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Equipment selection and instrumentation

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Equipment selection

Introduction

The selection of equipment for gynaecological ultrasound, as in other clinical areas, amounts to:

- selecting the scanner
- selecting the transducer
- selecting how best to use them

Although the operator may have little or no choice about the scanner to be used, it is important to recognise that it is the combination of all three of the above which is critical. A proficient operator getting the best out of poor equipment is frequently more effective than a poor operator using potentially good equipment in an uninformed, unthinking or poorly thought-out manner. It follows that whoever is using the equipment needs a good understanding of the ultrasonic imaging process, its limitations and characteristics. In particular, there is a need to understand the many compromises that exist, how they come about and how the operator can control the choices being made in order to optimise the quality of the scan. The list below summarises the main considerations to be taken into account before the scan begins:

- spatial resolution
- temporal resolution
- penetration
- contrast resolution
- probe shape and size
- scanning ergonomics
- operating modes (e.g. pulsed and colour Doppler)
- contrast agents
- safety (acoustic, mechanical, electrical, biological, chemical)

Note that the transducer frequency is omitted from the above list. This is partly because manufacturer's probe labelling may be inaccurate but, more importantly, because the probe frequency is not a good predictor of image quality and certainly does not describe it. The operator may well find that a low-frequency probe on one scanner gives a better image than a higher-frequency probe on another.

We will consider each of the features on the list in turn.

Spatial resolution

It is important that small details within a structure or small objects are adequately imaged. This ability may be referred to as the overall 'sharpness' or 'definition' of the image and is described as its spatial resolution. It may be defined more strictly as the ability of the system to identify correctly two targets lying close together. Thus, in Figure 1.1, the targets are sets of pairs of wires lying in a tissue-equivalent phantom and seen in cross-section. In the first case, only the pair in the lowest row are resolved and the other two pairs are blurred or smeared together but, when the wires are imaged using a different machine, the second pair are also resolved, although neither machine can resolve the top pair which are closest together.

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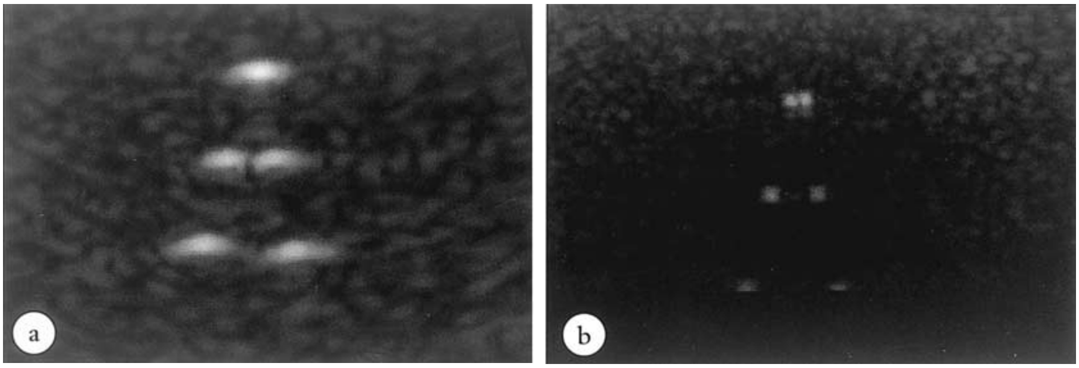

Figure 1.1 Images obtained by scanning wires in a tissue-equivalent phantom. (a) A 3.5-MHz probe is able to resolve the lowest pair (5 mm separation) satisfactorily, the middle pair (2.5 mm) is only just resolvable and the top pair is unresolvable. (b) Using a 7.5-MHz probe all the pairs are adequately demonstrated.

One peculiarity of ultrasound is that the spatial resolution depends not only on the position of the targets in the imaged section but also on the orientation of the targets in that section. One way of describing this is to use the concept of a *resolution cell*. We can imagine the section being imaged as divided into small volumes or cells. If two targets are so small that they fit within the same cell, then they will not be resolved. In other words, details which are small enough to fit entirely within a resolution cell will not be visualised by the scanner. The exact shape of a resolution cell may be complex (typically a little like a flattened sausage!) but it can be described as having three dimensions: an axial length, x, a lateral width, l, and a slice thickness, t (Fig. 1.2). This leads to the need to describe the resolution of an ultrasound scanner in at least three planes and the complication that the three values obtained may not only be very different from each other but may also vary throughout the image. The three values x, l and t are often described as three ultrasound resolutions: *axial, lateral and slice thickness*.

