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# Introduction

## About Point of Care Ultrasound

Point of care ultrasound (POCUS) is the use of limited ultrasound (US) protocols performed at the patient's bedside to assess a wide range of clinical conditions. This is distinctly different to the sonographer and radiologist delivered departmental studies which require many years of training and experience to provide a systematic structured assessment.

The purpose of POCUS is to answer key clinical questions that have been guided by the conventional history, physical examination and preliminary investigations (blood tests, X-rays). It is an invaluable tool in the arsenal of general clinicians and can avoid unnecessary delay in the confirmation and identification of pathology.

Point of care ultrasound has grown exponentially over the past 15 years in hospital settings and the COVID-19 pandemic has been a catalyst to accelerate training of this vital skill.

Point of care ultrasound has been facilitated by technological advances which have created more portable, handheld devices at significantly lower costs. Although bedside US is established within certain specialities, particularly Emergency Medicine, Intensive Care Medicine and Acute Medicine, it is becoming more accessible to all healthcare providers including Internists, General Practitioners, Family Physicians, Paramedics, Physiotherapists and Advanced Nursing groups. With the advent of portable US machines, clinicians can now apply the same principles and techniques in any location ranging from Critical Care to the more extreme, austere environments and low resource populations.

## How Point of Care Ultrasound Can Help

- Empowers you as a clinician.
- Puts you on the right pathway by improving diagnostic accuracy.
- Gives you confidence in referral and non-referral to specialists.
- Aids decision-making with ceilings of care and withdrawal of medical intervention.
- Identifies reversible pathology within the peri-arrest and arrest scenarios.
- Enhances safety and accuracy of procedural intervention.
- Reduces time to diagnosis leading to reduced length of stay in select cases.
- Gives you confidence in discharging patients.
- Improves the patient-doctor relationship and the patient journey.

## What Is the Evidence?

Unlike physical examination of palpation, percussion and auscultation, US allows clinicians to directly visualise what is going on inside the patient's body. It should be seen as an extension of your conventional clinical history and physical examination. There is a wealth of developing evidence suggesting POCUS is superior to physical examination and reduces time to diagnosis, augments the doctor-patient relationship and improves overall patient satisfaction. POCUS has been suggested to improve diagnostic accuracy and deliver these diagnoses at a lower overall cost.

Numerous studies have demonstrated that thoracic US outperforms auscultation and chest radiographs in diagnosing common causes of acute respiratory failure such as pneumonia, heart failure, asthma, COPD and pulmonary embolism.

One of the pioneering works was published by Lichtenstein and Meziere in 2008. They demonstrated excellent diagnostic accuracy of thoracic US in acute respiratory failure within a rapid, protocolised and reproducible framework – the *BLUE Protocol*. They reported an overall diagnostic accuracy of 90.5% which is significantly greater than auscultation and chest radiography combined. This protocol is described in more detail in Chapter 3 – 'Thoracic Ultrasound'.

In view of the growing popularity and evidence base for POCUS, there are published recommendations for the use of focused cardiac ultrasound in shocked patients which have been endorsed by the American Society of Echocardiography (ASE) and the British Society of Echocardiography (BSE).

## Point of Care Ultrasound Is Simple to Learn . . .

Physicians at different levels of training and experience appear to greatly improve their diagnostic ability beyond history and physical examination after brief training in POCUS. A study of first-year medical students who had received 18 hours of US training were able to detect pathology in 75% of cases in comparison to only 49% of certified cardiologists using a stethoscope.

Point of care ultrasound training is becoming widely implemented within the undergraduate curriculum within select medical schools across the world. Multiple postgraduate specialist training pathways endorse and mandate US training prior to completion of training. This is described in detail in Chapter 14 – 'Training and Accreditation'.

It is clear this skill can be learned quickly with effective outcomes no matter where you are in your training journey. The technological advances producing low-cost hand-held devices are making POCUS increasingly accessible and training should develop to reflect this change. Figure I.1 is an example of an 'all-in-one' hand-held US device.

