The physics of ultrasound

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Abstract

Ultrasound is a safe, non-invasive imaging modality which is increasingly used in anaesthesia to aid placement of central venous cannulae and local anaesthetic blocks. Transoesophageal echocardiography (TOE) is used to assess myocardial and valvular function during anaesthesia or on the intensive care unit. It is essential to understand the underlying principles of how the ultrasound image is created in order to optimize the image, and recognize and prevent artefacts.

This article describes the physics of waves and their interactions, and applies these principles to explain how the ultrasound machine produces an image. The Doppler effect and its application to measurement of blood flow and cardiac output is described.

Keywords Artefacts; Doppler effect; piezoelectric effect; imaging; ultrasound; waves

Learning objectives

After reading this article, you should be able to:
- describe the general properties of waves, and how they interact with each other and their environment
- explain how the ultrasound machine produces an image, and how artefacts are formed and prevented
- explain the Doppler effect, and how it may be used clinically to measure blood flow

Properties of waves

A travelling mechanical wave is a disturbance with a regularly repeating and progressively moving profile which propagates energy through a medium. Energy is transferred with no net displacement of the medium. In a **transverse wave** (e.g. ripples on water, electromagnetic radiation), the disturbance is perpendicular to the direction of travel of the energy. In a **longitudinal wave** (e.g. a row of cars colliding, or sound waves in liquid or gas), the disturbance occurs in the same direction as the direction of travel of energy, resulting in oscillating regions of compression (increased density) and rarefaction (decreased density).

From a graph of displacement against distance (Figure 1a), we can define wavelength (λ) as the distance between corresponding points on successive waves, amplitude (a) as the maximum displacement from the equilibrium position, and velocity (c) as how rapidly the energy moves through the medium. From a graph of displacement against time (Figure 1b), the distance between corresponding points on successive waves defines the period (T). The reciprocal of the period is the frequency (f) (i.e. $\boldsymbol{f = 1/T}$) and has derived SI units Hertz (Hz; per second). Alternatively, the frequency of a travelling wave is the number of peaks which pass a stationary observer per second. Velocity, frequency and wavelength are related by the formula: $\boldsymbol{c = f\lambda}$.

Waves of identical frequency may start their oscillations simultaneously (**in phase**), or at different times (**out of phase**); described by the **phase angle** (θ) between their vectors.

Electromagnetic waves can travel across a vacuum, but sound waves require a medium for propagation. The speed of sound (c) is fixed for any given medium. Dense, rigid materials (e.g. bone: $c \approx 3000$ m/s) transmit sound faster than light, compressible materials (e.g. air: $c \approx 330$ m/s). The speed of sound in the soft tissues of the body ranges from ∼1400 m/s (fat) to ∼1750 m/s (tendon), with an average speed of 1540 m/s.

Human hearing can detect sound in the range 20 Hz to 20 kHz (the upper limit decreases with age; presbyacusis). Frequencies below and above this range are called infrasound and ultrasound respectively. The amplitude of a sound wave determines the flow of energy or intensity (W/m^2), and is frequently expressed on a logarithmic scale as effective sound pressure relative to the threshold of hearing at 1 kHz in non-SI units decibels (dB).

Interactions of waves

If two waves of identical frequency, amplitude and phase combine, a single wave with twice the amplitude results (**constructive interference**). If the waves are 180° out of phase they will cancel each other out (**destructive interference**). Waves interact with their environment. They can bounce (**reflection**), bend (**refraction**), scatter (**diffraction**), and convert their kinetic energy into heat energy (**absorption**). Sound intensity decreases exponentially with distance from the source (**attenuation**; dB/cm) due to diffraction and absorption. Greater attenuation occurs at high frequencies and in light compressible media.