It seems obvious that smaller values of resolution are unambiguously 'better' and this is so, but the means by which smaller values are achieved may involve unacceptable compromise in other features. We first need to consider more carefully what governs each of these resolutions.

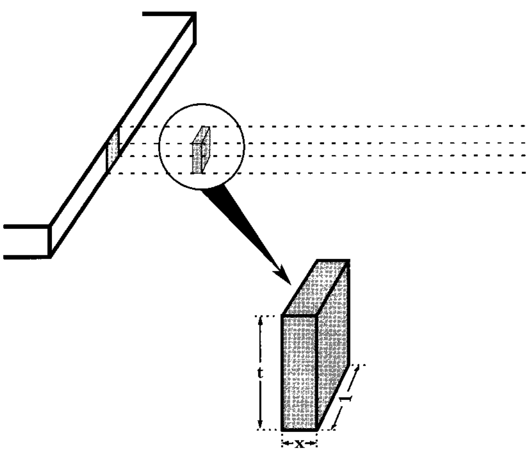

Figure 1.2 The shaded area represents a single resolution cell for the scanning system. Note that the dimensions x, l and t are the resolution values in each direction at the position of the specific cell. Elsewhere, the values may be different.

Axial resolution

The axial resolution, which is the x value of the resolution cell (Fig. 1.2), depends primarily on the pulse length. This is normally a fixed number of cycles (typically 2–3), and so it follows that higher frequencies, which bring shorter wavelengths, will give better axial resolution. For frequencies between 5 and 7 MHz, this will normally be between 0.5 and 1 mm. In almost all cases, it is the smallest and therefore the

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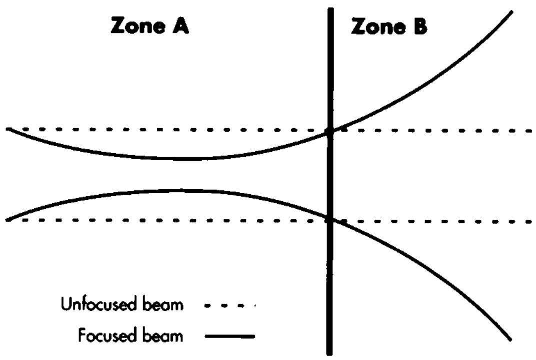

Figure 1.3 The effect of focusing is normally to reduce the lateral beamwidth, *l*, in the region close to the focal zone (zone A). However, away from the focus in zone B, the effect is to degrade the beamwidth and hence also the lateral resolution.

best of the resolutions and consequently, operators are encouraged to make measurements in an axial direction wherever possible.

Lateral resolution

This is the *l* value in Figure 1.2 and is often referred to as the *beamwidth*. Manufacturers use a wide variety of ingenious methods to minimise beamwidth since it manifestly has a profound effect on image quality. In many cases this involves electronic focusing of arrays, which allows the beam to be narrowed only in the plane of the scanning slice and is the reason why the beam cross-section is not circular. Furthermore, the focusing techniques used will often improve the resolution at some depths at the expense of degrading the resolution at others and hence the resolution depends additionally on depth of the target (Figs. 1.3 and 1.4). Manufacturers will often include a figure for lateral resolution in their specification for a probe and with modern equipment working between 5 and 7 MHz it is commonly between 2 and 8 mm. However, this will be a best case and may be quite misleading: the operator is very influential here. Since the focusing depth is normally selected from the scanner's control panel, care should be taken to match the depth selected to that of greatest clinical significance. Many machines now offer the facility for additional focusing on transmission which reduces the beamwidth still further. However, this normally

