Doppler in Obstetrics: book by K Nicolaides, G Rizzo, K Hecher

Chapter on Doppler ultrasound: principles and practice by Colin Deane

INTRODUCTION

Competent use of Doppler ultrasound techniques requires an understanding of three key components:

- The capabilities and limitations of Doppler ultrasound;
- The different parameters which contribute to the flow display;
- Blood flow in arteries and veins.

This chapter describes how these components contribute to the quality of Doppler ultrasound images. Guidelines are given on how to obtain good images in all flow imaging modes.

BASIC PRINCIPLES

Ultrasound images of flow, whether color flow or spectral Doppler, are essentially obtained from measurements of movement. In ultrasound scanners, a series of pulses is transmitted to detect movement of blood. Echoes from stationary tissue are the same from pulse to pulse. Echoes from moving scatterers exhibit slight differences in the time for the signal to be returned to the receiver (Figure 1). These differences can be measured as a direct time difference or, more usually, in terms of a phase shift from which the `Doppler frequency' is obtained (Figure 2). They are then processed to produce either a color flow display or a Doppler sonogram.

As can be seen from Figures 1 and 2, there has to be motion in the direction of the beam; if the flow is perpendicular to the beam, there is no relative motion from pulse to pulse. The size of the Doppler signal is dependent on:

- Blood velocity: as velocity increases, so does the Doppler frequency;
- Ultrasound frequency: higher ultrasound frequencies give increased Doppler frequency. As in B-mode, lower ultrasound frequencies have better penetration.
- The choice of frequency is a compromise between better sensitivity to flow or better penetration;
- The angle of insonation: the Doppler frequency increases as the Doppler ultrasound beam becomes more aligned to the flow direction (the angle between the beam and the direction of flow becomes smaller). This is of the utmost importance in the use of Doppler ultrasound. The implications are illustrated schematically in Figure 3.

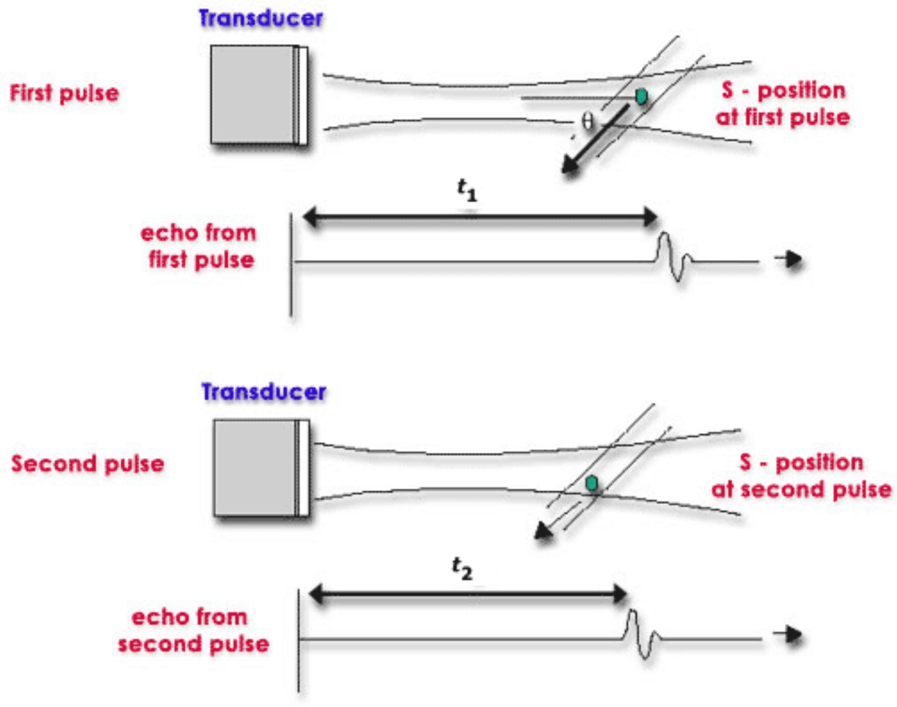

Figure 1: Ultrasound velocity measurement. The diagram shows a scatterer S moving at velocity V with a beam/flow angle. The velocity can be calculated by the difference in transmit-to-receive time from the first pulse to the second (t2), as the scatterer moves through the beam.

