Ultrasound in the Critically Ill

A Practical Guide

Andrew Walden
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Editors

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Preface

Historically, ultrasound has been delivered as a department-based diagnostic intervention within the radiology, cardiology and obstetric departments. As machines were often large and cumbersome, patients had to attend those departments for the examination to be performed. Rigorous training and governance structures developed to ensure a thorough and consistent approach among radiographers, obstetric sonographers and cardiac technicians. This system is very good for ambulatory patients in which a comprehensive assessment is required; however, for acutely unwell patients who may require intensive monitoring, oxygen therapy or organ support, this is not such a practical approach.

With the increased portability and usability of ultrasound machines, a new approach has developed where the machine comes to the patient rather than the other way round. This Point of Care approach to ultrasound has led to whole new areas of ultrasound examination and clinical decision-making. The time constraint on a clinician caring for a sick patient means that the comprehensive departmental use of ultrasound is replaced by a more abbreviated technique designed to answer specific questions, often in a dichotomous way and as an extension of clinical assessment and examination. Ruling in or ruling out certain pathologies can be invaluable in the deciding of patient triage, further investigations and the need for intervention or surgery.

Another advantage of point of care ultrasound over departmental ultrasound is the ability to look at dynamic changes in physiology following interventions. For instance, the effect of a fluid bolus on cardiac output or how a recruitment maneuver in a mechanically ventilated patient leads to improved lung aeration.

The use of point of care ultrasound has undoubtedly led to reduced morbidity around interventional procedures such as paracentesis, central venous cannulation and thoracocentesis.

One counterpoint to this flourishing of point of care ultrasound is the issue of training and competence. Sonographers and radiographers have to spend a long time training to ensure they see the range of pathology to be able to safely diagnose certain pathologies. Cognisant of this, clinicians have developed training curriculums with theoretical and practical modules to allow accreditation in a particular area of point of care ultrasound. Notably, within the United Kingdom, the Royal College of Radiologists has developed guidelines for non-radiology specialties (https://www.rcr.ac.uk/system/files/publication/field_publication_files/bfcr173_ultrasound_training_med_surg.pdf). In addition, several professional bodies have also developed similar guidelines and curriculums, e.g. Focused Acute Medicine Ultrasound (http://famus.org.uk/) and

Focused Ultrasound in Intensive Care (https://www.ics.ac.uk/ICS/FUSIC/ICS/FUSIC/FUSIC_Accreditation.aspx?hkey=c88fa5cd-5c3f-4c22-b007-53e01a523ce8).

This book is aimed at all frontline staff who are looking to use ultrasound in their clinical practice to try to improve the care of acutely and critically ill patients. The book is laid out in two sections. The first section attempts to take a comprehensive approach to specific systems of examination taking an organ-focused approach. The second part of the book attempts to pull those chapters together by looking at specific clinical scenarios.

We hope the reader of this book ends up with the same degree of enthusiasm that each of the editors has with respect to point of care ultrasound and how it improves the care of our patients.

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Chapter 1
Physics of Ultrasound

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Keywords Physics · Doppler · Point of care ultrasound

1.1 Introduction

Studying the physics of ultrasound allows for a greater understanding of how images are acquired and artefacts generated. A basic primer in physics is essential in any ultrasound based training program and this chapter sets out to give an overview and introduces common artefacts and imaging modes.

1.2 The Ultrasound Wave

Ultrasound waves are sound waves with similar characteristics. They have an amplitude, which represents the strength (peak pressure) and a period, which represents the length of time to complete 1 cycle (Fig. 1.1). The distance of a complete cycle is called wavelength (Fig. 1.2).

The frequency of a wave is the number of cycles over time:

$$\text{Frequency} = \text{n cycles}/\text{time}$$
$$1\,\text{Hertz}\,(\text{Hz}) = 1\,\text{cycle per second}$$

Ultrasound is sound of any frequency above the standard human pitch (>20 kHz). Diagnostic ultrasound uses frequencies from 1 to 20 MHz (Fig. 1.3).

Sound waves propagate through tissue with a Velocity, which is equal to wavelength (λ) times frequency (f):

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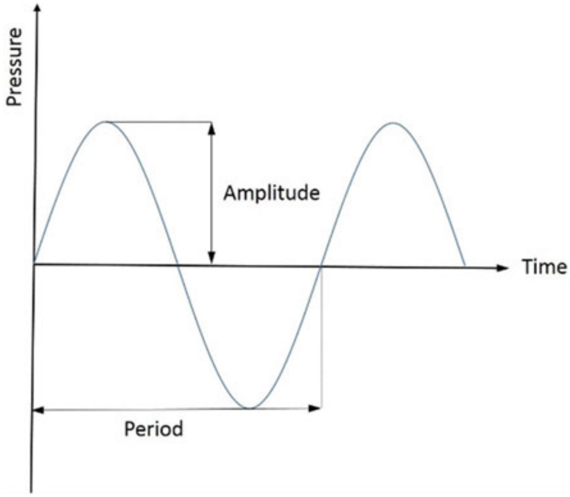


Fig. 1.1 Amplitude and period

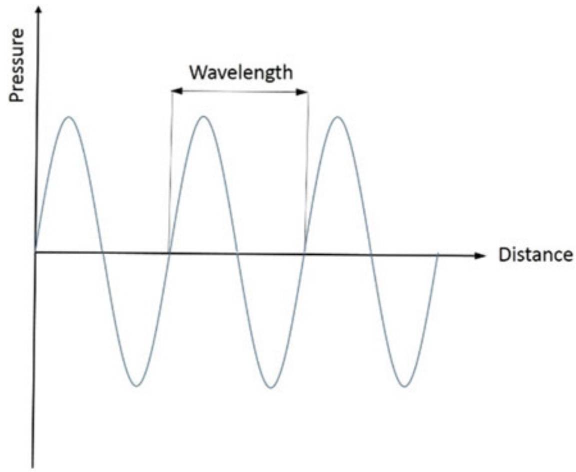


Fig. 1.2 Wavelength

$$V = \lambda \times f$$

The velocity is constant in a given medium and will be determined by the density and stiffness of the medium (Fig. 1.4). The ultrasound device uses a velocity of 1540 m/s for its calculations.