The **acoustic impedance** (z) (derived SI units: Rayl; $kg/m^2/s$) of a medium is analogous to electrical impedance, and depends on its density and stiffness. When a wave meets an interface between two media of different z, some of the wave's energy will be reflected, and the remainder will be transmitted. The proportion of wave energy reflected depends on the difference in z, and is described by the **amplitude reflection co-efficient**, R_A. For interfaces between most body tissues, around 1% of the beam is reflected ($R_A \sim 0.01$); however at an air–tissue interface >99% of the incident beam is reflected ($R_A \sim 0.999$) which results in the ultrasound machine being 'dazzled' by the reflected beam and unable to 'see' deeper structures. A **coupling medium** (mineral oil based gel) is therefore necessary to eliminate air between the ultrasound probe and the skin surface.

The ultrasound machine

In its simplest form, the ultrasound machine operates like a ship's depth-sounding device. Periodic electrical pulses are converted into ultrasound pulses by a **lead zirconium titanate (PZT) piezoelectric transducer**. The sound waves travel through the tissues until they meet a tissue interface, whereupon a proportion of the emitted signal (determined by R_A) is reflected back to the transducer, which converts the reflected waves back into electrical pulses which are amplified and displayed. The

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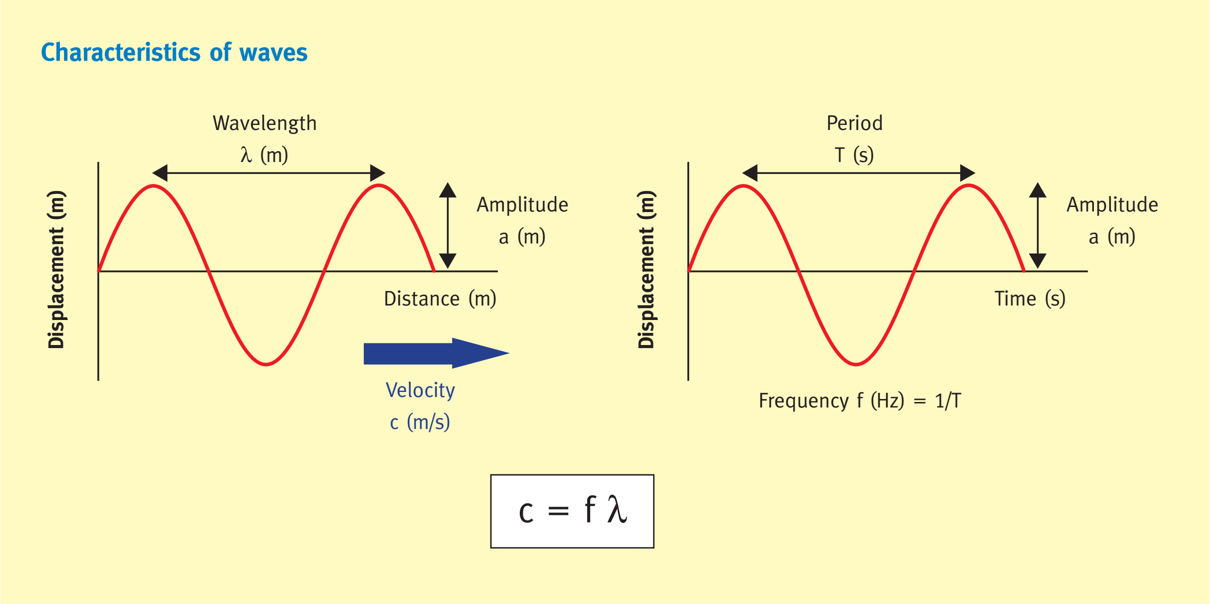

Figure 1

amplitude of the reflected wave provides information about the nature of the tissue interface. If the time taken for the sound to travel to the target and return to the transducer (t) and the speed of sound through the tissues ($c \sim 1540$ m/s) are known, then the depth of the target (d) is given by:

$$d = ct/2$$

An ultrasound probe typically emits sound waves in bursts or pulses of 1 μs duration spaced 1 ms apart, with a **pulse repetition rate** of 1000 pulses per second; so it transmits 1% of the time and 'listens' for the reflected echoes 99% of the time (Figure 2).

