Chapter 1

Introduction to B-mode imaging

Kevin Martin

The application of ultrasound to medical diagnosis has seen continuous development and growth over several decades. Early, primitive display modes, such as A-mode and static B-mode, borrowed from metallurgical testing and radar technologies of the time, have given way to high-performance, real-time imaging. Moving ultrasound images of babies in the womb are now familiar to most members of the public through personal experience of antenatal scanning or via television. Modern ultrasound systems do much more than produce images of unborn babies, however. Modern ultrasound systems are able to make detailed measurements of blood movements in blood vessels and tissues, visualize moving structures in 3D, and make measurements related to the stiffness of tissues.

Improvements in technology have been followed by widespread acceptance and use of ultrasound in medical diagnosis. Applications have progressed from simple measurements of anatomical dimensions, such as biparietal diameter, to detailed screening for fetal abnormalities, detection of subtle changes in tissue texture and detailed study of blood flow in arteries. In many areas, ultrasound is now chosen as the first line of investigation, before alternative imaging techniques.

This book describes the physics and technology of diagnostic ultrasound systems in use at the time of writing. The book may be divided into four sections; basic physics and B-mode imaging in Chapters 1–6; Doppler ultrasound in Chapters 7–10; quality assurance and safety in Chapters 11–12, and recent technology in Chapters 13–15. This chapter covers the very basic concepts involved in B-mode imaging.

Basic principles of ultrasound image formation

We begin the explanation of ultrasound image formation with a description of a B-mode image and the basic principles of its formation. In essence, these principles are still used in modern B-mode systems, although they may be used within more complex arrangements designed to enhance performance.

A B-mode image is a cross-sectional image representing tissues and organ boundaries within the body (Figure 1.1). It is constructed from echoes, which are generated by reflection of ultrasound waves at tissue boundaries, and scattering from small irregularities within tissues. Each echo is displayed at a point in the image, which corresponds to the relative position of its origin within the body cross section, resulting in a scaled map of echo-producing features. The brightness of the image at each point is related to the strength or amplitude of the echo, giving rise to the term B-mode (brightness mode).

Usually, the B-mode image bears a close resemblance to the anatomy, which might be seen by eye, if the body could be cut through in the same plane. Abnormal
1 Introduction to B-mode imaging

anatomical boundaries and alterations in the scattering behaviour of tissues can be used to indicate pathology.

To form a B-mode image, a source of ultrasound, the transducer, is placed in contact with the skin and short bursts or pulses of ultrasound are sent into the patient. These are directed along narrow beam-shaped paths. As the pulses travel into the tissues of the body, they are reflected and scattered, generating echoes, some of which travel back to the transducer, where they are detected. These echoes are used to form the image.

To display each echo in a position corresponding to that of the interface or feature (known as a target) that caused it, the B-mode system needs two pieces of information. These are
1. the range (distance) of the target from the transducer and
2. the direction of the target from the active part of the transducer, i.e. the position and orientation of the ultrasound beam.

Echo ranging

The range of the target from the transducer is measured using the pulse–echo principle. The same principle is used in echo-sounding equipment in boats to measure the depth of water. Figure 1.2 illustrates the measurement of water depth using the pulse–echo principle. Here, the transducer transmits a short burst or pulse of ultrasound, which travels through water to the seabed below, where it is reflected, i.e. produces an echo. The echo travels back through the water to the transducer, where it is detected. The distance to the seabed can be worked out, if the speed of sound in water is known and the time between the pulse leaving the transducer and the echo being detected, the ‘go and return time’, is measured.

To measure the go and return time, the transducer transmits a pulse of ultrasound at the same time as a clock is started \( t = 0 \). If the speed of sound in water is \( c \) and the depth is \( d \), then the pulse reaches the seabed at time \( t = d/c \). The returning echo also travels at speed \( c \) and takes a further time \( d/c \) to reach the transducer, where it is detected. Hence, the echo arrives back at the transducer after a total go and return time \( t = 2d/c \). Rearranging this equation, the depth \( d \) can be calculated from \( d = ct/2 \). Thus, the system calculates the target range \( d \) by measuring the arrival time \( t \) of an echo, assuming a fixed value for the speed of sound \( c \) (usually 1540 m s\(^{-1}\) for human tissues).

