

## 1

## How Does Ultrasound Work?

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### Introduction

The aim of this chapter is to outline the basics of how ultrasound works. The construction of an image and some of the physical principles that govern the behaviour of sound in tissue will be introduced.

### What is Ultrasound?

Sound is simply the transfer of mechanical energy from a vibrating source through a medium. *Ultrasound* is defined as sound of a frequency above the human audible range, that is, above 20 kHz.

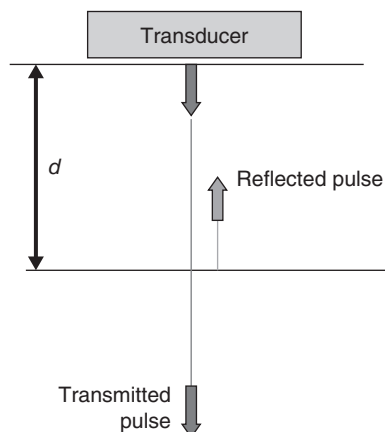
*Piezoelectric crystals* within the face of the transducer have the property of contracting or expanding when a voltage is applied across them. A thin layer of a synthetic piezoelectric material can be constructed to vibrate at a resonant frequency within the required range. This acts as a source of ultrasound. A very short (approximately 1  $\mu$ s) pulse is generated by the transducer and transmitted into the soft tissues. After generation of the 'pulse', the transducer receives no further electricity for a period of time (typically about 100–300  $\mu$ s) and acts as a 'listening device' to detect returning echoes generated within the medium of the soft tissues.

As the ultrasound wave of a returning 'echo' hits the transducer surface, the piezoelectric

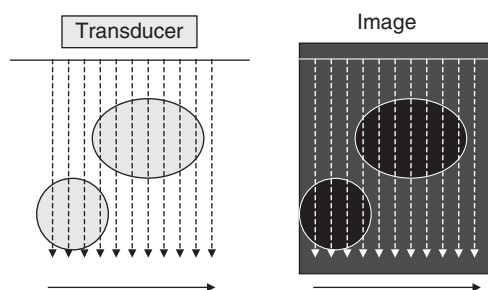
crystals vibrate, causing them to generate an alternating electric current. This is transmitted back to the ultrasound machine through the wires attached to the transducer. The magnitude of the voltage of this current is related directly to the amount of energy carried by the returning echo, and will determine the brightness level displayed for this location on the monitor. The machine measures the time that elapses between the *pulse* and the *echo*, and by using the known velocity of sound in soft tissues ( $1540 \text{ m s}^{-1}$ ) the distance to the echoing object can be calculated. Many animals (e.g., bats and marine mammals) use the same principle for echo-location of objects in their environment. (It is worth noting that the construction of the transducer with its sensitive crystal elements does not respond favourably if it is dropped or if the wheels of the machine run over its wires.) Diagnostic ultrasound utilises the pulse-echo principle to construct a two-dimensional sectional image of anatomical structures (Figure 1.1).

### Constructing the Image

Each pulse of sound transmitted into the patient generates a stream of echoes from multiple reflectors at various depths. As noted, the energy carried by each echo is converted into electrical energy by the piezoelectric crystals. In simple terms, these values are then stored



**Figure 1.1** The time taken ( $t$ ) for the echo to return to the transducer, and the speed of sound in soft tissue ( $v$ ), can be used to calculate the depth ( $d$ ) of the reflecting interface, where  $d = vt/2$ .



**Figure 1.2** Pulses of sound are fired in sequence from multiple adjacent crystals across the face of the transducer. These are used to produce contiguous scan lines from which a single *brightness mode* (B-mode) 'frame' of information can be produced that represents a two-dimensional anatomical cross-section.

within a computer memory as a single 'scan line' of information, and used to determine the brightness levels allocated to points in a vertical line on the image to represent corresponding depths in the patient. By firing pulses of sound in sequence from multiple adjacent crystals across the face of the transducer, numerous contiguous scan lines can be generated and a single 'frame' of information is produced to represent a two-dimensional anatomical cross-section (Figure 1.2). This type of ultrasound imaging is referred to as 'brightness mode' ('B-mode' or 'gray-scale') because the strength

of the echoes are represented by the brightness of the ultrasound image at that location.