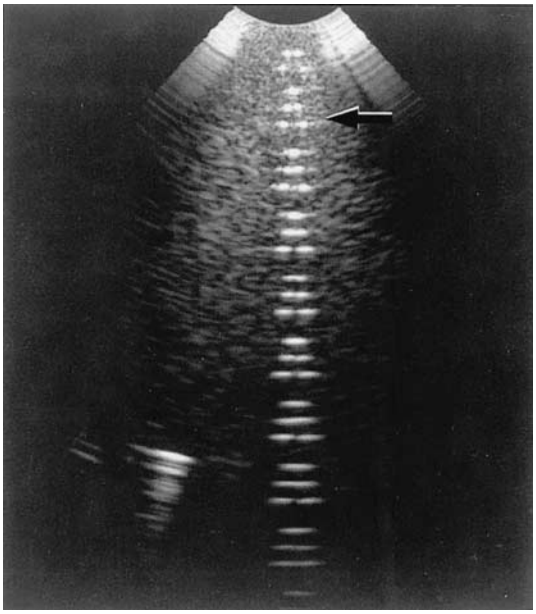

Figure 1.4 Lateral resolution is normally depth-dependent. The region nearest the probe (arrow) has significantly better resolution than at greater depths.

incurs a frame rate penalty and it is the operator who must decide whether the additional resolution gain is worth the price.

Slice thickness

The third dimension of the resolution cell is known as slice thickness and is the *t* value in Figure 1.2. In this case, electronic focusing will have no effect and so it is likely that this resolution will be relatively poor. Some focusing can be achieved by including lenses in the front face of the probe, but this will be at a fixed depth. For electronic probes, this will result in slice thickness resolution in the range 5–10 mm, although for mechanical scanners, the figure will be the same as for lateral resolution since the beam cross-section will be circular. The impact of this clinically is to produce slice thickness artefacts which, for example, will result in transonic areas such as cysts becoming partially filled with echoes which are generated within surrounding tissue. Thus it is important that the operator is aware of the resolution characteristics

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of the probe in use in order to avoid being misled by such appearances.

Spatial resolution – key points

- The shorter the pulse, the better the axial resolution, i.e. higher frequencies are better
- The narrower the beam, the better the lateral resolution, i.e. in the focal zone of the beam. (Focusing is usually worse at greater depths, with consequent inferior lateral resolution)
- The narrower the slice thickness, the better the resolution. i.e. lenses or curved elements in a plane at right angles to the image

Temporal resolution

Temporal resolution is the term often used to describe the ability of the scanner to detect and display rapid movement. Clearly this is associated with the time between samples at a given site, in other words, the *frame rate*. Here we have another compromise involving the operator but based on a fundamental limitation.

The frame rate can be increased by either accepting a reduced number of lines in the image or a reduced imaged depth or both. There are two additional points to note. The first is that if lateral resolution is improved by selecting transmit focusing, this requires more pulses to acquire each scan line. In effect, this is increasing the time per line. Thus the improved resolution must be 'bought' by a reduced frame rate, a reduced depth, a reduced number of lines in the image or some combination of these options. It is the operator who makes these decisions and selects the best compromise, although the control panel of the machine might obscure these stark choices in some cases. For a machine using a sector-shaped field of view, such as a curvilinear array, the compromise might appear as a reduced sector angle, which is a means of reducing the total number of scan lines without sacrificing line density (Fig. 1.5b). Manufacturers of more modern equipment have devised means by which some of these compromises are less critical than was once the case, but the user