## The Momentum Is Growing

Emergency Care across the world has led the POCUS momentum by mandating accreditation before qualification. It is now gaining popularity in other acute specialties with established training pathways such as Acute Medicine and Intensive Care Medicine. Europe, USA, Canada and Australia have pathways and curricula for family physicians and this book aims to carry the principles learned from acute settings and apply them to patient care in any environment by any healthcare provider. We anticipate the greatest diagnostic gains will be seen within lower resource settings, including general practice, where accessibility to definitive investigation is limited and POCUS may rapidly exclude key pathology in a timely manner.

## A Mandatory Skill for all Generalists

As experienced clinicians within POCUS we believe this core skill should be mandated for all generalists. Not only is there mounting evidence of its benefits but it is becoming increasingly cost effective. Throughout medical school we continue to teach the same clinical examination skills we used centuries ago. Whilst there is rationale behind teaching the principles and processes of a detailed examination there are many skills, such as tactile vocal fremitus and whispering pectoriloquy, that are rarely performed in day-to-day clinical practice. There are many examples of technological advances improving patient care and superseding historic clinical standards. US in the hands of general clinicians is one of these advances.

With significantly increased time pressure and volume of patients we need to work efficiently to

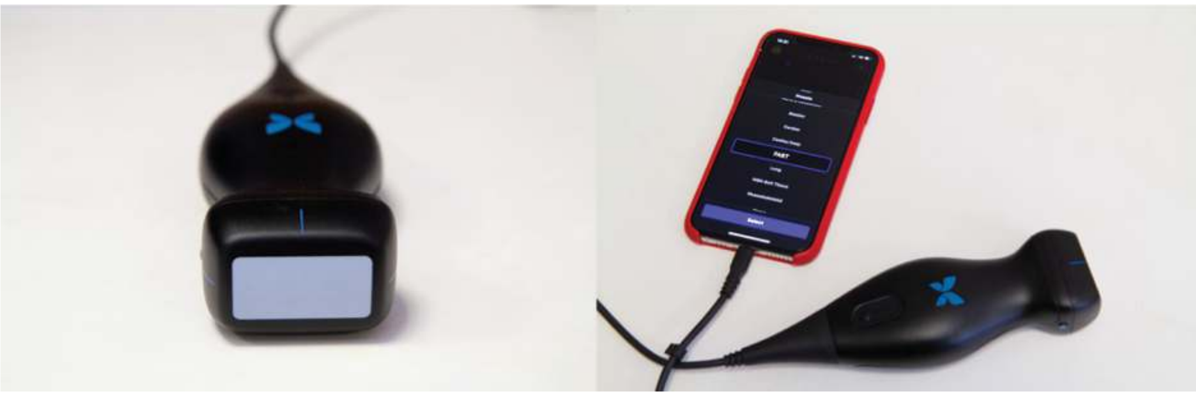

**Figure I.1 The Butterfly iQ is an example of an 'all-in-one' ultrasound probe that plugs directly into a phone or tablet.** Other examples of portable all-in-one probes include the Philips Lumify, EchoNous Kosmos, GE Vscan, Sonosite iViz, Clarius C3 and the Healcerion Sonon.

ensure patients receive high quality care in a timely manner. Ensuring we get the diagnosis correct first time is key to streamlining the patient journey and POCUS vastly enhances the diagnostic capability of frontline and generalist clinicians.

Mandating POCUS as a core skill at undergraduate level will aid the understanding of anatomy and pathology by seeing it in real life rather than simply reading about in books. This will lead to competence and consolidation of knowledge and aid a seamless transition from theory to clinical practice.

It is key to emphasise that POCUS will never replace conventional history and basic examination. These core steps of patient assessment guide the indications for US which vastly enhances the pre-test probability for POCUS. Users should understand the limitations of the training pathways they are accredited within and not attempt to diagnose beyond their expertise.