The velocity of ultrasound is very similar in fluids and solid organs. In contrast the velocity is much lower in air and much higher in bone (Table 1.1).

Given the constant velocity in a tissue, a higher frequency will decrease the wavelength, which will result in a better resolution. However, the higher the

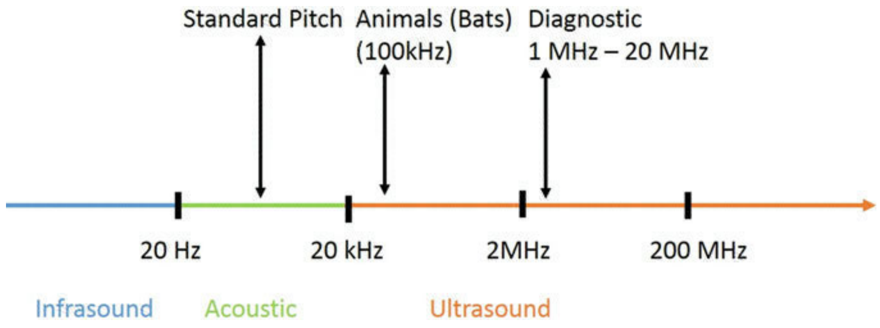


Fig. 1.3 Standard pitch and ultrasound frequency range

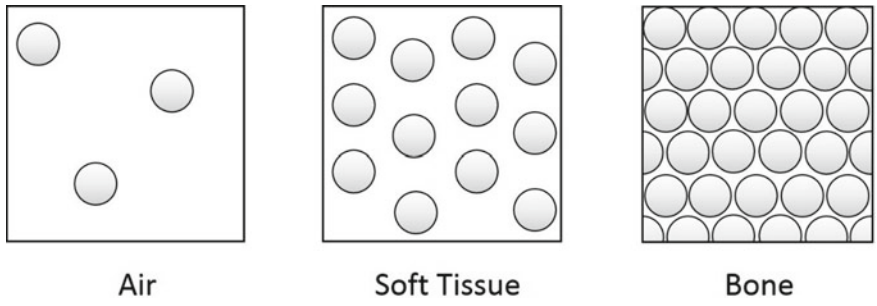


Fig. 1.4 Density of different body organs

Table 1.1 Velocity of ultrasound in different tissues

Tissue	Air	Fat	Water	Kidney	Spleen	Muscle	Liver	Bone
V (m/s)	331	1470	1490	1560	1565	1575	1570	3360

frequency the larger the attenuation of the ultrasound wave, which will result in a lower depth:

↑ Frequency → ↓ Wavelength → ↑ Resolution

↑ Frequency → ↑ Attenuation → ↓ Depth of Field

Figure 1.5 shows the ultrasound absorption rising in all media with rising frequencies. Please note that while bone will absorb most of the ultrasound even at low frequencies, fluid filled structures will absorb almost nothing and so are ideal for use as ultrasound windows to visualise deeper areas (i.e. for pelvic ultrasound your patient should always have a full bladder (Fig. 1.6)).

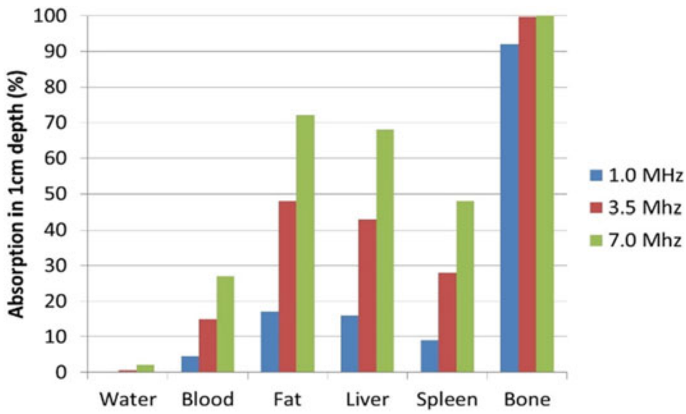


Fig. 1.5 Ultrasound absorption in 1 cm depth for different tissues and frequencies

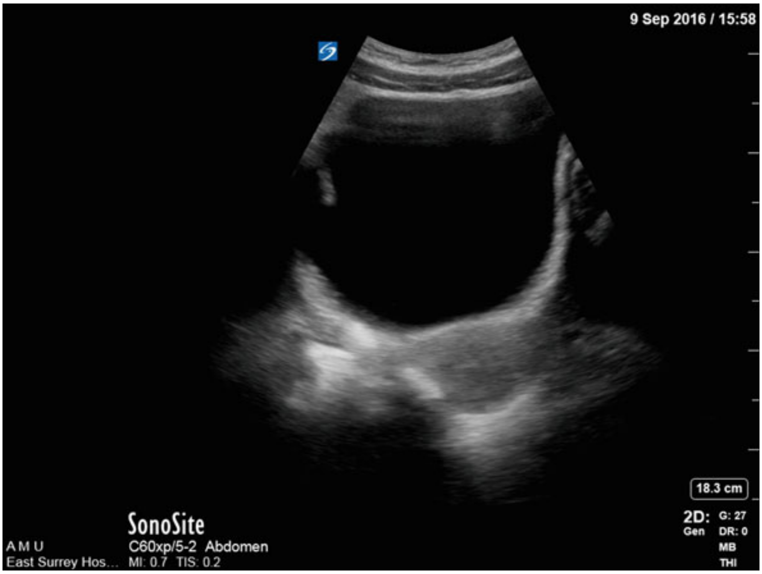


Fig. 1.6 Use fluid filled organs (bladder) as windows to visualise deeper structures

1.3 The Origin of the Ultrasound Image

Ultrasound machines use the piezoelectric principle to transform electrical energy into vibrations and hence ultrasound waves. It then receives ultrasound waves and transforms these waves into electrical energy.