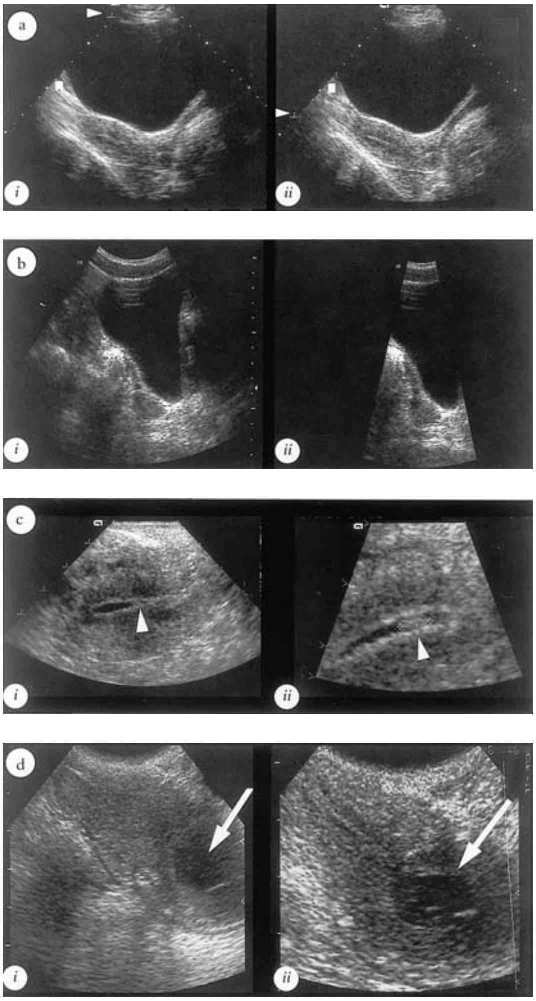

Figure 1.5 Practical image optimisation. (a)(i) The focal zone has been incorrectly placed in the near field. (ii) Correct focal zone placement at the depth of the uterus narrows the beam at this point and results in improved resolution. (b) The longitudinal image of this ovary (i) is improved by narrowing the sector angle (ii), thus increasing the line density. (c)(i) This small endometrial polyp in a patient with postmenopausal bleeding is unclear on the transvaginal scan (arrowhead). (ii) By reducing both the sector angle and depth, increasing the line density, it now becomes apparent. (d)(i) Fluid (arrow) is demonstrated in the endometrial cavity of this postmenopausal patient. (ii) It is better emphasised by adjusting the postprocessing options to improve the contrast resolution.

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should watch the displayed value of the frame rate to check how this is working in practice. Gynaecological ultrasound, unlike cardiac or obstetric scanning, does not demand a high frame rate and there is a strong case for using all available means to maximise resolution even if the frame rate drops to around three or four frames per second or less. It is the informed operator who must make this decision.

Temporal resolution – key points

- Depends on the frame rate
- Frame rate is faster when less time is taken to construct the image, i.e. when the image has a small field (in terms of depth and/or width), or is constructed of fewer lines of information, which reduces image quality
- Frame rate is usually of less importance in gynaecological scanning than spatial or contrast resolution and is therefore often sacrificed to improve these latter considerations
- The frequency label on the transducer may not necessarily be a reliable indicator of either the penetration or the resolution capabilities

Penetration

The operator will want to be reassured that the equipment selected is capable of producing images down to a clinically acceptable depth. The maximum depth at which useful information can be obtained is determined by many factors, the dominant one of which is tissue attenuation, although it can be increased by one or more of the following:

- reducing the frequency
- using bigger output pulses
- reducing the system noise

The attenuation suffered by the pulse tissue in travelling through the tissue depends only on the frequency of that pulse for a given tissue type. In normal gynaecological practice, this limits 5 MHz ultrasound to a depth range of about 7 cm and 7 MHz ultrasound to about 5 cm. Modern transducer technology does now allow probes to be used well away from their basic resonant frequency (multifrequency probes) (Fig. 1.5) and this allows the operator to trade off frequency and penetration more explicitly in some cases.

Penetration – key points

- Depends primarily on the attenuation of the pulse, which is less with lower frequencies
- Greater penetration is achieved either by using a lower-frequency transducer or by electronically manipulating the existing resonant frequency
- It also depends on the power setting
- And it depends on the level of system noise or artefact, which can be reduced by using the correct time gain compensation, and is highly operator-dependent

Using larger pulses does provide some additional penetration but, because the attenuation is logarithmic, the effect is less than might be expected. Thus a doubling of output power will typically result in an increased penetration at 7 MHz of roughly 5 mm. As we shall see later, there is insufficient evidence to establish firm safety limits at present, and so doubling the power is not immediately vetoed on safety grounds. However, tissue does not behave in a way which might be expected in response to higher outputs and the effect is often to increase non-linear effects and harmonic generation (see section on harmonic imaging, below) which will not improve penetration at all. We therefore conclude that, for the most part, if the probe selected will not provide the penetration required at the highest practical gain levels available, then the operator can only change to a probe at a lower frequency or else find a closer approach to the target of interest.