We promote the mantra of history, examination, observation, palpation, percussion, auscultation and guided sonography as compulsory elements of clinical assessment of all patients.

## Summary

- Point of care ultrasound is designed to answer key questions at the bedside and is becoming more accessible for all clinicians with the advent of smaller, portable hand-held devices.
- There is an increasing evidence base for POCUS highlighting that it is superior to physical examination and traditional diagnostics and may be delivered in a time-efficient manner.
- Across the world there is an increasing momentum of training and accreditation within undergraduate and postgraduate training programmes.
- Ultrasound for the Generalist is a critical mandatory skill within the medical field and, alongside history and physical examination, will become an indispensable tool for modern clinical practice.

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Chapter 1

# Basic Physics, Knobology and Artefacts

Ultrasound physics is a dreaded and frequently neglected topic by many POCUS enthusiasts. However, a basic understanding of the principles behind how US generates images will aid the clinician with interpretation, optimisation and troubleshooting unexpected findings. Many signs, particularly in lung ultrasound (LUS), rely solely on the interpretation of artefact patterns, making it an essential element to diagnosis.

This chapter will discuss the basic physics of US, common artefacts and top tips the user needs to know when learning to scan. Understanding the machine and controls ('knobology') is a critical step in acquiring the best possible image.

## Physics

### Introduction to Ultrasound

Sound travels as longitudinal mechanical waves through mediums such as air, water or solid substances. It therefore cannot be transmitted through a vacuum. Each soundwave is characterised by its frequency and intensity. US describes soundwaves with a frequency higher than the threshold of human hearing.

Ultrasound probes contain a grid of crystals known as **piezoelectric crystals** which deform when a charge is applied to them. Using an alternating current, they will oscillate (rapidly expand and contract), which leads to generation of US. The transformation of electrical oscillations into mechanical oscillation (sound) is known as the **piezoelectric effect**.

These same crystals are able to act as receivers. The transducer will emit a burst of US for a few microseconds and then wait for a returning signal for the same period of time. The time taken for a signal to return and the intensity of that signal is used to construct an US image. Key elements to the US transducer are shown in Figure 1.1.

**Frequency** describes the number of oscillations per second and is measured in Hertz (Hz). Audible sound is roughly 20–20,000 Hz (20 KHz). US is characterised by frequencies over 20,000 Hz (20 KHz). As the frequency increases, common order of magnitude prefixes may be used such as kilohertz (KHz, 1000 Hz) and megahertz (MHz, 1,000,000 Hz). Medical US typically uses frequencies between 1 and 20 MHz. Figure 1.2 shows the spectrum of sound frequency.

When sound travels through a medium there are regions of higher density and pressure where particles have been pushed closer together known as *compression*. Other particles are subsequently under less pressure and density and therefore spread further apart. This is *rarefaction*.

This longitudinal wave may be plotted on a graph with *distance* on the x-axis and *time* on the y-axis creating a graph that is analogous to a normal sinusoidal waveform. The time taken for one complete cycle of moving from resting pressure, to compression, rarefaction and back to resting pressure equates to the **wavelength** (see Figure 1.3).

If this graph were to plot *pressure* (y-axis) against *time* (x-axis) describing the single point in space going through a complete cycle of compression, rarefaction and back to resting pressure, this is known as the **period** (Figure 1.3).

**Amplitude** describes the *strength* of a sound wave measured as the difference between the peak pressure and average pressure in decibels (dBs). This is a logarithmic scale with a change of 6 dBs representing a doubling of amplitude.

**Propagation velocity** is the speed at which the sound wave travels through a particular medium. This relates to the speed upon which the US wave travels through the patient and back to the probe. Propagation velocity is variable depending on the *medium* through which it is travelling (Table 1.1). The US machine takes the average propagation velocity and assumes the beam is travelling at a constant velocity of 1,540 m/s.