In the above example, only one reflecting surface was considered, i.e. the interface between the water and the seabed. The water contained no other interfaces or irregularities, which might generate additional echoes. When a pulse travels through the tissues of the body, it encounters many interfaces and scatterers, all of which generate echoes. After transmission of the short pulse, the transducer operates in receive mode, effectively listening for echoes. These begin to return immediately from targets close to the transducer, followed by echoes from greater and greater depths, in a continuous series, to the maximum depth of interest. This is known as the pulse–echo sequence.

Image formation

The 2D B-mode image is formed from a large number of B-mode lines, where each line in the image is produced by a pulse–echo sequence. In early B-mode systems, the brightness display of these echoes was generated as follows.

As the transducer transmits the pulse, a display spot begins to travel down the screen from a point corresponding to the position of the transducer, in a direction corresponding to the path of the pulse (the ultrasound beam). Echoes from targets near the transducer return first and increase the brightness of the spot. Further echoes, from increasing depths, return at increasing times after transmission as the spot travels down the screen. Hence, the distance down the display at which each echo is displayed is related to its depth below the transducer. The rate at which the display spot travels down the screen determines the scale of the image. A rapidly moving spot produces a magnified image.
1 Introduction to B-mode imaging

Fig. 1.3 Formation of a 2D B-mode image. The image is built up line by line as the beam is stepped along the transducer array.

The pulse–echo sequence, described above, resulted in the display of one line of information on the B-mode image. A complete B-mode image, such as that in Figure 1.1, is made up typically of 100 or more B-mode lines.

Let us consider a linear array probe, as described in Chapter 3, where the image is formed as illustrated in Figure 1.3. During the first pulse–echo sequence, an image line is formed, say on the left of the display. The active area of the transducer, and hence the beam, is then moved along the array to the adjacent beam position. Here a new pulse–echo sequence produces a new image line of echoes, with a position on the display corresponding to that of the new beam. The beam is progressively stepped along the array with a new pulse–echo sequence generating a new image line at each position.

One complete sweep may take perhaps 1/30th of a second. This would mean that 30 complete images could be formed in 1 s, allowing real-time display of the B-mode image. That is, the image is displayed with negligible delay as the information is acquired, rather than recorded and then viewed, as with a radiograph or CT scan.

B-mode formats

The B-mode image, just described, was produced by a linear transducer array, i.e. a large number of small transducer elements arranged in a straight line (see Chapter 3). The ultrasound beams, and hence the B-mode lines, were all perpendicular to the line of transducer elements, and hence parallel to each other (Figure 1.4a). The resulting rectangular field of view is useful in applications, where there is a need to image superficial areas of the body at the same time as organs at a deeper level.

Other scan formats are often used for other applications. For instance, a curvilinear transducer (Figure 1.4b) gives a wide field of view near the transducer and an even wider field at deeper levels. This is also achieved by the trapezoidal field of view (Figure 1.4c). Curvilinear and trapezoidal fields of view are widely used in obstetric scanning to allow imaging of more superficial targets, such as the placenta, while giving the greatest coverage at the depth of the baby. The sector field of view (Figure 1.4d) is preferred for imaging of the heart, where access is normally through a narrow acoustic window between the ribs. In the sector format, all the B-mode lines are close together near the transducer and pass through the narrow gap, but diverge after that to give a wide field of view at the depth of the heart.

Transducers designed to be used internally, such as intravascular or rectal probes, may use the radial format (Figure 1.4e) as well as sector and linear fields of view. The radial beam distribution is similar to that of beams of light from a lighthouse. This format may be obtained by rotating a single element transducer on the end of a catheter or rigid tube, which can be inserted into the body. Hence, the B-mode lines all radiate out from the centre of the field of view.