The most obvious consequence of the high attenuation of overlying tissue has been the introduction of *transvaginal (TV)* probes. Instead of the conventional transabdominal (TA) approach which involves the beam traversing up to 7 cm of tissue, the TV approach will allow many of the key structures to

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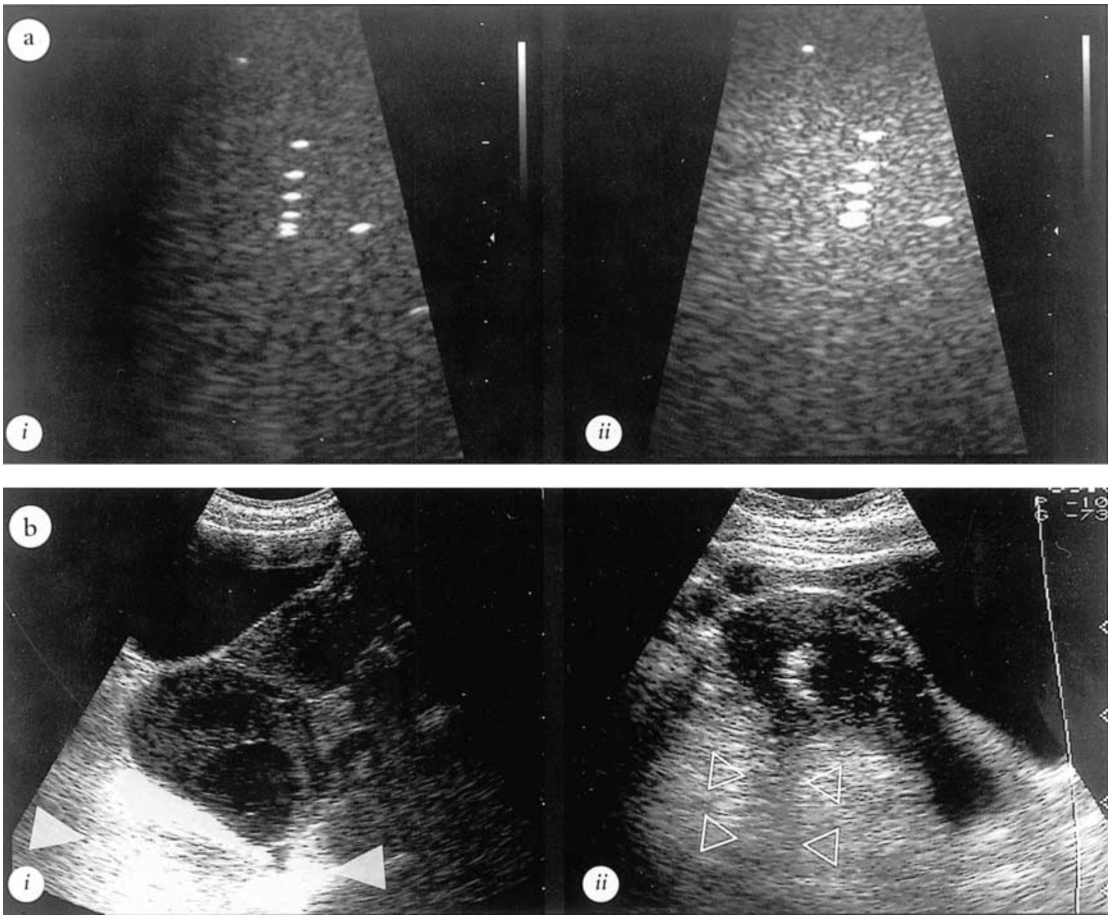

Figure 1.6 Inappropriate time gain compensation (TGC) settings can cause misleading impressions. (a)(i) Correct TGC with good resolution of all the wires. (ii) Inappropriately increased overall gain causes deterioration of both lateral and axial resolution. (b) Acoustic characteristics aid diagnosis: (i) a band of enhancement (arrows) behind this ovarian mass is due to reduced attenuation within the mass, and is indicative of its fluid content (despite the rather solid-looking echoes within it). (ii) The opposite effect of increased attenuation through a calcified fibroid causes posterior shadowing.

be positioned within 2–3 cm of the probe. This allows 7 MHz scanning with its consequent resolution improvement and also allows the operator to avoid other anatomical barriers.