If performed fast enough, the rapid update of frames can create a 'real-time' dynamic image of the scanning plane. Frame rate is limited by several factors. The ultrasound machine 'waits' for the echoes to return from the maximum depth of interest along each scan line before the next pulse is sent out. Thus, the frame rate depends on the *depth* of interest and the total number of scan lines of the image (*field of view*). Adjusting the depth and field of view allows the operator of the ultrasound machine to optimise the frame rate and the resolution of the image. In general, the image should be adjusted to the minimum depth that will include the entire object of interest.

## Making Sense of Ultrasound Images

During an ultrasound examination, most of the diagnostic conclusions about normal and abnormal appearances are based on pattern recognition. This includes a number of key observations:

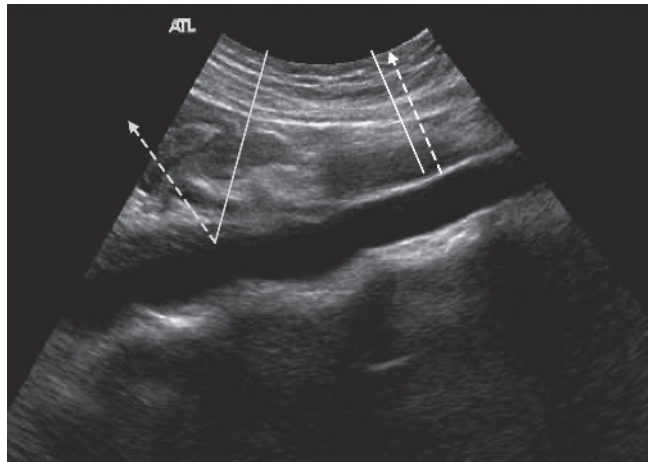
- the spatial definition of tissue boundaries;
- relative tissue reflectivity;
- echo-texture; and
- the effect of tissue on the transmission of sound.

These appearances are determined by the physical properties of the ultrasound waves and their interactions with tissues. Some of these key interactions are outlined below.

## What Happens to a Pulse of Sound as it Travels Through a Patient?

Reflection, scattering and refraction are common to both sound and light waves. An appreciation of this helps us make sense of why structures appear as they do in an ultrasound image.

**Figure 1.3** The divergent ultrasound beams generated by this curved-array probe demonstrate the effect of angle of insonation on the visualisation of vessel walls. A pulse of sound hitting the wall at 90° (solid yellow arrow) will be reflected back to the transducer (dashed yellow arrow). A pulse hitting the wall at any angle other than 90° will be reflected at an equal and opposite angle (green pathway), with the result that the echo may not be detected by the transducer. This is why in the image, the aortic wall appears well defined in the region of the yellow arrows and cannot be clearly discerned in the region of the green pathway.



### Reflection

Reflection of the ultrasound pulse occurs at interfaces between two media that have differences in acoustic *impedance*, which is a medium's physical properties as a transmitter of sound. Impedance is determined primarily by the medium's density and elasticity). At such boundaries, a proportion of the sound energy will be reflected, while the remaining sound energy is transmitted beyond the boundary. If the impedance difference at a boundary is high enough, for example at a soft tissue/air interface or at a soft tissue/solid interface, total reflection occurs and no sound energy is transmitted to deeper structures. Gas-filled structures and bone are therefore a significant challenge in ultrasound imaging.

### Specular Reflection

If a reflective boundary is smooth and large, specular reflection occurs. This is similar to when light is reflected from a smooth surface. Typical specular reflectors include the diaphragm, renal capsule and vessel walls.

Where the sound pulse hits a boundary (especially if it is specular) at an angle other than 90°, then by the basic 'law of reflection' it will not be reflected back towards the transducer, which means that the structure will not be detected by the ultrasound machine. Conversely, boundaries will be detected most

clearly if they are at 90° to the direction of travel of the ultrasound wave. This phenomenon is demonstrated in Figure 1.3.