**Table 1.1** Propagation velocity through different mediums

| Tissue | Air | Water | Muscle | Fat | Liver | Spleen | Kidney | Bone |
|---|---|---|---|---|---|---|---|---|
| Velocity (m/s) | 331 | 1496 | 1568 | 1476 | 1570 | 1565 | 1560 | 3360 |

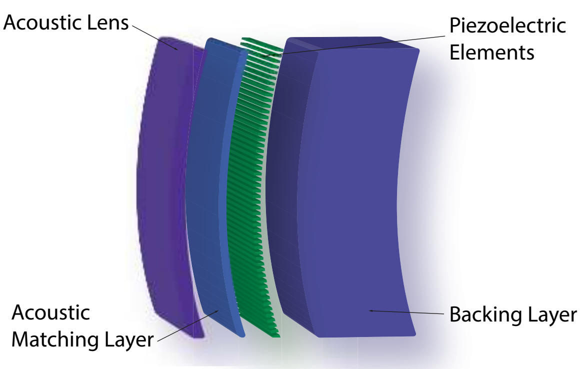


**Figure 1.1** Key elements of the ultrasound transducer.

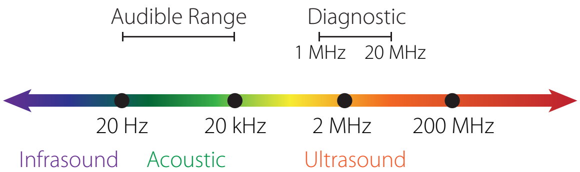


**Figure 1.2** Spectrum of sound frequency.

The equations that describe the relationships between these parameters are listed below:

$$Frequency\ (Hz) = 1\ /\ Period\ (s)$$

$$Velocity\ (m/s) = Frequency\ (Hz) \times Wavelength\ (m)$$

$$Wavelength\ (m) = Velocity (m/s)\ /\ Frequency\ (Hz)$$

These equations demonstrate that frequency is *inversely related* to wavelength. This is a key principle to understand for clinical US.

*Wavelength* is one of the key determinants for *axial resolution* – the ability to distinguish between structures along the axis of the US beam. Our ability to visualise a structure relies on it being larger than the wavelength of the US beam. As the frequency falls, the wavelength will increase. This describes how better *resolution* may be achieved by using a *higher frequency* transducer.

## Ultrasound in the Body

Clinical US relies on the generated kinetic energy being reflected back towards the probe to be processed into an image. Tissues have a different degree of **acoustic impedance** which is closely related to the density – higher density tissues have a higher acoustic impedance.

Structures with a low acoustic impedance will allow US to pass readily through them leading to less reflection and a darker image to be generated. Liquid allows

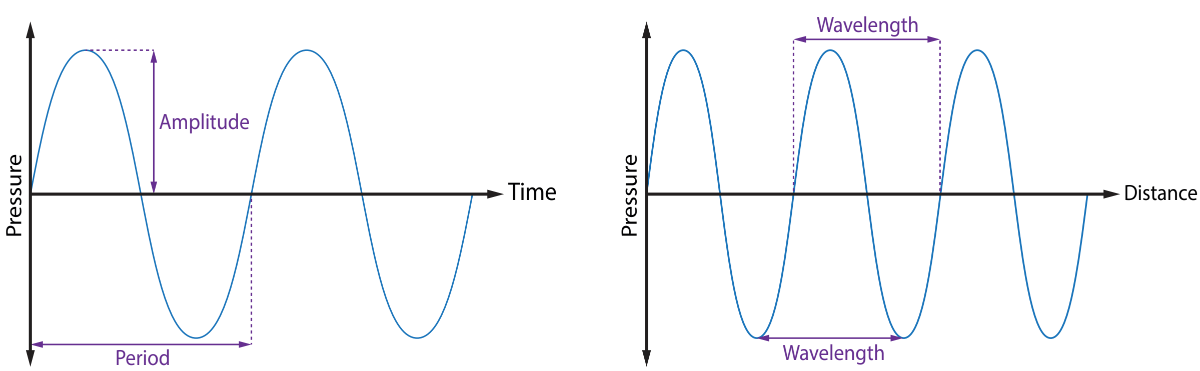


**Figure 1.3** Sound waves plotted as graphs showing pressure on the y-axis and either time or distance on the x-axis. Note the annotations describing amplitude, period and wavelength.

easy transmission of US with minimal reflection and therefore appears black on the screen. This is described as *anechoic* (see Figure 1.4). This explains the dark appearance of structures such as blood vessels, heart chambers, effusions, ascites and the bladder.