Options for reducing the system noise seem unlikely to provide dramatic improvements in penetration for the foreseeable future. However, the operator has many opportunities to make it worse! Significant image degradation can be caused by misuse of the controls (Fig. 1.6a). If the time gain compensation (TGC) and other controls are inappropriately set then regions which are generating echoes of an adequate size may not be displayed because the operator has intervened to prevent it. Similarly, the opportunities for creating misleading appearances of either echogenic or transonic regions are many. The operator may also have the opportunity to achieve some noise reduction using frame averaging at the expense of frame rate, although at present the effects are marginal.

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Manufacturers may be tempted to declare that their probes are working at a higher frequency than they really are in order to impress a customer with what appears to be extremely high penetration with the tacit assumption that the corresponding resolution gains are available. The user needs to set more store by the actual performance of the probe than by the frequency label.

Contrast resolution

Whereas spatial resolution can be defined as the ability of the system to distinguish two closely spaced targets, the contrast resolution is its ability to distinguish two targets of almost the same nature. In other words, the ability to identify one point or region as being qualitatively different from another solely from the grey levels of the echo displayed from the two. If the echoes generated are in fact different but are assigned the same grey levels by the machine, then the operator will have no way of knowing they are different. In practice, this will always be true to some extent since the range of incoming echo sizes is many times greater than the number of available grey levels in the machine and even when the number of grey levels within the machine is increased, the fundamental limit is set by the number which can be meaningfully displayed by a television monitor and distinguished by the eye. Manufacturers have responded to this by providing a wide range of options for determining which echo amplitudes are translated into which grey levels and most equipment has controls labelled pre- or postprocessing, which allows the operator to choose, although there remains considerable uncertainty about how this can be optimised. The clinical significance of this is illustrated in Figure 1.5d where the same region is scanned at two different grey-scale settings and the diagnostic consequences are clear. Operators should be aware that the 'best' setting will differ between clinical areas and most scanners are set up according to some general compromise. The more sophisticated machines allow the operator to use dedicated set-ups if the machine is dedicated to one clinical area, e.g. gynaecology. How this is determined and validated is problematical.

Contrast resolution – key points

- Depends on the perceived number of grey levels
- By using different processing or set-up options, contrast resolution may be improved over certain relevant regions. However, this will differ according to the tissues under observation

Probe shape and size

Transabdominal imaging

The modern ultrasound machine consists of a main viewing and control console to which one or more probes can be attached. The operator on a day-to-day basis may have to choose between three or four probes but at the time of purchase or upgrade, a wider choice will be available.

Linear array This is the most traditional of electronic array formats. It is characterised by being relatively long and narrow, giving a large anterior field of view but requiring good acoustic contact over its whole length. It is not ideal for most gynaecological use because of its large contact area, often referred to as its *footprint*.

Curvilinear array The curvilinear array was developed as a sector version of the linear array and is now the workhorse of many general scanning departments. It has a smaller footprint than the corresponding linear array but is subject to some loss of resolution at the edges of sector towards the larger depths.

Phased array This type of probe has a particularly small footprint because it uses all of the elements in its length all of the time rather than having the active section stepping along the array in sequence. It is most frequently found in cardiology departments where the narrow acoustic window prevents other probe types from being effective. Its main drawback in imaging the pelvis is that its anterior field of view

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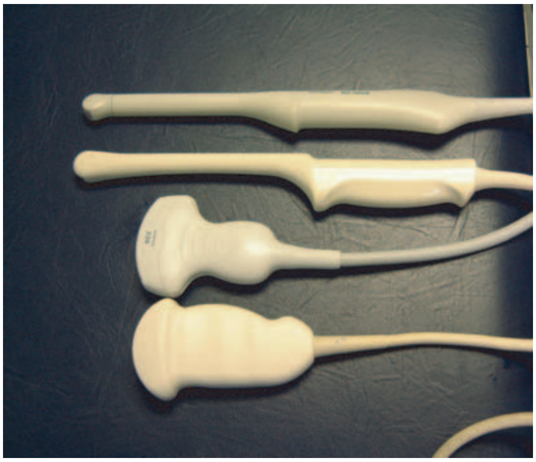

Figure 1.7 Examples of transvaginal (top) and transabdominal (bottom) probes used for gynaecological imaging.

is very limited. In addition it is particularly prone to sidelobe artefacts because of its scanning action.