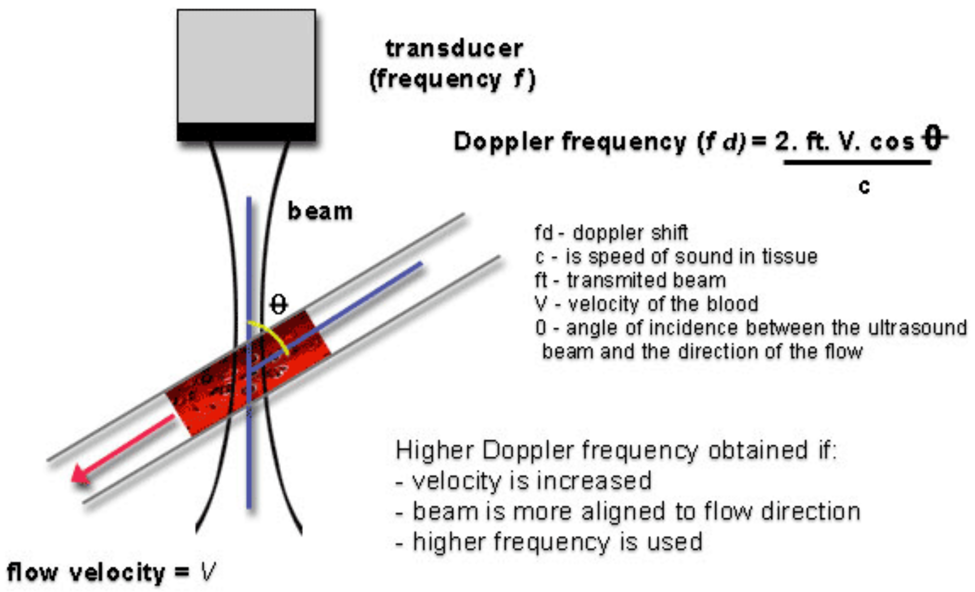

Figure 2: Doppler ultrasound. Doppler ultrasound measures the movement of the scatterers through the beam as a phase change in the received signal. The resulting Doppler frequency can be used to measure velocity if the beam/flow angle is known.

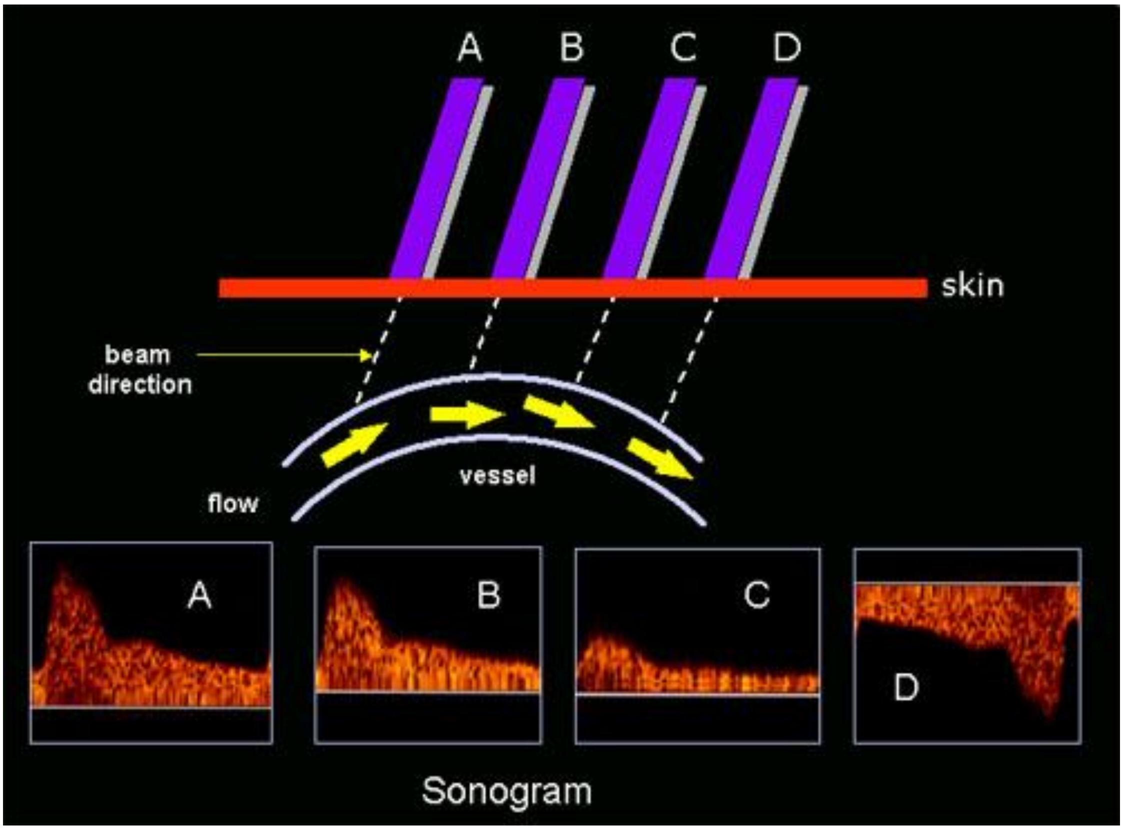

Figure 3: Effect of the Doppler angle in the sonogram. (A) higher-frequency Doppler signal is obtained if the beam is aligned more to the direction of flow. In the diagram, beam (A) is more aligned than (B) and produces higher-frequency Doppler signals. The beam/flow angle at (C) is almost 90° and there is a very poor Doppler signal. The flow at (D) is away from the beam and there is a negative signal.

All types of Doppler ultrasound equipment employ filters to cut out the high amplitude, low-frequency Doppler signals resulting from tissue movement, for instance due to vessel wall motion. Filter frequency can usually be altered by the user, for example, to exclude frequencies below 50, 100 or 200 Hz. This filter frequency limits the minimum flow velocities that can be measured.

CONTINUOUS WAVE AND PULSED WAVE

As the name suggests, continuous wave systems use continuous transmission and reception of ultrasound (Figure 4). Doppler signals are obtained from all vessels in the path of the ultrasound beam (until the ultrasound beam becomes sufficiently attenuated due to depth). Continuous wave Doppler ultrasound is unable to determine the specific location of velocities within the beam and cannot be used to produce color flow images. Relatively inexpensive Doppler ultrasound systems are available which employ continuous wave probes to give Doppler output without the addition of B-mode images. Continuous wave Doppler is also used in adult cardiac scanners to investigate the high velocities in the aorta.