By contrast, solid structures with a high acoustic impedance, such as bone, cause a higher degree of reflection leading to a much brighter image. This is described as *hyperechoic*. As minimal US will be transmitted beyond the bright reflective surface an *acoustic shadow* develops beyond the hyperechoic structure. This is commonly seen with bone, stones (e.g. gallstones, renal calculi) and foreign bodies (see Figure 1.5).

**Figure 1.4 Anechoic fluid-filled bladder.** Note the bright area deep to the bladder. This is due to acoustic enhancement.

Remaining structures in the body will have an *echogenicity* that is between these two extremes. The brightness may be described in relation to one another. *Isoechoic* describes structures that appear to have the *same brightness* whereas *hypoechoic* will describe an object that is *darker* than surrounding structures.

An example of a structure with variable echogenicityis the kidney where the medullary pyramids are more hypoechoic than the renal cortex. Figure 1.6 shows a normal kidney.

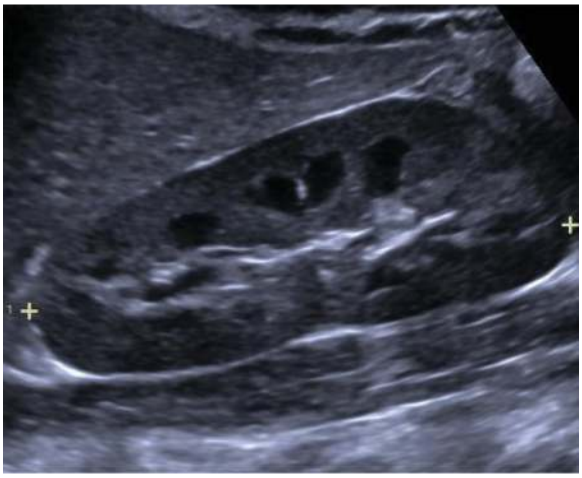

**Figure 1.6 The kidney is an example of a structure with variable echogenicity. Note the hyperechoic pelvis compared with the hypoechoic medulla.**

