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 directionality 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 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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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 and fluid within the body (Figure 1).

The **frequency** of a sound wave (measured in 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 sound waves that have too high a frequency for the human ear to detect, that is above 20 kilohertz (kHz); however, the frequencies used in medical imaging are far greater, typically 2–10 megahertz (MHz).

Wavelength is the distance travelled by sound in one cycle. It is inversely proportional to the frequency, i.e. the shorter the wavelength the higher the frequency (Figure 2). Shorter wavelengths result in higher resolution images but less penetration into the soft tissues. Therefore, in medical imaging higher frequency probes (5–10 MHz) are used for superficial structures, (e.g. peripheral vessel visualization) and lower frequency probes (2–5 MHz) for imaging deeper structures (e.g. the abdominal and pelvic organs).

Learning objectives

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

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 repeated at 1 ms intervals. Each crystal therefore emits ultrasound waves 0.1% of the time and receives the returning echoes for the remaining 99.9% 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 around 60 degrees then some of the reflected echoes will return to the transducer. The piezoelectric crystal converts the reflected 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 an interface between tissues depends on the difference in **acoustic impedance** of those tissues. The acoustic impedance (Z) of a tissue is the product of its density and the velocity that sound travels through it. 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 between two materials at an interface, the more energy will be reflected, and the brighter the resulting

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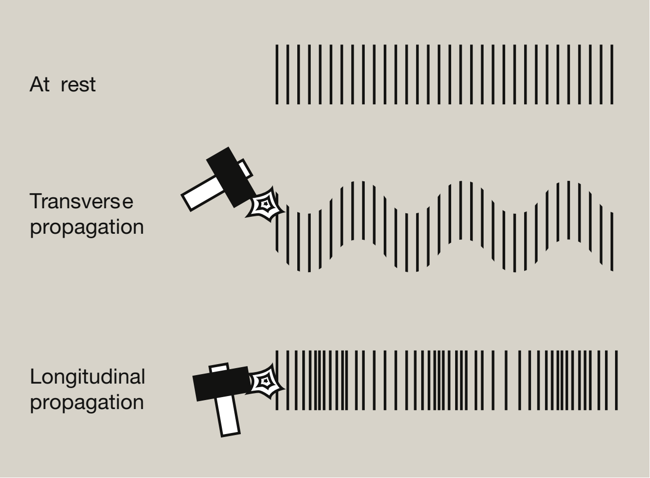

Figure 1 Diagrammatic representation of the propagation of a mechanical force transversely as can occur only in solids or longitudinally as occurs with sound in the tissues of the body.

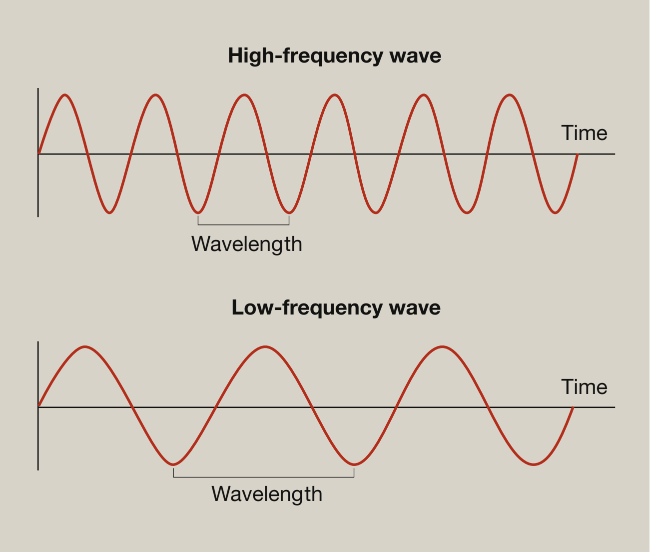

Figure 2 Displays the relationship between wavelength and frequency.

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 deeper than 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 and why air bubbles must be avoided to minimize any reflection at the skin/probe interface.

To create a 2D image, the depth (d) of the tissue interface must be calculated. Ultrasound travels at an average speed (c) of 1540 ms^{-1} through soft tissue. The time (t) taken for the ultrasound pulse to travel the distance (d) to the interface, and for the reflected wave to return to the transducer, is:

$$t = 2d/c$$

Rearranging, the tissue interface depth 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: **reflection, refraction, scatter** and **absorption** (Figure 3). Reflection and refraction occur at the interfaces between tissues. Reflection, as already described, is responsible for the production of the required echoes. Refraction causes a transmitted wave to be deflected from its original direction where it passes through an interface between tissues having differing wave speed. Scatter describes the scattering of the wave in all directions which occurs when a wave encounters a structure much smaller than its wavelength, typically occurring on interaction with red blood cells. 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 general attenuation through all tissue types, and the fact that only a small proportion of the wave's energy is reflected at many of the tissue interfaces (which 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 a more even image.

Image resolution

Spatial resolution is the ability of an imaging system to distinguish two points as separate in space.

Axial or **depth resolution** is the ability to distinguish between two structures in the direction parallel to the beam, that is, along the same scan line. A structure can only be visualized if it is larger than several wavelengths of the emitted ultrasound. Remembering that wavelength is inversely proportional to frequency, the higher the frequency (shorter the wavelength) the better the axial resolution. Hence a high-frequency probe is required to image small structures. However, as discussed above, 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 at the same depth. This is dependent on the beam width being narrower than the distance between the two structures and is also improved by **focussing**. By exploiting the phased array of the probe, if a delay is introduced energizing the outermost elements first with a short time interval to the inner elements and finally central element, there will be a point at which the pulses all arrive together and thus reinforce allowing the beam to be focussed. Practically it is important that the operator correctly positions the focal zone when scanning to ensure the best lateral resolution for assessment of a given structure.

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