Thus it is probable that some form of electronic array will be the normal probe of choice for gynaecological imaging. The majority of patients will be satisfactorily imaged using 5-MHz probes, although a small number of difficult or obese cases will only be properly imaged at a lower frequency. In some cases, a higher frequency such as 7.5 MHz will give even better results.

Transvaginal imaging

It is now widely accepted that the optimal images from many gynaecological patients will be obtained using a TV rather than TA technique. The probes developed for this purpose can almost always be fitted directly on to the console of standard machine. Indeed, a number of small portable scanners are now available with TV probes as an option. The range of probe types, shapes and sizes is surprisingly large and there is a marked lack of standardisation (Fig. 1.7 and *see* Fig. 2.7). Potential purchasers would do well to check the viewing angle of a TV probe and be aware of the compromises in resolution and frame rate which can be associated with working with wide angles.

Scanning ergonomics

The choice of probes and consoles is not entirely objective and operator preferences continue to be important. Having all the controls within easy reach is critical but there are those who prefer more adjustments and those who wish to minimise the number of knobs. There are variations in the weight of probes, the use of foot pedals, the arrangements for caliper measurements and hard copy, the choice of slider controls or others for TGC and the difficulty or ease with which probes can be interchanged. In addition, consideration must be given to whether portability is important. Even the largest machines should be moveable with good wheel design, but there are many small, light-weight, inexpensive scanners available now which can easily be picked up and carried around. The compromise in this case is between portability and image quality and facilities.

Operating modes

The normal operating mode of a conventional diagnostic ultrasound scanner is real-time B-mode. In addition, there may be an option of using a mode called harmonic imaging, which is described below.

Harmonic imaging

It is a feature of soft tissue (and indeed many materials) that as the pulse travels through them it suffers distortion. One aspect of this is the generation of additional frequencies which were not present in the original pulse when it set out. It turns out that if the original pulse was at a frequency f, then the ‘extra’ frequencies will be at multiples of f. In other words, frequencies $2f$, $3f$, $4f$ etc. will be generated and these are known as harmonics of f. When harmonic imaging mode is selected, the scanner ‘tunes in’ to one of these higher frequencies (usually $2f$) when it is receiving rather than looking for echoes at the same frequency as it sent out. Since the resolution normally improves with increasing frequency, it might be expected that this would improve the

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image quality, and in many cases it does. However there is another, more important bonus. Much of the artefact such as reverberation which obscures the ultrasound image is from echoes which do not contain a significant amount of harmonic. By tuning the receiver to the harmonic frequency, these artefacts are partially suppressed. The net result is a sharper and clearer image.

Of course, this will not improve all scanning on every occasion, but there are situations where it makes a significant difference. Some manufacturers offer transducers which can be used in harmonic mode if extra software is bought and hence the machine can be readily upgraded. In other cases, especially if the machine is relatively small and portable, this may not be an option and so purchasers need to consider carefully what their needs really are.

Doppler

For the detection, assessment and measurement of flow, one of the various Doppler modes should be considered. They can be categorised as follows:

- continuous-wave (CW) Doppler
- pulsed Doppler
- colour flow Doppler
- power Doppler

CW Doppler In CW Doppler it is necessary to have separate transducers for transmission and reception, although both can be incorporated into a single housing.

The main problems with CW Doppler are:

- There is uncertainty about the anatomical position of the origin of the signals
- It is difficult to use since, unless the probe is positioned correctly, there may be no signal at all and the operator may not know where to look.
- The angle dependence (Cos θ term) implies that if the vessel is approached at or close to 90°, no Doppler shift will result
- Other nearby moving structures, such as vessel walls, may generate much larger Doppler signals, obscuring those of interest