The piezoelectric crystals and with that the ultrasound probes are the most expensive parts of the machines and should be treated with caution. Cleaning the transducers after use is mandatory, dried ultrasound gel on transducers will distort the pictures for the next user.

The ultrasound device sends an ultrasound signal out and measures the time and strength of the returning signals. The device assumes that the velocity of ultrasound in human tissue is constant (1540 m/s). It uses the time until the signal returns to calculate the depth of the structure (Fig. 1.7). The higher the intensity of the returning echo, the brighter the speckle will be on B-mode (for Brightness, also called 2d on some devices).

The intensity of the returning echo is dependent on the impedance difference of the interface between two tissues (Fig. 1.8).

Homogenous substances (e.g. fluids) will not produce any echoes. In Fig. 1.9 the ultrasound picture of an Oil/Water mix is shown. On the left hand side, the fluids are not mixed, resulting in only one interface between oil and water, and thus a bright line. On the right hand side there are millions of small interfaces, resulting in a picture with millions of interfaces (Fig. 1.9).

The laws of optics are valid for ultrasound waves. Ultrasound waves can be reflected, refracted, dispersed, absorbed and diverged. The most important attenuation processes for practising ultrasound are reflection and absorption (Fig. 1.10).

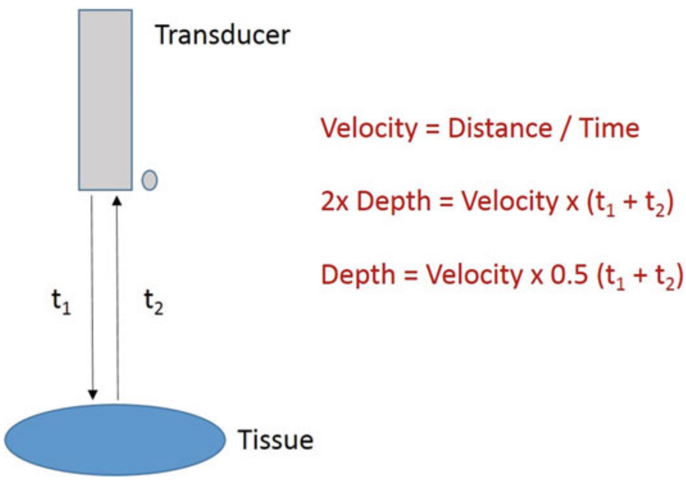
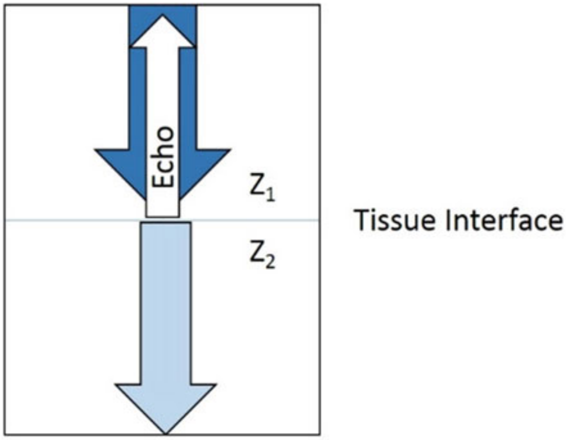


Fig. 1.7 Depth and time



$$I_{Echo} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \times I_0$$

Fig. 1.8 Impedance difference and Echo intensity

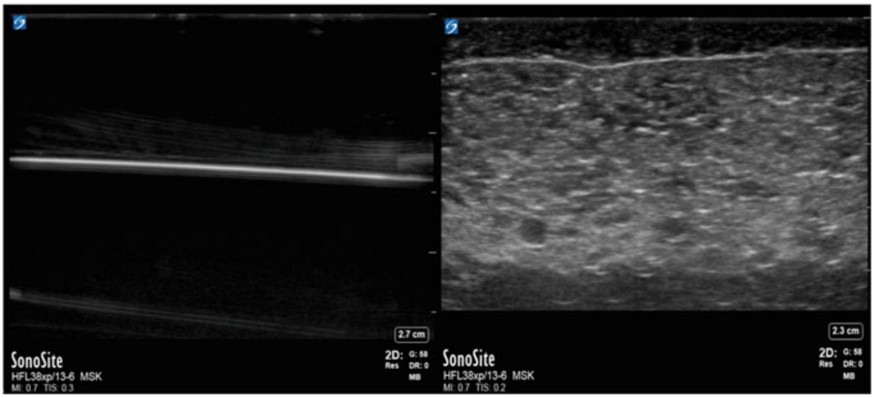


Fig. 1.9 Ultrasound of oil/water solution (unmixed and mixed)