Doppler ultrasound in general and obstetric ultrasound scanners uses pulsed wave ultrasound (Figure 4). This allows measurement of the depth (or range) of the flow site. Additionally, the size of the sample volume (or range gate) can be changed. Pulsed wave ultrasound is used to provide data for Doppler sonograms and color flow images.

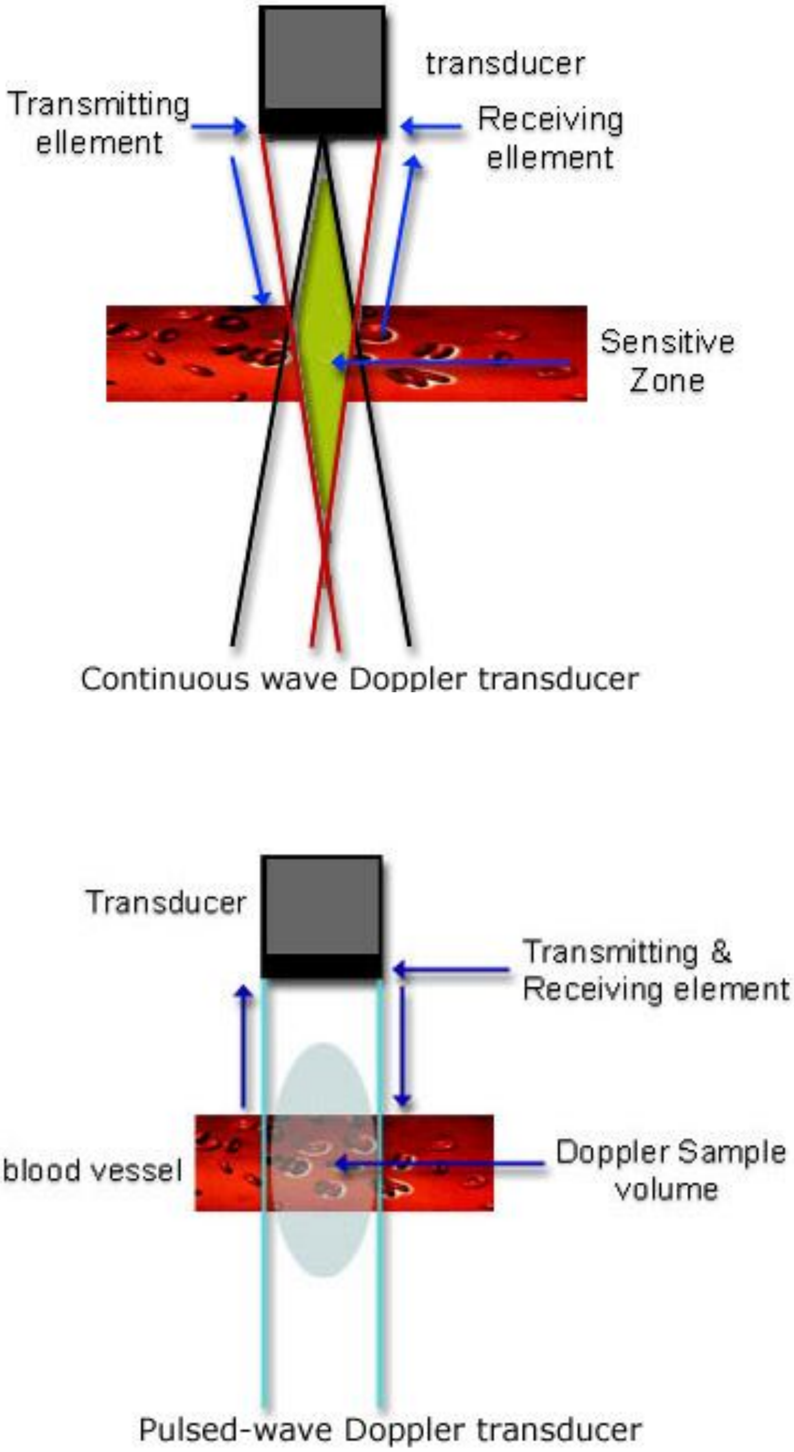

Figure 4: Illustration of continuous wave and pulsed wave Doppler.

Aliasing

Pulsed wave systems suffer from a fundamental limitation. When pulses are transmitted at a given sampling frequency (known as the pulse repetition frequency), the maximum Doppler frequency d that can be measured unambiguously is half the pulse repetition frequency. If the blood velocity and beam/flow angle being measured combine to give a d value greater than half of the pulse repetition frequency, ambiguity in the Doppler signal occurs. This ambiguity is known as aliasing (Figures 5 and 6). A similar effect is seen in films where wagon wheels can appear to be going backwards due to the low frame rate of the film causing misinterpretation of the movement of the wheel spokes.

