characteristics of sound waves
- explain how ultrasound waves are produced and how they interact with the tissues they encounter to produce echoes which are then interpreted to form a two-dimensional image
- identify common ultrasound imaging artefacts
- explain the Doppler effect and its use in ultrasound imaging

Wave characteristics

Sound is a mechanical wave that causes disturbance in a medium, transferring energy from one point to another. As the sound wave travels through a medium the energy is propagated through collisions of adjacent particles which oscillate around their resting position without net displacement. Sound waves can be longitudinal or transverse depending on the direction of their oscillations in relation to the direction of the energy travelling through the medium. Only solids can propagate sound waves transversely, whereas all materials can support a longitudinal wave, and this is therefore how ultrasound is transmitted through the soft tissues (including liquids) within the body (Figure 1).

The frequency of a sound wave (hertz, Hz) is the number of oscillations (or cycles) per second. If a particle completes one full oscillation per second, its frequency is 1 Hz. Ultrasound refers to any sound waves that have a frequency that is too high for the human ear to detect (i.e. >20 kHz), however the frequencies used in medical imaging are far greater: typically 2–18 MHz.

Wavelength is the distance travelled by sound in one cycle. It is inversely proportional to the frequency, that is, the shorter the wavelength the higher the frequency (Figure 2). Shorter wavelengths produce higher resolution images but less penetration into the soft tissues. In medical imaging therefore higher frequency probes (5–10 MHz) are used for superficial structures, for example peripheral vessel visualisation, and lower frequency probes (2–5 MHz) for deeper structures such as abdominal organs.

Ultrasound image production

Production of echoes

Ultrasound waves are produced by briefly passing an electrical current through a piezoelectric crystal within the ultrasound probe. The resulting pulse of ultrasound waves is delivered to the tissues. The crystal then waits for the rebounding echoes to be received before transmitting the next pulse. The pulse duration is typically 1 μs and repeated at 1 ms intervals. Each crystal therefore emits ultrasound waves 1% of the time and receives the returning echoes for the remaining 99% of the time. In practice, the probe contains a **phased array** of many piezoelectric crystals which are stimulated sequentially by electronic pulses which sweep from one side of the probe to the other.

As the ultrasound wave passes through the patient it encounters interfaces between different tissues. At these interfaces a proportion of the wave's energy is reflected and the remainder is transmitted. If the angle between the interface and transducer is greater than 60 degrees then the reflected echoes will return to the transducer. The piezoelectric crystal converts the reflected

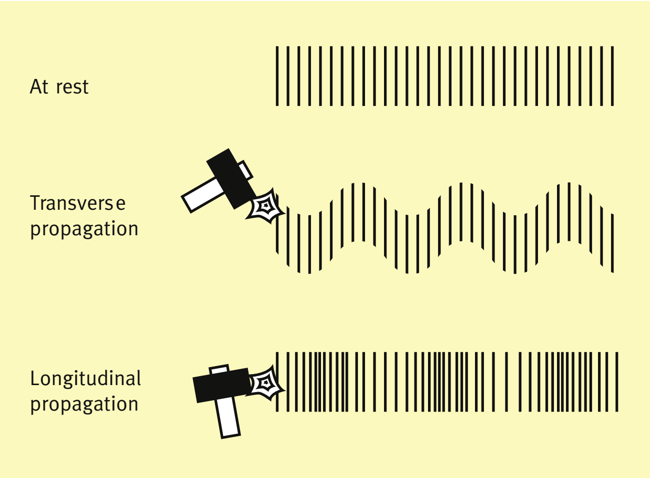

Figure 1 Diagrammatic representation of the propagation of a mechanical force transversely as can occur only in solids or longitudinally as occurs with sound in the tissues of the body.

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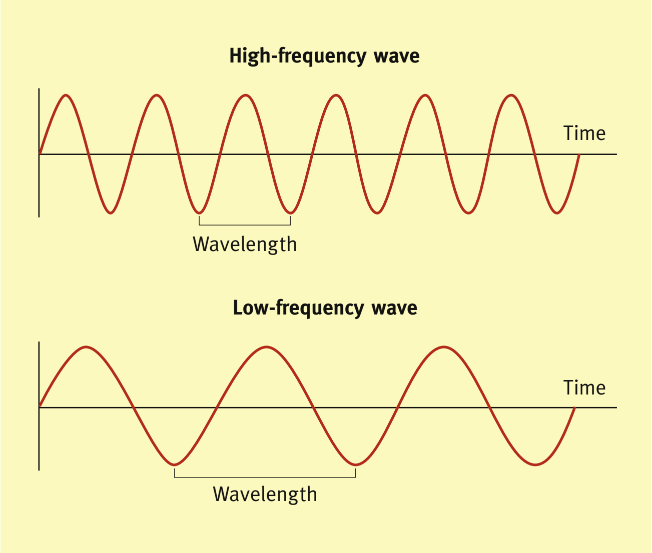

Figure 2 The relationship between wavelength and frequency.

sound waves into electrical pulses, and these are interpreted into a two-dimensional (2D) image. The more energy in the returning echoes, the brighter the image displayed.