The earliest ultrasound machines simply plotted the amplitude of the reflected wave against time on an oscilloscope ('Amplitude'

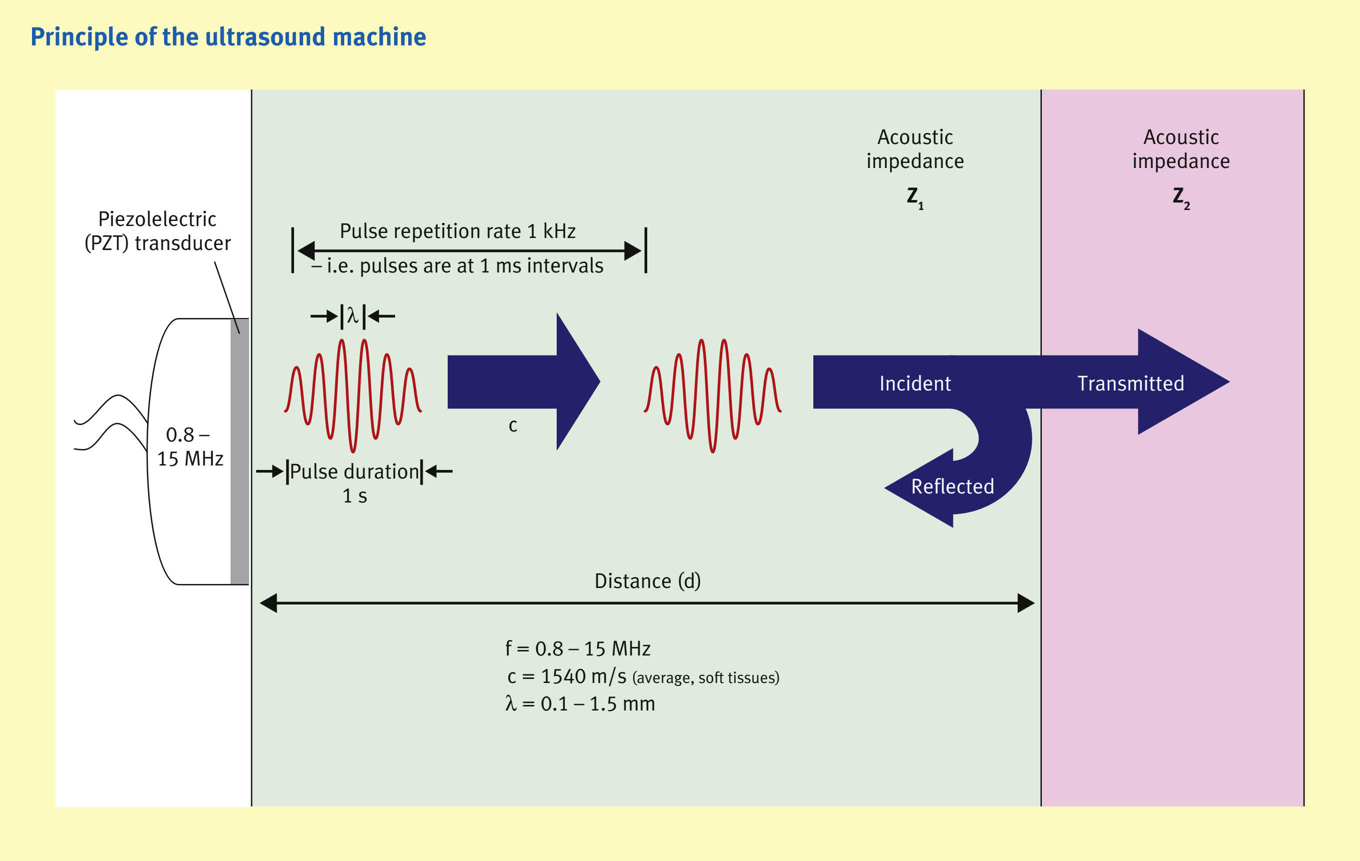

Figure 2