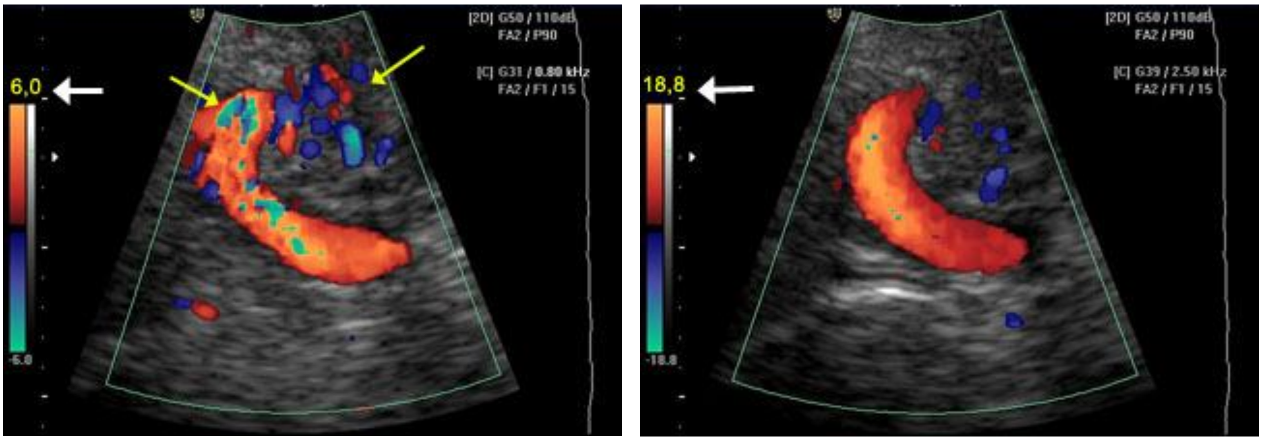

Figure 5: Aliasing of color doppler imaging and artefacts of color (left). Color image shows regions of aliased flow (yellow arrows). This problem is avoided by reducing color gain and increasing pulse repetition frequency (Right).

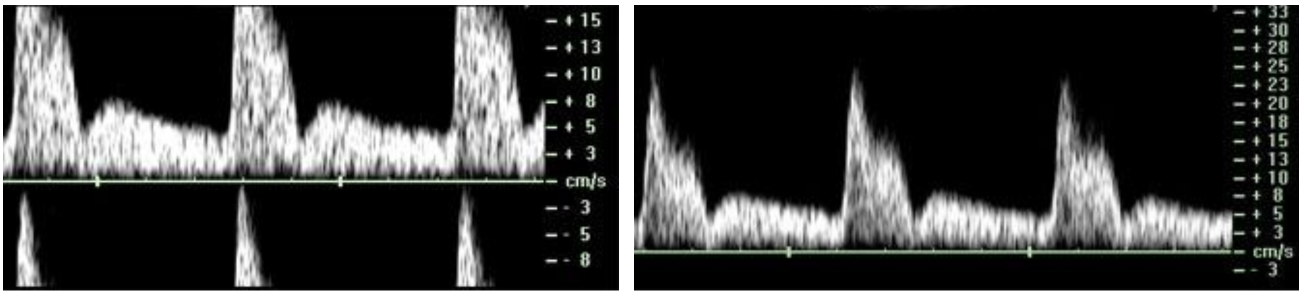

Figure 6: Example of aliasing and correction of the aliasing. Left: waveforms with aliasing, with abrupt termination of the peak systolic and display this peaks bellow the baseline. Right: Sonogram clear without aliasing. Correction: increase the pulse repetition frequency and adjust baseline (move down)

The pulse repetition frequency is itself constrained by the range of the sample volume. The time interval between sampling pulses must be sufficient for a pulse to make the return journey from the transducer to the reflector and back. If a second pulse is sent before the first is received, the receiver cannot discriminate between the reflected signal from both pulses and ambiguity in the range of the sample volume ensues. As the depth of investigation increases, the journey time of the pulse to and from the reflector is increased, reducing the pulse repetition frequency for unambiguous ranging. The result is that the maximum d measurable decreases with depth.

Low pulse repetition frequencies are employed to examine low velocities (e.g. venous flow). The longer interval between pulses allows the scanner a better chance of identifying slow flow. Aliasing will occur if low pulse repetition frequencies or velocity scales are used and high velocities are encountered (Figure 7). Conversely, if a high pulse repetition frequency is used to examine high velocities, low velocities may not be identified.