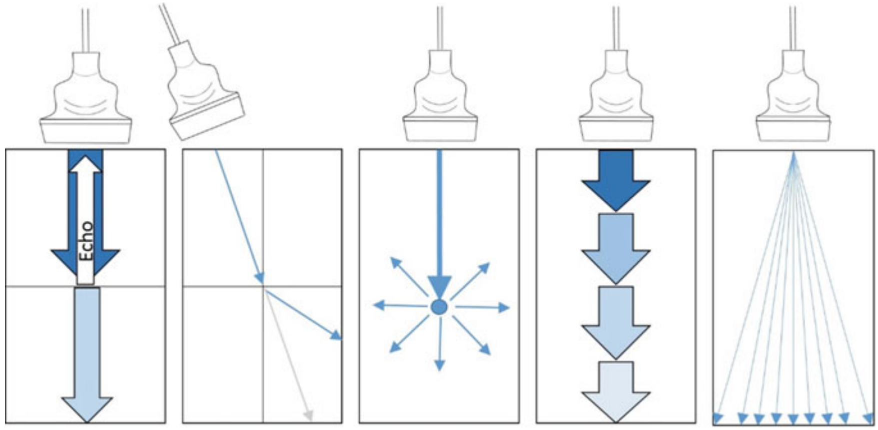


Fig. 1.10 Attenuation of ultrasound waves

1.4 Ultrasound Modes

1.4.1 A—Mode

(not used much in today's medical practice)

For Amplitude. In the early years of ultrasound before easy access to CT scanners ultrasound was used to monitor midline shifts in traumatic brain injuries. Amplitudes over time were used to show structural shifts over time. A-Mode scanning is still in use in Ophthalmology for measuring the axial length of the eye.

1.4.2 B—Mode

Brightness mode also called 2D mode. Ultrasound signals are send out over whole ultrasound transducer and returning signals are plotted against time delays. The result is a 2-dimensional picture showing impedance differences at different depths (Fig. 1.11).

1.4.3 M—Mode

M—Mode (motion) showing the change over time on one line of ultrasound waves. This enables the device to show an area of interest with high temporal resolution. Used for assessment of cardiac muscle, valve assessment and IVC measurements (Fig. 1.12).

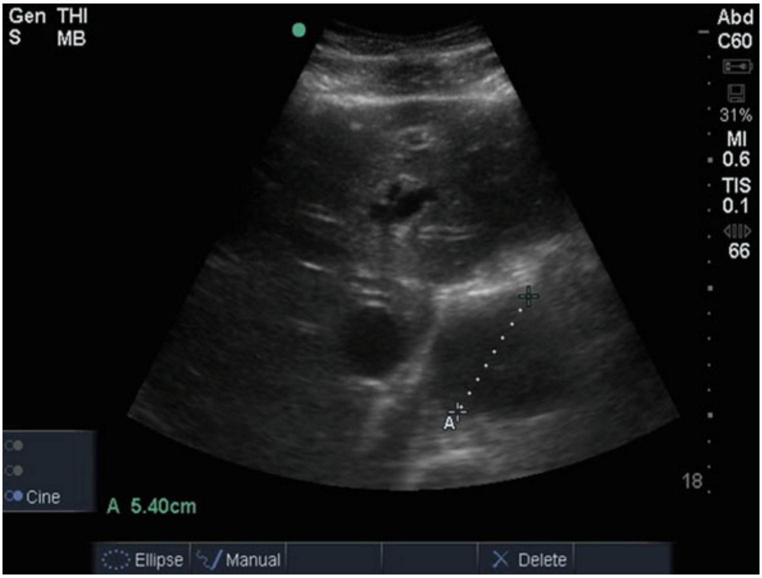


Fig. 1.11 B—mode showing 2d picture

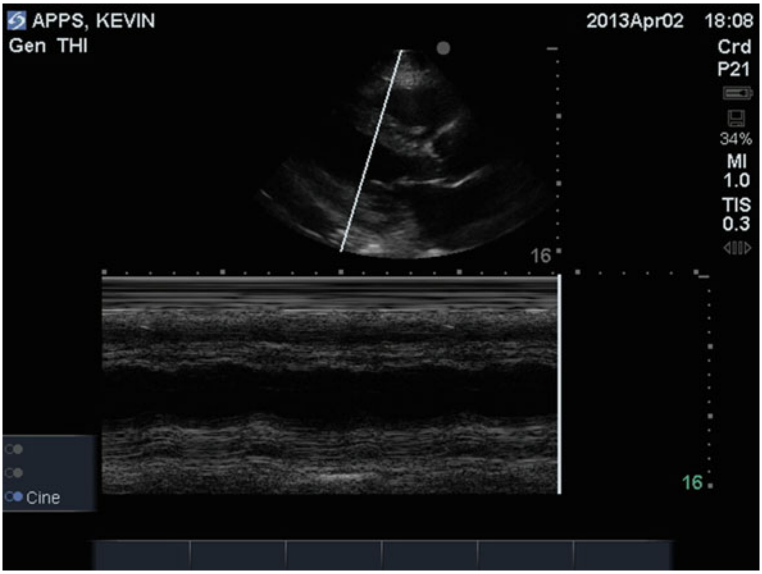


Fig. 1.12 M-mode, showing the change over time across a single plane of Ultrasound

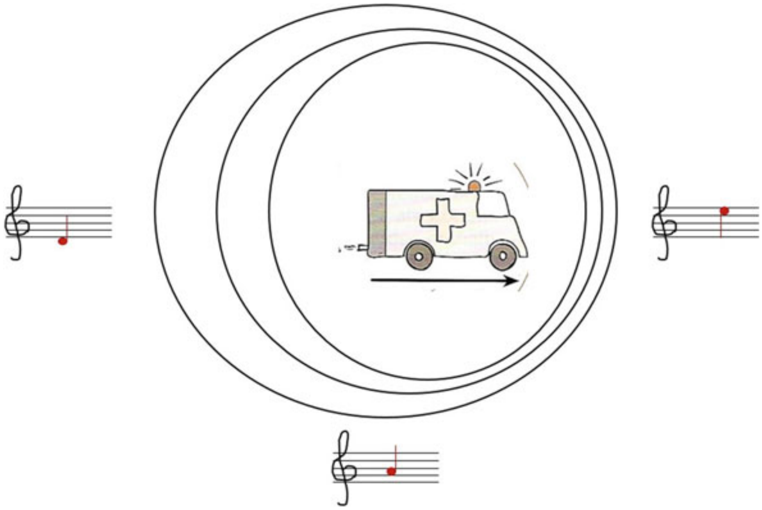


Fig. 1.13 Doppler effect—change of frequency depending on direction of sound waves

1.4.4 Doppler

The Doppler Effect describes a change in frequency of sound waves depending on the direction. As an example, in Fig. 1.13 the pitch (and with that the frequency) changes depending on the relative movement of the ambulance towards a listening person. If the ambulance travels towards a person the pitch is relatively high, gets lower once the ambulance is passing and even lower once the ambulance is moving away.

