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Introduction to B-mode imaging

KEVIN MARTIN

INTRODUCTION

Ultrasound is one of the most widely used non-invasive imaging techniques in medical diagnosis. In the year from July 2016 to July 2017, over 9.2 million ultrasound scans were carried out on National Health Service (NHS) patients in England (NHS England 2017). This is almost twice the number of computed tomography (CT) scans and almost three times the number of magnetic resonance imaging (MRI) scans carried out in the same period. Ultrasound is an interactive imaging technique in which the operator holds the ultrasound probe in contact with the patient and observes images of internal anatomy in real time. In most instances, interpretation of the images is carried out simultaneously, rather than being reported by someone else at a later time. This, and the ultrasound examination's lower cost (£40–£49) compared to CT (£71–£199) and MRI (£116–£225) (NHS Improvement 2016) makes it attractive as a first line of investigation in many circumstances. As it is radiation free, ultrasound is the preferred imaging modality in obstetric and paediatric investigations. Ultrasound is most useful for imaging soft tissue anatomy and is widely used in the abdomen, pelvis, heart and neck. It has become a widely used imaging tool in musculo-skeletal investigations of muscles, tendons and joints. In addition to its well-established use in imaging soft tissue anatomy, ultrasound is a powerful tool in the study of blood flow in arteries and veins, where use of the Doppler effect enables blood velocity to be measured and imaged.

Commercial ultrasound systems incorporate many complex technologies which provide improved image quality and enable the system to image subtle changes in tissue and finer detail at greater depths in tissue. Additional techniques include elastography, in which the stiffness of the tissue can be evaluated. The use of contrast agents with ultrasound imaging can increase its diagnostic accuracy in differentiating benign from malignant lesions. Standard ultrasound systems produce two-dimensional cross-sectional images of anatomy, but these may be extended to acquire data in three dimensions. The range of technologies available to the user to enhance the imaging performance is ever growing. However, these additional tools bring with them a need to understand when and where they should be used and how they affect what is seen on the screen. All such technologies are still ruled by the laws of physics, some of which can lead to misleading artefacts in the image. The safe use of ultrasound in medical imaging has two aspects. First, ultrasound imaging involves depositing ultrasound energy within the patient, which can lead to some warming of exposed tissue. Clearly, it is important to minimise such effects in obtaining a diagnosis. Second, perhaps a greater hazard is misdiagnosis. The risk of misdiagnosis must be controlled by ensuring that the ultrasound system is performing as intended and is operated competently.

The intention of this text is to provide the reader with an understanding of the physics and technology necessary to use ultrasound imaging systems safely and efficiently. It might also serve as a first-level text for those training as scientists. The text may be divided into four sections: Chapters 2 through 6 describe the physics and technology of ultrasound imaging systems in addition to their limitations and use in measurement. Chapters 7 through 11 describe the principles and applications of Doppler ultrasound, including a description of flow in blood vessels. This is followed by descriptions of three-dimensional ultrasound, contrast agents and elastography in Chapters 12 through 14. Ultrasound quality assurance and safety are covered in Chapters 15 and 16. This introductory chapter explains some of the basic concepts involved in forming an ultrasound image.

BASIC PRINCIPLES OF ULTRASOUND IMAGE FORMATION

We begin with a description of the ultrasound image and an explanation of the basic principles of its formation. In essence, these simple principles are still used in commercial ultrasound imaging systems, but they are likely to be enhanced by numerous additional image-forming and processing techniques designed to improve image quality and performance. These are described in later chapters.

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

Figure 1.1 An example of a B-mode image showing reflections from organ and blood vessel boundaries and scattering from tissues.

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 along the same path, where they are received. 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 produced it, the B-mode system needs two pieces of information. These are as follows:

1. The range (distance) of the target from the transducer.
2. The direction of the target from the active part of the transducer, i.e. the position and orientation of the ultrasound beam.

The pulse-echo principle

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 the 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 received. The distance to the seabed can be worked out, if the speed of sound in water is known and the time between the transmission pulse leaving the transducer and the echo being received, the 'go and return time', is measured.

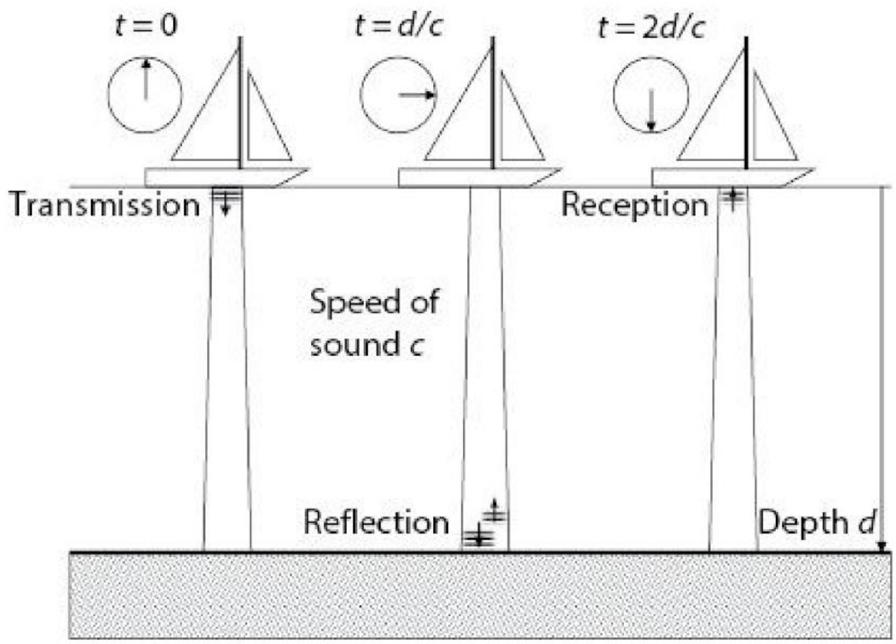

Figure 1.2 Measurement of water depth using the pulse-echo principle. A short burst or pulse of ultrasound is transmitted at time $t = 0$. It takes time d/c to travel to depth d, where c is the speed of sound. The echo arrives back at the source at time $2d/c$. The depth d can be worked out from the go and return time $2d/c$ if the speed of sound c is known.

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 received. 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 this 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 time of arrival of echoes after transmission increases with target depth. As the sequence of echoes arrives, it is used to form a line in the image, the brightness of the line at each depth changing with the amplitude or strength of the echo. Each pulse-echo sequence results in the display of one line of information on the B-mode image. The two-dimensional B-mode image is formed from a large number of B-mode lines. A complete B-mode image, such as that in Figure 1.1, is made up typically of 100 or more B-mode lines.

Figure 1.3 illustrates the formation of a B-mode image. During the first pulse-echo sequence, an image line is formed, say on the left of the display (Line 1). The beam is then moved to the adjacent position. Here a new pulse-echo sequence produces a new image line, with a position on the display corresponding to that of the new beam (Line 2). The beam is progressively stepped across the image with a new pulse-echo sequence generating a new image line at each position. Figure 1.4 is a B-mode image of a section through the head of a fetus from an early ultrasound scanner. The image is made up of approximately 160 individual B-mode lines, which can be seen in the image. One complete sweep of the 160 lines takes approximately 1/30th of a second. This means that about 30 complete images could be formed in each second, 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 being recorded and then