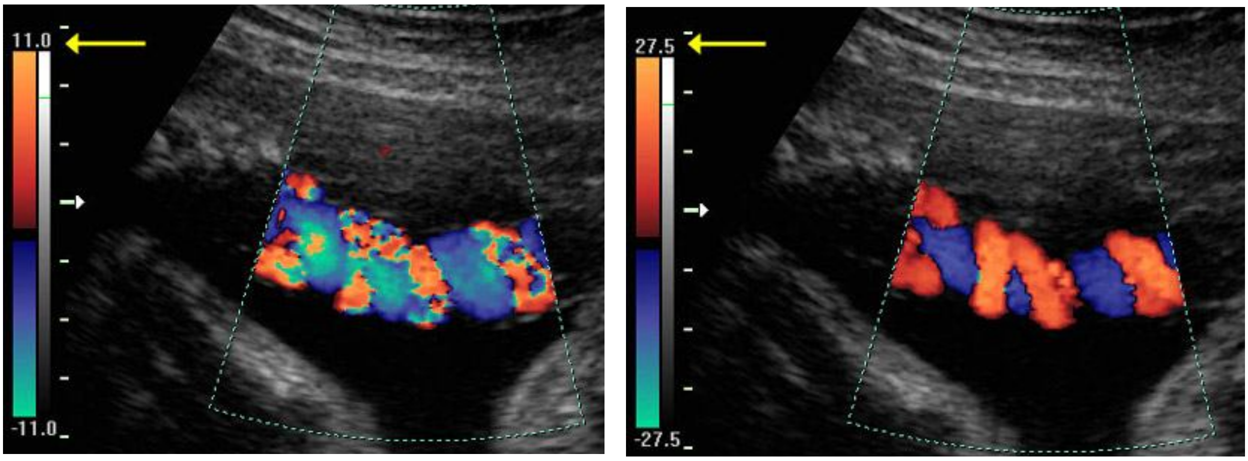

Figure 7: Color flow imaging: effects of pulse repetition frequency or scale. The pulse repetition frequency or scale is set low (yellow arrow). Left: the color image shows ambiguity within the umbilical artery and vein and there is extraneous noise. Right: the pulse repetition frequency or scale is set appropriately for the flow velocities. The color image shows the arteries and vein clearly and unambiguously.

ULTRASOUND FLOW MODES

Since color flow imaging provides a limited amount of information over a large region, and spectral Doppler provides more detailed information about a small region, the two modes are complementary and, in practice, are used as such.

Color flow imaging can be used to identify vessels requiring examination, to identify the presence and direction of flow, to highlight gross circulation anomalies, throughout the entire color flow image, and to provide beam/vessel angle correction for velocity measurements. Pulsed wave Doppler is used to provide analysis of the flow at specific sites in the vessel under investigation. When using color flow imaging with pulsed wave Doppler, the color flow/B-mode image is frozen while the pulsed wave Doppler is activated.

Some manufacturers have produced concurrent color flow imaging and pulsed wave Doppler. When these modes are used simultaneously, the performance of each is decreased. Because transducer elements are employed in three modes (B-mode, color flow and pulsed wave Doppler), the frame rate is decreased, the color flow box is reduced in size and the available pulse repetition frequency is reduced, leading to increased susceptibility to aliasing.

In power Doppler the magnitude of the color flow output is displayed rather than the Doppler frequency signal (Figure 8). Power Doppler does not display flow direction or different velocities. It is often used in conjunction with frame averaging to increase sensitivity to low flows and velocities. It complements the other two modes (Table 1). Hybrid color flow modes incorporating power and velocity data are also available from some manufacturers. These can also have improved sensitivity to low flow. A brief summary of factors influencing the displays in each mode is given in the following sections. Most of these factors are set up approximately for a particular mode when the application (e.g. fetal scan) is chosen, although the operator will usually alter many of the controls during the scan to optimize the image.

Table 1: Flow imaging modes
Spectral Doppler • Examines flow at one site • Detailed analysis of distribution of flow • Good temporal resolution - can examine flow waveform • Allows calculations of velocity and indices
Color flow • Overall view of flow in a region • Limited flow information • Poor temporal resolution/flow dynamics (frame rate can be low when scanning deep) • Color flow map (diferent color maps) • Direction information • Velocity information (high velocity and low velocity) • Turbulent flows
Power / energy / amplitude flow • Sensitive to low flows • No directional information in some modes • Very poor temporal resolution • Susceptible to noise

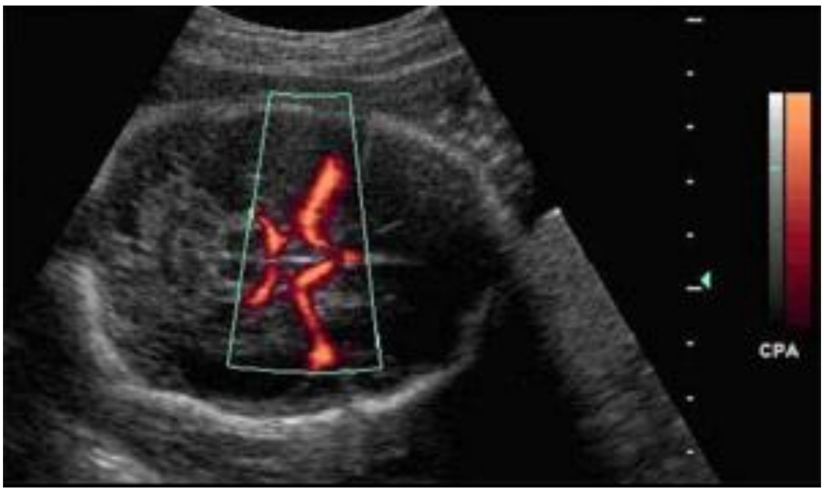

Figure 8: Color Power Doppler of the Circle of Willis

Color flow imaging

Color flow Doppler ultrasound produces a color-coded map of Doppler shifts superimposed onto a B-mode ultrasound image (Color Flow Maps). Although color flow imaging uses pulsed wave ultrasound, its processing differs from that used to provide the Doppler sonogram. Color flow imaging may have to produce several thousand color points of flow information for each frame superimposed on the B-mode image. Color flow imaging uses fewer, shorter pulses along each color scan line of the image to give a mean frequency shift and a variance at each small area of measurement. This frequency shift is displayed as a color pixel. The scanner then repeats this for several lines to build up the color image, which is superimposed onto the B-mode image. The transducer elements are switched rapidly between B-mode and color flow imaging to give an impression of a combined simultaneous image. The pulses used for color flow imaging are typically three to four times longer than those for the B-mode image, with a corresponding loss of axial resolution.