### Diffuse Reflection

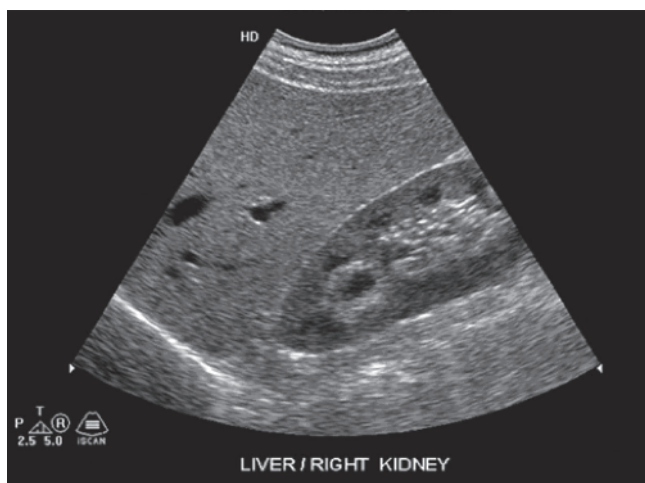
Diffuse reflection occurs where irregularities in the tissue boundary exist that are small compared to the wavelength of the sound. (At 5 MHz this is approximately 0.3 mm or less.) These irregularities cause the sound energy to be reflected in multiple directions – an optical analogy would be to consider the difference between gloss and matt paint. In practice, most soft-tissue boundaries are irregular and produce diffuse reflection to some degree.

### Scattering and Echo Texture

Acoustic impedance changes occur at large-scale boundaries, but are also present throughout soft-tissue structures. Small-scale localised changes in acoustic properties act as tiny reflecting targets that *scatter* the sound in many directions. This is what produces the characteristic *echo texture* (graininess) that is associated with solid structures on ultrasound, and the relative *echogenicity* (brightness) of adjacent organs (Figure 1.4).

### Attenuation

As sound travels through tissues, it loses energy. A number of interactions contribute to this



**Figure 1.4** Small-scale localised changes in the acoustic properties of many tissues act as tiny reflecting targets that *scatter* the sound in many directions. This produces the characteristic *echo texture* (graininess) associated with solid organs and their relative *echogenicity* (brightness) compared to adjacent organs, as seen in this view of the right lobe of the liver and right kidney.

process of *attenuation*, including reflection, scattering and absorption. This results in the pulse becoming progressively lower in intensity (and therefore producing weaker echoes) the deeper it travels into the patient.

In practice, Time Gain Compensation (TGC: increasing amplification or ‘gain’ of the electric signals generated by returning echoes from increasingly deep structures) is used to compensate for this reduction in signal strength with depth. Scattering contributes to beam attenuation and increases significantly with increasing frequency of the ultrasound wave. This results in increased attenuation, and thus a reduced *penetration* of the sound beam to deeper structures, when higher transmit frequencies are used.

### Absorption

Absorption is the process by which the mechanical energy carried by the pulse is converted into heat within the tissues. Absorption is the most significant form of attenuation in soft tissue. As sound travels through the patient, there is the potential for tissue damage, either through heating or mechanical effects (such as shearing or cavitation). In practice, ultrasound machines are designed to continually minimise the power of the ultrasound waves according to the principle of ALARA (‘as low as reasonably attainable’). While deleterious bio-effects caused by diagnostic

B-mode ultrasound have never been conclusively demonstrated, in case such bio-effects actually exist (albeit at levels below current powers of detection), ultrasound should be used clinically in situations where the information it provides is of potential net benefit, especially when used in the evaluation of pregnancy.

### Why is Frequency Important?

Both, absorption and scattering result in reduced penetration to deeper tissues with higher frequencies. Unfortunately, higher frequencies result in a higher image resolution, and therefore there must be a trade-off between image quality and penetration. In practice, the highest frequency should be used that allows adequate penetration to the depth of interest.

## Summary

The power of ultrasound in a clinician’s hands will be significantly affected by his or her ability to operate the machine in such a way that it can obtain the highest-quality images. This, in turn, entails an understanding of the physics of ultrasound. This brief overview should serve as an introduction, but further study is called for if the reader wishes to use ultrasound in anything more than a rudimentary fashion, and especially

for the effective use of any of the Doppler applications described in this book. The references listed below provide useful sources of more detailed information.

## Further Reading

Gibbs, V., Cole, D., Sassano, A. (2009) *Ultrasound Physics and Technology – How, Why and When?* Churchill Livingstone.

Guidelines for the Safe Use of Diagnostic Ultrasound Equipment (2009) British Medical Ultrasound Society. Available at: <http://www.bmus.org/policies-guides/pg-safetystatements.asp>  
Hoskins, P.R., Thrush, A., Martin, K., Whittingham, T.A. (2010) *Diagnostic Ultrasound Physics and Equipment*. Cambridge Medicine.