The amount of energy reflected at the interface between tissues depends on the difference in acoustic impedance of those tissues. The acoustic impedance of a tissue is mainly determined by its density. Air has a much lower density than water or soft tissue, which in turn have a much lower density than bone. The larger the difference in acoustic impedance, the more energy will be reflected, and the brighter the resulting image. At the interface of tissues of similar densities, such as liver and kidney, less than 1% of the wave's energy is reflected. However at the interface between soft tissue and air or bone, nearly all of the wave's energy is reflected. No energy is transmitted, and hence no information can be gained about tissues which lie deep to this point. This explains why ultrasound is generally not useful for assessment of bone, bowel, or lung. It also explains why a coupling gel is required between the probe and patient's skin to eliminate air.

To create a 2D image, the depth (d) of the tissue interface must be calculated. Ultrasound travels at an average speed (c) of 1540 m/second through soft tissue. The time (t) taken for the ultrasound pulse to travel distance (d) to the interface, and for the reflected wave to return to the transducer, is therefore:

$$d = ct/2$$

Sound attenuation and compensation

As a sound wave passes through the body it gradually loses its energy in a process called **attenuation**. The causes of this are: **absorption, reflection, diffraction and refraction** (Figure 3). Reflection and refraction occur at the interface between tissues. Reflection as already described is responsible for the production of echoes. Refraction causes a transmitted wave to be deflected from its original course. Diffraction is scattering of the wave which occurs particularly when a wave interacts with small structures. The majority of attenuation however occurs due to absorption. The energy of the sound wave is converted into friction between oscillating tissue particles and is lost in the form of heat.

The combination of attenuation, and the fact that only a small proportion of the wave's energy is reflected at many of the tissue interfaces (and is then attenuated further as it travels back towards the probe), means that the ultrasound transducer will only receive a very small amount of energy from the returning echoes, particularly from deeper structures. To compensate for this loss of energy the ultrasound machine uses a process called **time gain compensation**. This gives greater amplification to those echoes which take longer to return to the transducer, producing an even image.

Image resolution

Axial resolution is the ability to distinguish between structures lying perpendicular to the beam. A structure can only be visualized if it is larger than the wavelength of the emitted ultrasound. As wavelength is inversely proportional to frequency, a high-frequency probe is required to view small structures. However, higher frequency waves are attenuated more rapidly, and therefore will only be able to visualize superficial structures.

Lateral resolution is the ability to distinguish two structures lying side by side. Diffraction causes divergence of the original beam soon after it leaves the probe, as well as of reflected echoes from a tissue interface. If two structures are lying closely adjacent, the reflected waves can interact and appear to the transducer as if they originate from the same structure, and will appear so on the image created.

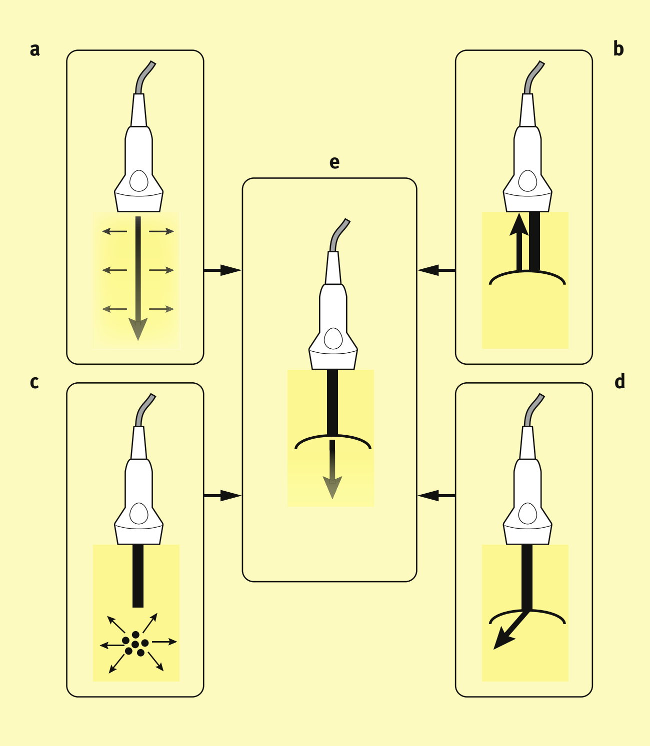

Figure 3 Causes of attenuation: (**a**) absorption, (**b**) reflection, (**c**) diffraction and (**d**) refraction all contribute to the overall attenuation of the ultrasound wave seen in (**e**).