Assignment of color to frequency shifts is usually based on direction (for example, red for Doppler shifts towards the ultrasound beam and blue for shifts away from it) and magnitude (different color hues or lighter saturation for higher frequency shifts). The color Doppler image is dependent on general Doppler factors, particularly the need for a good beam/flow angle. Curvilinear and phased array transducers have a radiating pattern of ultrasound beams that can produce complex color flow images, depending on the orientation of the arteries and veins. In practice, the experienced operator alters the scanning approach to obtain good insonation angles so as to achieve unambiguous flow images.

FACTORS AFFECTING THE COLOR FLOW IMAGE

The controls that affect the appearance of the color flow image are summarized in Table 2. The main factors include:

- Power and gain: Color flow uses higher-intensity power than B-mode. Attention should be paid to safety indices. Power and gain should be set to obtain good signal for flow and to minimize the signals from surrounding tissue (Figure 9).

- Frequency selection: Many scanner / transducer combinations permit changes of frequency. High frequencies give better sensitivity to low flow and have better spatial resolution. Low frequencies have better penetration and are less susceptible to aliasing at high velocities.

- Velocity scale / pulse repetition frequency: Low pulse repetition frequencies should be used to examine low velocities but aliasing may occur if high velocities are encountered (Figure 6).

- Region of interest: Because more pulses are needed to look at flow than for the B-mode image, reducing the width and maximum depth of the color flow area under investigation will usually improve frame rate and may allow a higher color scan line density with improved spatial resolution.

- Focus: The focus should be at the level of the area of interest. This can make a significant difference to the appearance and accuracy of the image (Figure 10).

Table 2: Factors affecting color flow image
Main factors
• Power: transmitted power into tissue*
• Gain: overall sensitivity to flow signals
• Frequency: trades penetration for sensitivity and resolution*
• Pulse repetition frequency (also called scale): low pulse repetition frequency to look at low velocities, high
• pulse repetition frequency reduces aliasing*
• Area of investigation: larger area reduces frame rate*
• Focus: color flow image optimized at focal zone*
Other factors
• Triplex color: pulse repetition frequency and frame rate reduced by need for B-mode/spectral pulses
• Persistence: high persistence produces smoother image but reduces temporal resolution*
• Pre-processing: trades resolution against frame rate*
• Filter: high filter cuts out more noise but also more of flow signal*
• Post-processing assigns color map/variance*

* Settings appropriate for specific examinations assigned by set-up / application keys

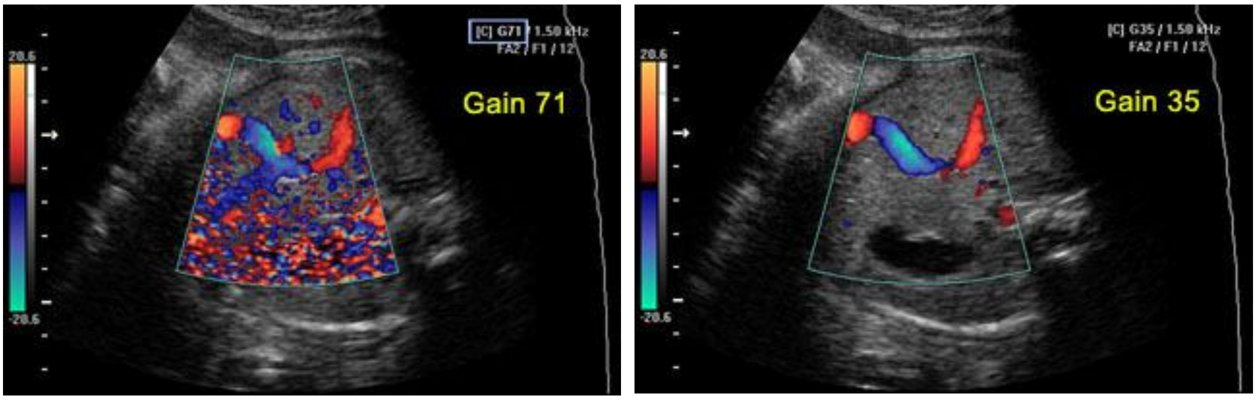

Figure 9: Setting the color gain to minimize the signals (artifacts) from surrounding tissue.