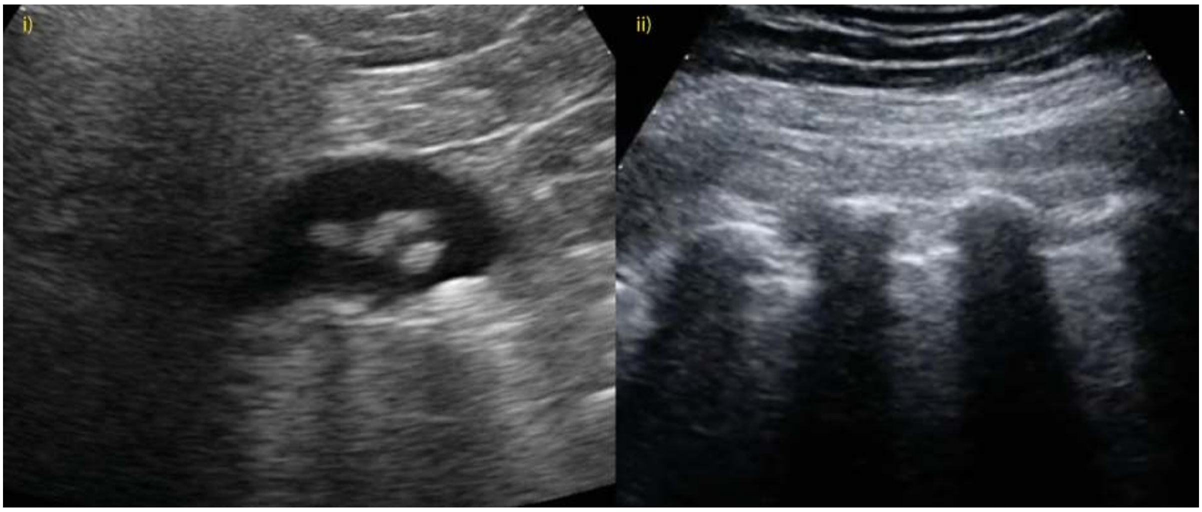


**Figure 1.5 (i) Bright, hyperechoic gallstones. Note the acoustic shadowing deep to the stones. (ii) Ribs are hyperechoic structures that cause a very prominent acoustic shadow.**

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**Table 1.2** Acoustic impedance of different mediums'

| Medium | Impedance Z ($10^6$ Ns/m$^3$) | Velocity (m/s) | Density ($10^3$ kg/m$^3$) |
|---|---|---|---|
| Air | 0.00041 | 331 | 0.0012 |
| Fat | 1.47 | 1476 | 0.928 |
| Water | 1.49 | 1496 | 0.997 |
| Kidney | 1.61 | 1560 | 1.032 |
| Liver | 1.65 | 1570 | 1.051 |
| Muscle | 1.66 | 1568 | 1.058 |
| Spleen | 1.66 | 1565 | 1.061 |
| Bone | 6.2 | 3360 | 1.85 |

As US crosses the boundary between two tissues with very different acoustic impedance, such as air and soft tissue, a higher proportion will be reflected back towards the probe. The use of US gel limits the acoustic impedance between the air and skin which would result in much of the US reflecting before it even reached the body. Table 1.2 shows the various acoustic impedance for different mediums.

Most US imaging arises from scattering of transmitted waves from small structures within tissues which are too small to resolve. This results in interference and produces a speckled appearance due to the various intensities of echoes received by the transducer causing irregularities in the greyscale of the image. To the untrained eye this looks like a snowstorm, but with experience it may be sufficiently characteristic to assist in tissue differentiation. Modern ultrasound systems use image post-processing to smooth the image and reduce the specular appearance to varying degrees depending on the settings and user preference.

Specular reflection and backscatter are two simplified concepts of reflection depending upon the size of the reflective structure and the wavelength (Figure 1.7):

– **Specular reflection** – this is a 'mirror-like' reflection that occurs at a reflector that is relatively large – at least two wavelengths in size. The degree of reflection is highly dependent on the *angle of incidence* of the beam. The greatest degree of reflection occurs when the probe is *perpendicular* to the reflective surface. As the angle of incidence moves further away from 90 degrees, less of the reflected energy will return to the probe, resulting in the image appearing less bright.

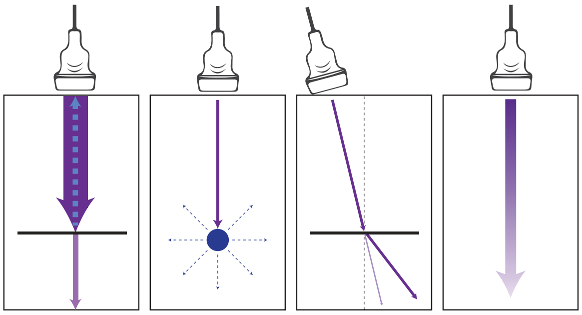


**Figure 1.7** Key ultrasound principles.

– **Backscatter** – this occurs with small structures that are smaller than the wavelength. When the US beam hits these structures, it is reflected in many different directions independent of the angle of incidence. The strength of the returning signal is many times weaker than with specular reflection.

**Attenuation** is the final principle to consider. As US passes through tissue it will gradually lose energy. This is through several mechanisms:

– **Absorption** – energy will be converted to heat due to absorption by the tissues it passes through. This is responsible for the largest proportion of attenuation.