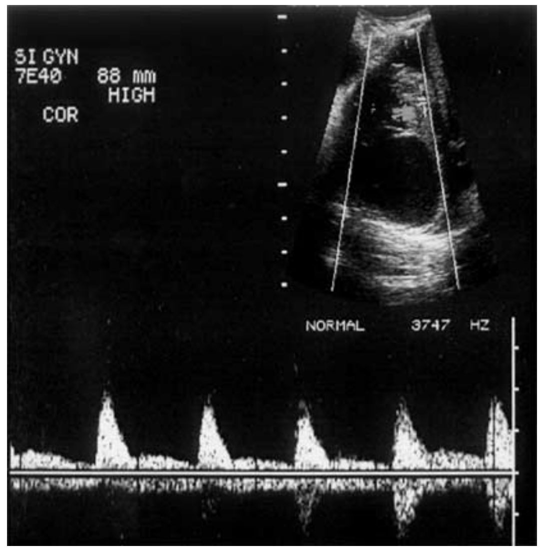

Figure 1.8 The sample volume has been placed over a small artery within this ovarian mass. The resulting spectrum from the artery is displayed as a high-resistance waveform.

As a result of the above, the use of CW Doppler in gynaecology is virtually non-existent and will not be discussed further.

Pulsed Doppler The main advantage of pulsed Doppler is that the operator can select the region from which the Doppler information is to be obtained because the use of pulses allows the timing to be used as a marker. The commonest approach is to arrange for a line to be generated on the image along which Doppler signals will be received and then for a small 'sample volume' to be moved along the line by the operator to indicate the precise depth at which the information is required (Fig. 1.8). The display then shows the Doppler spectrum at that depth and hence the technique is also known as *spectral Doppler*.

Electronic arrays can be used for this purpose since individual elements or groups of elements can be made to generate the extended pulses or act as receivers for the Doppler shifted signals. When the appropriate command is given, the display switches

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Figure 1.9 The colour box has been located over a mass in the lower uterus, demonstrating vigorous arterial and venous flow around an area of trophoflagtic invasion of a caesarean-section scan.

to the Doppler spectrum which looks much the same as one from a CW system. It is possible using many electronic systems to continue to obtain a live image while the pulsed Doppler information is shown but this inevitably compromises the quality of both.

The spectral trace obtained from a pulsed Doppler system shows an overall pulsatility which is heavily influenced by the downstream impedance. Users wishing to exploit this will want to characterise the shape of this spectral outline and most machines have extensive computerised facilities to allow this.

The main problems with pulsed Doppler are:

- There is a limit to the velocity which can be correctly measured. If the blood velocity exceeds this limit, *aliasing* occurs, which results in the spectrum showing the movement as being in the opposite direction
- Greater depths and higher frequencies lead to reduced velocities before aliasing. Furthermore, if some time is spent in updating the displayed image, then this reduces the maximum still further and hence it is more common for operators to work with recently frozen images of the section of interest
- The operator must select the region to be interrogated by the Doppler beam and only one can be used at any one time. If there is doubt as to whether blood flow is present anywhere in a given region, then this makes searching for it very difficult, if not totally impractical

Colour flow Doppler Colour flow mapping (CFM) Doppler systems superimpose flow information encoded as colours on a real-time grey-scale ultrasound image. With CFM, Doppler information is obtained simultaneously from a large region, possibly even the whole image, allowing the operator to form an immediate impression of the blood flow in the displayed section as a whole (Fig. 1.9). The convention is to use shades of *red* when the net flow is towards the probe and *blue* when it is away from it. The compromise in this case is with the quality and nature of the Doppler information obtained. In order to sample and process signals from the whole section in real time, the complete spectral analysis of the Doppler shifts has to be abandoned. Each scan line is sampled several times (typically eight) in quick succession and the sampled lines are analysed in pairs. A calculation reveals the mean velocities and the uncertainties or spreads are expressed as variances. Thus each small picture element or *pixel* is associated with a single number, which is a mean blood velocity, a positive or negative sign indicating flow direction and a variance value which can be interpreted as a measure of turbulence. The sign determines whether that pixel is red or blue, the mean value is displayed as a shade of the chosen colour and the variance is shown in one of many ways, typically as the addition of some other colour such as yellow or green. It is unfortunate in some ways that the convention is for red and blue to be used as main flow indicators since the ill-informed can misinterpret them as meaning arterial or venous.

Thus CFM systems are very useful for giving a quick indication of the extent of blood flow in a given region but it is important to recognise their limitations:

- The extra time per line carries a penalty in terms of image quality. This may be manifest as a reduced frame rate, resolution degradation or both

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