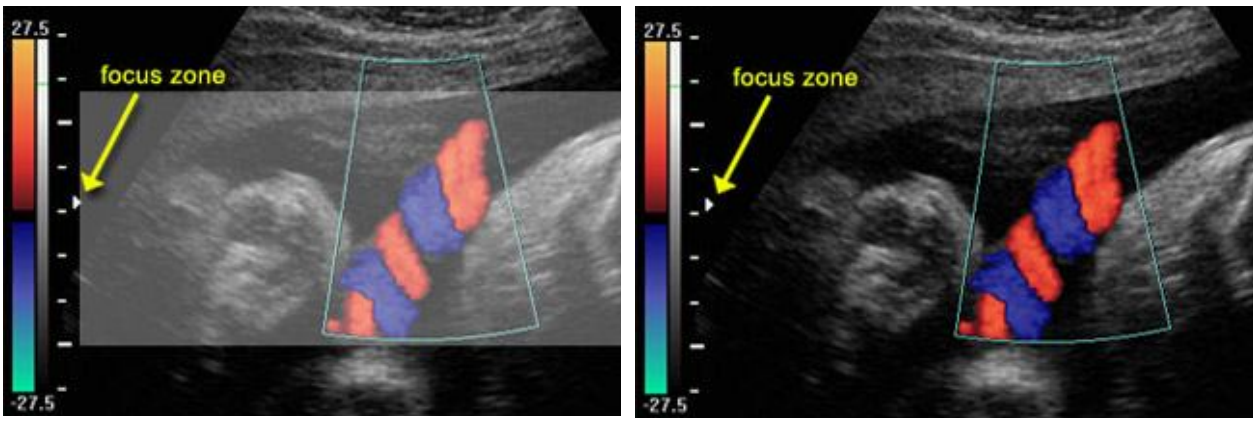

Figure 10: Set the focus at the region of interest.

In practice, the operator will make many changes to the controls and will try different probe positions to optimize the image. Practical guidelines are given in Table 3.

Table 3: Color flow imaging: practical guidelines
• Select the appropriate applications/set-up key. This optimizes parameters for specific examinations
• Set power to within fetal study limits. Adjust color gain. Ensure focus is at the region of interest and adjust gain to optimize color signal
• Use probe positioning/beam steering to obtain satisfactory beam/vessel angle
• Adjust pulse repetition frequency/scale to suit the flow conditions. Low pulse repetition frequencies are more sensitive to low flows/velocities but may produce aliasing. High pulse repetition frequencies reduce aliasing but are less sensitive to low velocities
• Set the color flow region to appropriate size. A smaller color flow `box' may lead to a better frame rate and better color resolution/sensitivity

SPECTRAL OR PULSED WAVE DOPPLER

Pulsed wave Doppler ultrasound is used to provide a sonogram of the artery or vein under investigation (Figure 10). The sonogram provides a measure of the changing velocity throughout the cardiac cycle and the distribution of velocities in the sample volume (or gate) (Figure 11). If an accurate angle correction is made, then absolute velocities can be measured. The best resolution of the sonogram occurs when the B-mode image and color image are frozen, allowing all the time to be employed for spectral Doppler. If concurrent imaging is used (real-time duplex or triplex imaging), the temporal resolution of the sonogram is compromised.

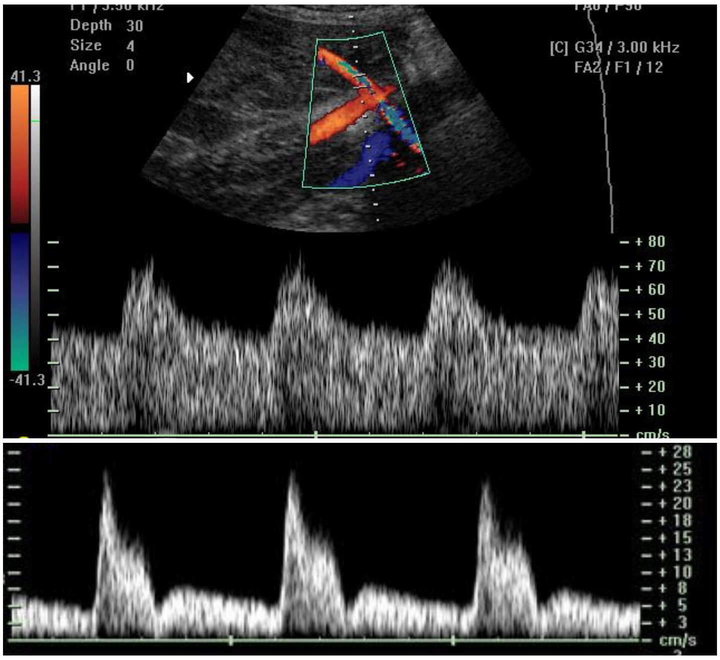

Figure 11: Doppler spectra of uterine artery flow. The color flow image allows beam / flow angle visualization. The sonogram on the top shows high velocities throughout the cardiac cycle, indicating low distal resistance. The sonogram at the bottom shows a pulsatile flow waveform with low diastolic velocities; this is indicative of high distal resistance.

FACTORS AFFECTING THE SPECTRAL IMAGE

The controls that affect the appearance of the sonogram are summarized in Table 4. The main factors include:

- Power and gain: Pulsed wave Doppler uses higher intensity power than B-mode. Attention should be paid to safety indices. Power and gain should be set so that clear signals are obtained.
- Velocity scale / pulse repetition frequency: Low pulse repetition frequencies should be used to look at low velocities but aliasing may occur if high velocities are encountered.
- Gate size: If flow measurements are being attempted, the whole vessel should be insonated. A large gate may include signals from adjacent vessels (Figure 12).

Figure 12: Influence of gate size. The spectral Doppler gate insonates an artery and vein and the sonogram shows flow from both of these vessels. The calculation of mean velocity (arrow) is meaningless since velocities from one vessel subtract from those of the other.