The ultrasound angle for Doppler measurements should be different from 90°, otherwise no flow can be observed (particularly in veins, where velocities are low). The amplitude and direction of the Doppler signal will change depending on the angle of the ultrasound transducer towards the flow through a blood vessel or heart valve (Fig. 1.14).

1.5 Ultrasound Transducers

For point of care ultrasound (POCUS), the most used probes are curvilinear, linear and phased array transducers. Other more specialised probes are cavity (gynaecology), hockey stick and TOE (both cardiology) transducers.

The Linear probe (Fig. 1.15) is a high frequency transducer (>7 MHz, small wavelength), which has excellent superficial resolution. However, secondary to the high frequencies the absorption of ultrasound is large, resulting in a small (usual less than 9 cm) depth. It is used for the visualisation of superficial structures (i.e.

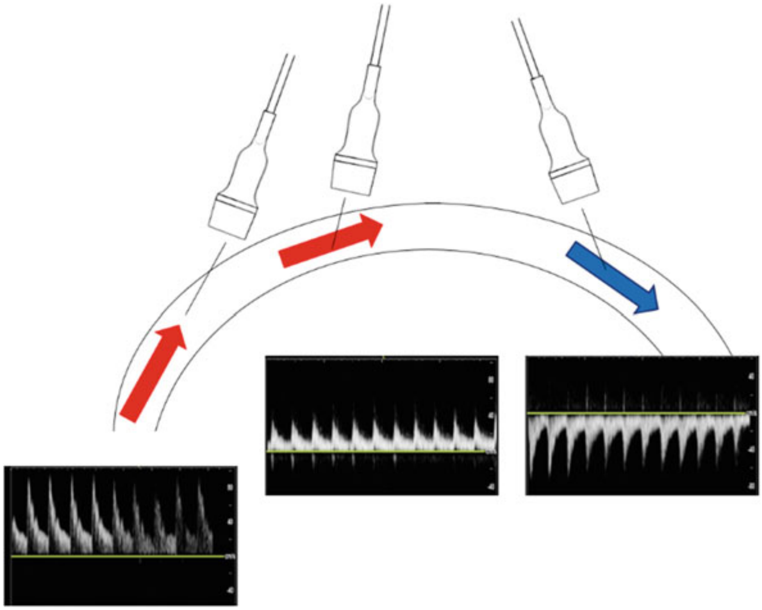


Fig. 1.14 Ultrasound angle and doppler signal

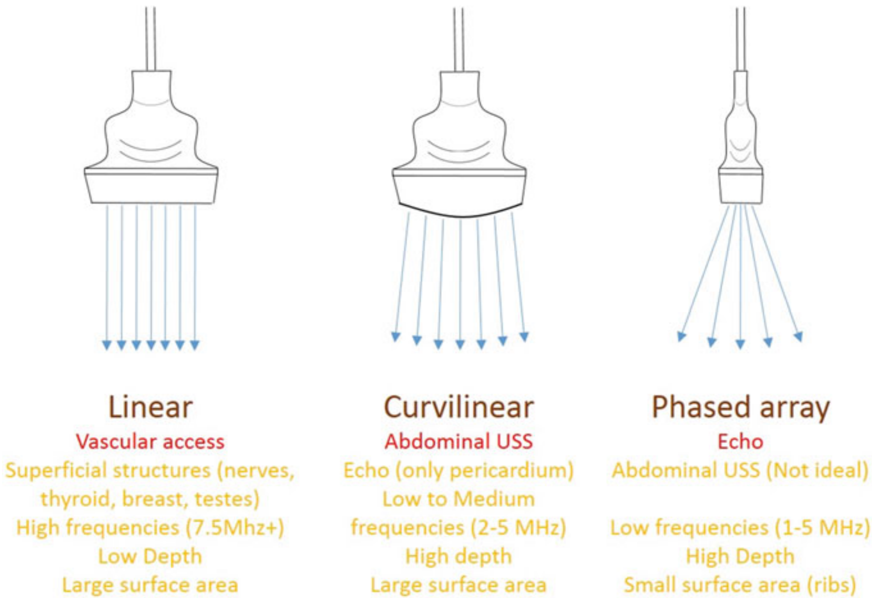


Fig. 1.15 Ultrasound transducer

nerves, muscles, arteries, veins, thyroid, breast and testes) and needle guidance for biopsies, nerve blocks and vascular access.

The curvilinear probe (Fig. 1.15) is a low frequency transducer with a relatively preserved superficial resolution and a great depth (up to 30 cm). It is used for thoracic and abdominal ultrasound and can be used for purposes of the linear probe if greater depth is required (e.g. patients with higher BMI). It has a relatively large footprint.

The phased array probe (Fig. 1.15) is a low frequency transducer with a small footprint. Superficial resolution is extremely poor. It is ideal for Echocardiography with great depth (up to 30 cm), and the right pulse repetition to assess muscle and valvular movement.