– **Reflection** – energy is lost to specular reflection and backscatter. Whilst some energy is reflected back to the probe, much is reflected away from the probe and therefore lost.

Attenuation is directly related to the **frequency** of the US wave. Waves with a higher frequency are associated with a greater degree of attenuation meaning they are unable to reach deep structures. This explains the trade-off between using a *high frequency* transducer to achieve **good resolution** but at the expense of limited tissue **penetration.** A *low frequency* transducer will allow visualisation of **deeper** structures but with poorer **resolution**.

Higher frequency → Smaller wavelength → Better resolution at superficial structures

Lower frequency → Longer wavelength → Better visualisation of deeper structures

Understanding these concepts will allow the user to select the optimal transducer to achieve the best possible resolution for each scan.

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## Beginning to Scan

There are six fundamental steps to consider when beginning to scan:

Step 1 – Know your machine.

Step 2 – Choose the correct probe and preset.

Step 3 – Understanding orientation.

Step 4 – Acquiring your images.

Step 5 – Image optimisation.

Step 6 – Saving your images.

## Step 1 – Know Your Machine

The US machine may appear intimidating to novice users due to the perceived complexity. Figure 1.8 is a typical portable US machine. For POCUS, only a few essential features are required and most users can ignore many of the remaining buttons. Understanding the knobs on the machine is the art of *knobology* and critical in acquiring the highest quality images possible.

**Figure 1.8** **A typical portable ultrasound machine.**

Getting to know your machine will also increase the speed of image acquisition and user confidence which is key for busy general clinicians. All machines will have the same basic settings and their use will become second nature with practice.

### Power Button

Turning on the machine is clearly an essential initial step! When the machine is not in use it should be switched off and placed on charge. The battery life of machines tends to reduce rapidly and many do not function without mains connection after several years of use. Remember to plug into mains when performing scans to avoid loss of images.

### Patient Details

Including patient demographics when saving images is important for governance and quality assurance. This should include name, date of birth, hospital number (patient identifier) and the person completing the scan (Figure 1.9). In an emergency setting this may not be possible but the users should enter details retrospectively or clearly document an emergency scan number.

### Ultrasound Basic Controls and Functions

All machines will have the same basic controls. Figure 1.10 shows an example of a layout with annotations. Understanding the machine control panel will allow rapid image optimisation and seamless freezing, saving and switching between imaging modes.

All machines will have a central control wheel and adjacent buttons. This should be considered as the ‘computer mouse’ of the ultrasound machine and

**Figure 1.9** **Data entry screen for patient demographics.**

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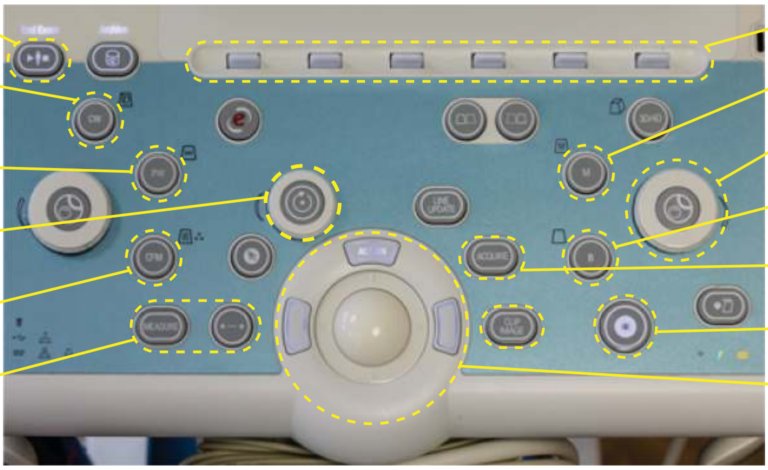


**Figure 1.10** **Basic controls available on any ultrasound machine.**

enables direction of the screen cursor, sizing of colour boxes and directing of spectral doppler pathways.