1.6 Ultrasound Terminology

Echogenic: ability to produce echoes

Isoechoic: similar echogenicity to a neighbouring structure

Anechoic: no echoes, appears black on ultrasound (fluid, Fig. 1.16)

Hyperechoic: highly reflective, bright when compared with neighbouring structures

Hypoechoic: less reflective, less bright when compared with neighbouring structures (see Fig. 1.17).

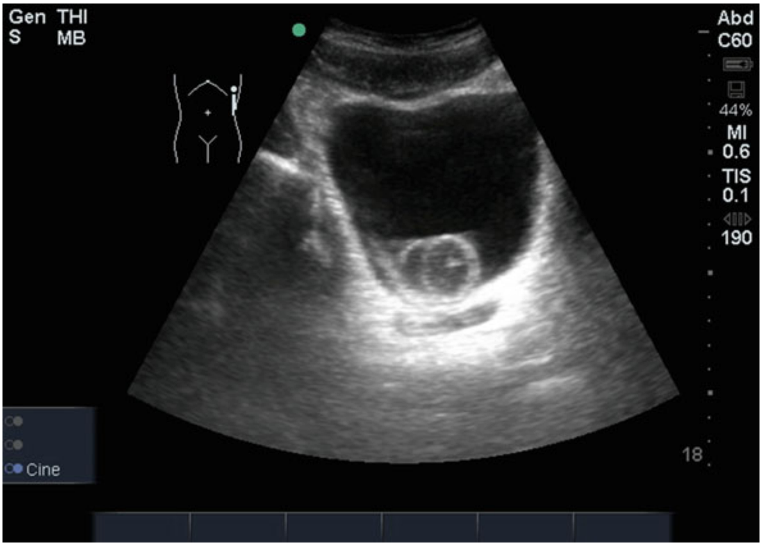


Fig. 1.16 The urine in the bladder is anechoic, the balloon of the catheter is hyperechoic compared to surrounding fluid: Note the posterior enhancement behind the fluid filled bladder

1.7 Artefacts

Ultrasound images may show structures which are not there or changes which are not anatomical. These phenomena are called artefacts. Some artefacts are avoidable while others are used for diagnostic purposes. The following elaboration introduces some general artefacts. Organ specific artefacts will be presented in their respective chapters.

1.7.1 Dorsal Acoustic Shadow

If there is a large difference of impedance between tissues, as in soft tissue to bone, almost all of the ultrasound energy will be reflected, resulting in a very bright echo. Additionally, in the case of bone or calcium (stones) the little non reflected ultrasound will be absorbed, leaving an echo free (shadow) area behind the reflexion.

1.7.2 Posterior Enhancement

The word enhancement is not quite correct. A fluid filled area will absorb less ultrasound than the surrounding areas. Having gained deeper areas more than superficial areas (TGC), the structures behind a fluid filled space will appear brighter than the surrounding tissue. This is one of the diagnostic criteria for fluid filled spaces (e.g. cysts) see Fig. 1.16.

1.7.3 Lateral Wall Sign

If ultrasound hits a round structure tangentially, it will be deflected. No ultrasound waves will be found just behind the lateral wall resulting in a narrow shadow.

1.7.4 Mirror Artefact (Figs. 1.18 and 1.19)

If the ultrasound hits a strong reflector at around 45° angle (e.g. the hemi-diaphragm), a second mirrored structure will appear on the screen on the other side of the reflector, caused by the longer travelling time for the reflected ultrasound wave (the ultrasound device does not know that reflection happened and so will show the structure at the measured depth according to the time taken). The mirror artefact can be used as a diagnostic aid. A mirrored liver above the hemi-diaphragm excludes a pleural effusion at the scanned level.

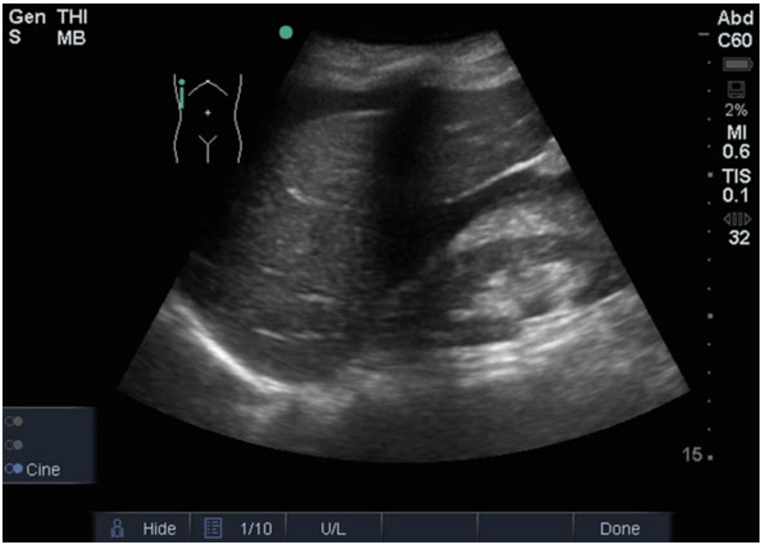


Fig. 1.17 Liver and kidney tissues are isoechoic, the surrounding ascites is anechoic

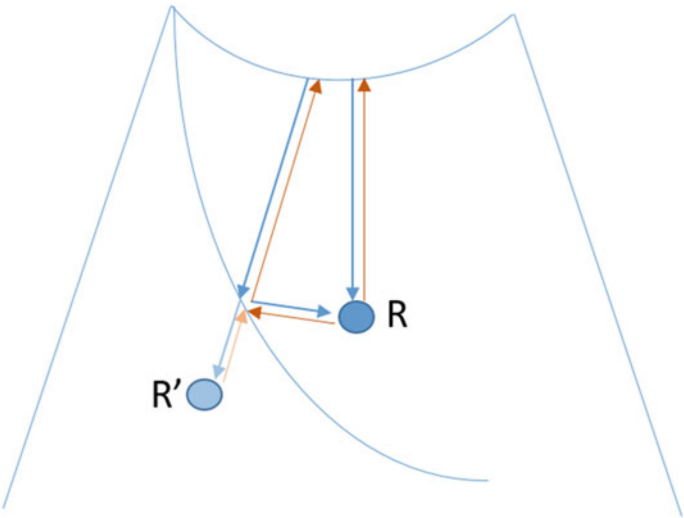


Fig. 1.18 A structure R will be shown as R' behind a strong reflector, caused by reflection of ultrasound

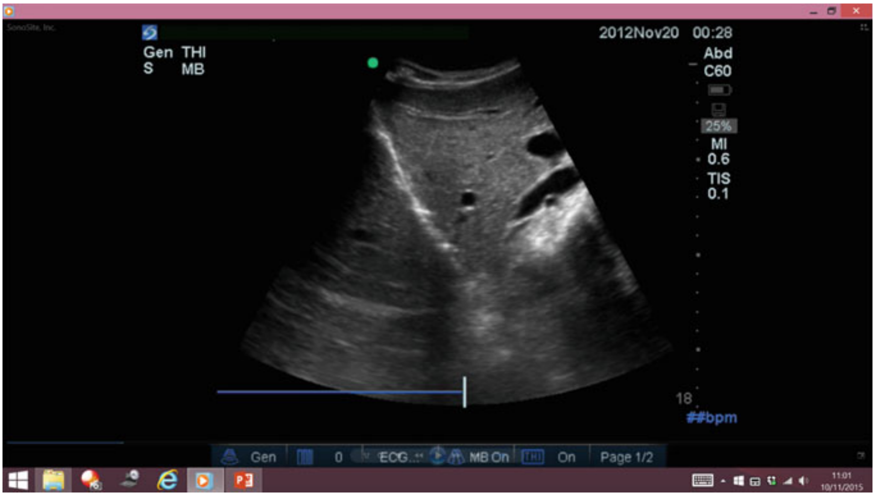


Fig. 1.19 The diaphragm will act as a strong reflector if there is no pleural effusion and so the mirrored liver tissue can be used as a diagnostic marker to exclude a pleural effusion

1.8 Conclusion

An understanding of the physics of ultrasound is vital as it allows the point of care ultrasound operator to understand the genesis of artefacts, how to avoid them and also how to use them diagnostically.

See also Chap. 2.

Chapter 2
Preparation and Image Optimisation

Martin R. Dachsel

Keywords Physics · Doppler · Point of care ultrasound

2.1 Introduction

There are many customs which have developed for ultrasound examination of different body systems and within different areas of ultrasound. The principles of preparation and image optimisation remain much the same regardless of which part of the body is being examined. This chapter elaborates on how to orientate and optimise ultrasound images.

2.2 Preparation

In abdominal ultrasound and lung ultrasound, the marker dot should be on the left hand side of the screen. The corresponding marker on the ultrasound transducer should aim towards the patient's head or the patient's right hand side.

For vascular access the marker should always be on the left hand side of the operator (particularly important if used from the head end to insert central lines!). In echocardiography the marker dot should be on the right hand side of the screen with different probe positions for different windows.

If the picture quality is suboptimal, there are some important manoeuvres to attempt. A left lateral position is useful for echocardiography (minimising lung between chest wall and heart) and abdominal ultrasound (displacing bowel).

Deep inspiration will move the liver inferiorly and will enable the liver to be used as a window to assess deeper structures.

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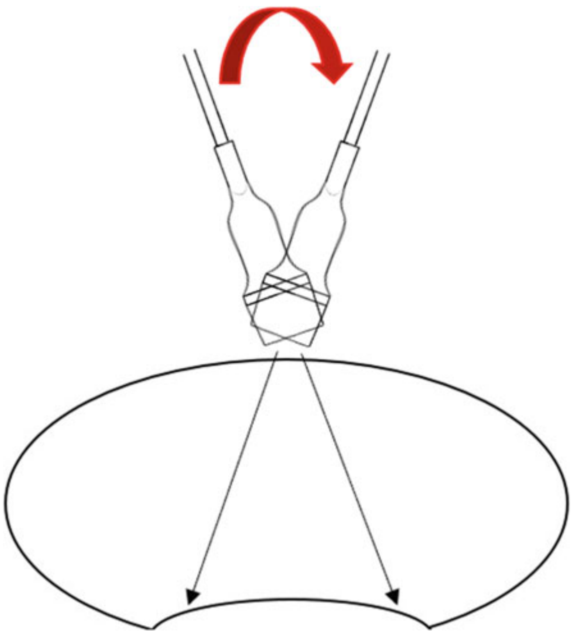
Fig. 2.1 Tilting (short axis of curvilinear probe shown)



The use of pressure (after warning your patient) can be also useful in displacing air from stomach or bowel.

Once an organ has been found, the whole organ should be imaged. It is best to move to a position where the organ has just disappeared and then to image through the whole organ. The next step is to change to a different axis and repeat the process. The following transducer movements are possible (Figs. 2.1, 2.2 and 2.3).

2.3 Image Optimisation

2.3.1 Depth (Fig. 2.4)

The depth of the ultrasound field is important for imaging. It is always worthwhile to start with an extended depth and once satisfied that there is no pathology behind the structures of interest, the depth can be decreased (particularly important when imaging the heart to assess for pericardial/pleural fluid). When decreasing the depth remember that in most point of care ultrasound systems, the focus zone cannot be changed and is in the middle of the screen (the focus zone is the area with the narrowest beam and hence the best resolution).