## Step 2 – Choose the Correct Probe and Preset

### The Probes

Correct probe selection is essential to acquiring an interpretable image based on the indication.

Before you start scanning ask yourself the following questions:

- What part of the body am I scanning?
- How deep are the structures?
- Is the footprint big or small?
- Am I doing a procedure?

All probes consist of the head, wire and the connector. The transducers may be detached from the machine to allow it to be interchangeable. Some machines will allow multiple probes to be connected simultaneously and selected using the probe button or icon on the screen.

### Footprint and Field of View

The skin area that needs to be contacted by the probe to produce an image is called the *footprint* of the probe. This is dictated by the size of the piezoelectric array and can easily be appreciated by the size of the probe tip.

Larger footprints provide a more expansive scanning field but will struggle to image through small acoustic windows. For example, the curvilinear probe and phased array probe have very similar imaging frequencies and both allow visualisation of deep structures. The phased array transducer is far more suited to cardiac imaging due to the smaller footprint allowing imaging through the rib spaces. A larger footprint is particularly suited for scanning large structures close to the surface of the body such as in abdominal ultrasound. The field of view is also an important characteristic for deciding which probe to use. The curvilinear and phased array probes generate a 'wedge shaped' field of view due to the beam fanning outwards from the probe. The distance between these structures on the screen may appear greater if they are situated deeper in the imaging field. Modern machines aim to compensate for this by beam steering or image reconstruction. Linear probes, by default, will create a 'rectangular' field of view using a higher resolution. This makes them ideally suited for US-guided procedures as they provide a more reliable location of needles as they are advanced. Figure 1.11 shows the commonly used US probes.

**Figure 1.11** **Commonly used ultrasound probes.** From left to right: high frequency linear probe; curvilinear probe; phased array probe.

A guide to the common imaging modalities used with different probes is listed in Table 1.3.

### Curvilinear Probe (Figure 1.12)

- Low frequency 2–5 MHz.
- Allows for visualisation of deep structures at the expense of resolution.
- Large footprint so not ideal for small acoustic windows.

**Table 1.3** Types of probe, imaging frequency and common applications

| Probe | Frequency (MHz) | Applications |
|---|---|---|
| Curvilinear | 2–5 | Abdominal<br>Thoracic<br>Bladder<br>Focused assessment with sonography in trauma (FAST)<br>Aorta<br>Spinal |
| Linear | 5–18 | Thoracic – particularly for pleural abnormalities e.g. pneumothorax/pleural line irregularities<br>Vascular access<br>DVT<br>MSK and soft tissue<br>Optic nerve sheath |
| Phased Array | 1–5 | Cardiac<br>Abdominal<br>Inferior vena cava (IVC)<br>Transcranial Doppler |

- Generates a wedge-shaped field of view.
- Generally used for abdominal and pelvic examination. Thoracic imaging when deeper imaging required e.g. diaphragm or effusion assessment. Use for cardiac imaging limited by its large footprint providing poor visualisation through rib spaces.

### Linear Probe (Figure 1.13)

- High frequency 5–18 MHz.
- High resolution of superficial structures at the cost of penetration. Reliable to 6–8 cm.
- Large footprint.
- Generates rectangular field of view which makes it suited for US-guided procedures.
- Should be used for imaging of any superficial structure where a small footprint is not required.

### Phased Array Probe (Figure 1.14)

- Low frequency probe 1–5 MHz.
- Designed to provide a small footprint to enable penetration through rib spaces for cardiac imaging.
- Array of piezoelectric elements that are steered electronically to fan backwards and forwards across an image.
- Better focusing capability than other probes.
- May be used for other ‘low frequency applications’ such as abdominal US but will tend to provide poorer resolution.
- Probe marker will default to the *right* side of the screen when selected as this is the automatic setting for cardiac imaging presets.

**Figure 1.12** The curvilinear probe.

**Figure 1.13** The linear probe.