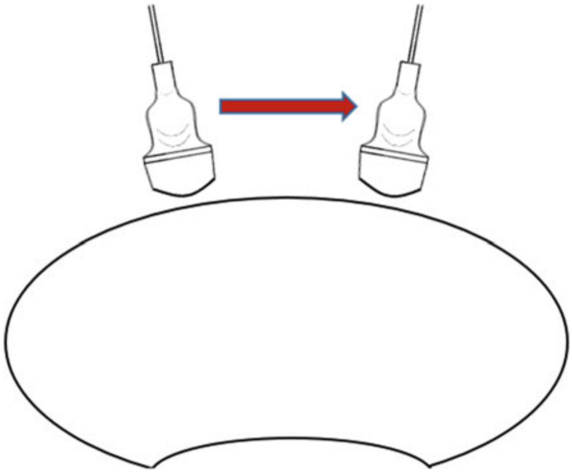


Fig. 2.2 Sliding

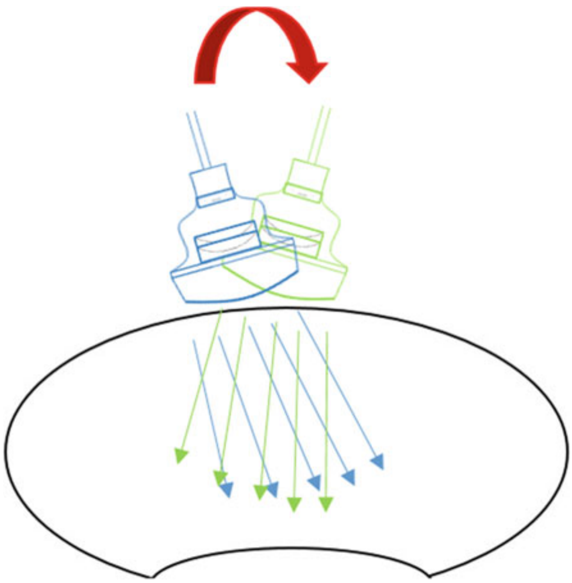


Fig. 2.3 Rocking (long axis of curvilinear probe shown)

2.3.2 Gain (Fig. 2.5)

Gain is adjusting the overall brightness of the image. Ideally the image should have good contrast without being too dark or bright. Increasing the gain will also increase the noise in the image. Most current point of care ultrasound devices will have an Autogain button.

Fig. 2.4 B-mode image of right upper quadrant with extended, ideal and insufficient depth

Fig. 2.5 B-mode image of right upper quadrant with too little, optimal and too much gain

2.3.3 Time Gain Compensation (TGC, Fig. 2.6)

Ultrasound waves will be attenuated while passing through tissue. Signals from deeper areas (more time) therefore need to be more gained than superficial areas (less time). Point of care ultrasound devices usual have a near field and a far field knob, while departmental devices have 6 to 8 different sliders to change TGC.

Fig. 2.6 B-mode image of right upper quadrant with different settings for TGC: left: superficial area too much gained, middle: optimal, right: deeper areas too much gained

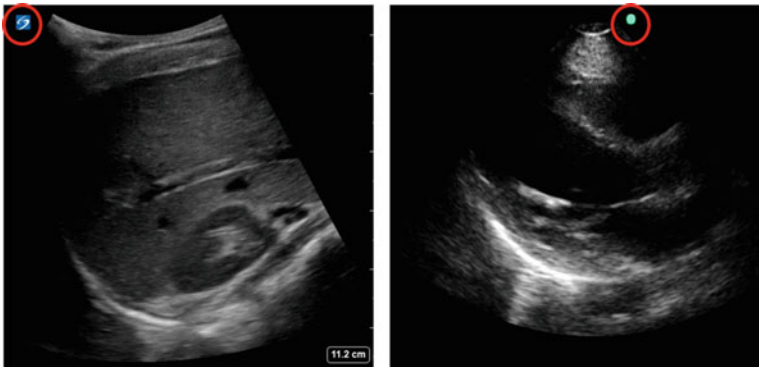


Fig. 2.7 Orientation of marker dot in abdominal/chest ultrasound (left picture) and echocardiography (right picture)

On the left hand side of Fig. 2.6 the superficial areas were gained too much, while on the right hand side the deeper structures were gained too much. The middle image shows optimal TGC.

2.3.4 Orientation (Fig. 2.7)

In abdominal and chest ultrasound, the marker dot should always be on the left hand side of the screen (Fig. 2.7, left picture). In echocardiography however, the marker dot should be on the right hand side of the screen (Fig. 2.7, right picture). Newer ultrasound systems will change the orientation of the screen according to the ultrasound program. In older devices however it is important to check to avoid difficulties in interpreting the ultrasound image.

2.4 Conclusion

Adequate preparation and image optimisation are especially important in point of care ultrasound where patient positioning and access may be difficult. Mastering these skills will enhance the diagnostic performance of point of care ultrasound.

See also Chap. 1 Physics of Ultrasound.

Chapter 3
Clinical Governance

Sonya Daniel and Tom Holmes

Keywords Governance · Point of Care Ultrasound

3.1 Introduction

'Clinical Governance is the system through which NHS organisations are accountable for continuously improving the quality of their services and safeguarding high standards of care, by creating an environment in which clinical excellence can flourish', DoH 1998.

Responsibility for ultrasound clinical governance exists at an organisational, departmental and individual level. The exact structure and process may vary between organisations. However, the general purpose is always to ensure a service delivers high quality patient care that continuously improves. The Institute for Healthcare Improvement has developed a list of attributes that define high quality healthcare including: safety, effectiveness, patient-centredness, timeliness, efficiency and equity.

The two unique responsibilities specific to ultrasound governance are: to ensure the service has well trained, high performing ultrasound practitioners; and that equipment has appropriate specification and adequate maintenance. This chapter will outline the governance of these two specific areas in the context of a hierarchy of governance responsibility.

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