Table 4: Factors affecting the spectral Doppler image
Main factors
• Power: transmitted power into tissue*
• Gain: overall sensitivity to flow signals
• Pulse repetition frequency (also called scale): low pulse repetition frequency to look at low velocities, high pulse repetition frequency reduces aliasing*
• Gate size*
• Beam steering can allow improved beam/flow angle for better accuracy of velocity calculation*
• Live duplex/triplex spectral resolution constrained by need for B-mode/color pulses
Other factors
• Gate: sharpness of resolution*
• Filter: high filter cuts out more noise but more of flow signal*
• Post-processing: assigns brightness to output*

* Settings appropriate for specific examinations assigned by set-up/application keys

Guidelines for a practical approach to obtain good-quality spectral images are given in Table 5.

Table 5: Spectral Doppler imaging: practical guidelines
• Set power to within fetal study limits • Position the pulsed wave Doppler cursor on the vessel to be investigated • Adjust gain so that the sonogram is clearly visible and free of noise • Use probe positioning/beam steering to obtain a satisfactory beam/vessel angle. Angles close to 90° will give ambiguous/unclear values. The beam/vessel angle should be 60° or less if velocity measurements are to be made • Adjust the pulse repetition frequency/scale and baseline to suit flow conditions. The sonogram should be clear and not aliased • Set the sample volume to correct size. Correct the angle to obtain accurate velocities. Use the B-mode and color flow image of the vessel to make the angle correction

BLOOD FLOW MEASUREMENTS

Velocity measurement

Theoretically, once the beam/flow angle is known, velocities can be calculated from the Doppler spectrum as shown in the Doppler equation. However, errors in the measured velocity may still occur. Sources of error can be broadly divided into three categories (Table 6).

Table 6. Errors in measurement of velocity
Errors in the formation of the Doppler spectrum due to: • Use of multiple elements in array transducers; • Non-uniform insonation of the vessel lumen; • Insonation of more than one vessel; • Use of filters removing low-velocity components.
Errors in the measurement of the ultrasound beam/flow velocity angle. • Use of high angles (>60°) may give rise to error because of the comparatively large changes in the cosine of the angle which occur with small changes of angle (Figure 13). • The velocity vector may not be in the direction of the vessel axis.
Errors in the calculation packages provided by the manufacturers for analysis of the Doppler spectrum (for instance, of intensity weighted mean velocity). • While efforts can be made to minimize errors, the operator should be aware of their likely range. It is good practice to try to repeat velocity measurements, if possible using a different beam approach, to gain a feel for the variability of measurements in a particular application. However, even repeated measurements may not reveal systematic errors occurring in a particular machine. • The effort applied to produce accurate velocity measurements should be balanced against the importance of absolute velocity measurements for an investigation. • Changes in velocity and velocity waveform shape are often of more clinical relevance when making a diagnosis.

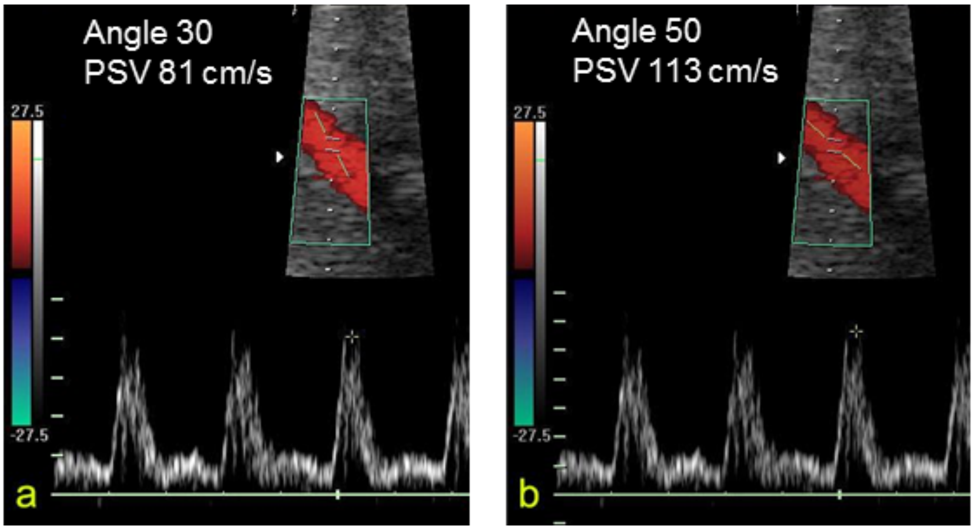

Figure 13: Effect of high vessel/beam angles. (a) and (b) A scan of fetal aortic flow is undertaken at a high beam / vessel angle. Beam/flow angles should be kept to ≤60°. A huge discrepancy is observed when using angles > 60°. If absolute velocities are to be measured, beam/flow angles should be kept to ≤60°.

Calculation of absolute flow

Total flow measurement using color or duplex Doppler ultrasound is fraught with difficulties, even under ideal conditions. Errors that may arise include:

- Those due to inaccurate measurement of vessel cross-sectional area, for example the cross-sectional area of arteries which pulsate during the cardiac cycle;

- Those originating in the derivation of velocity (see above).

These errors become particularly large when flow calculations are made in small vessels; errors in measurement of diameter are magnified when the diameter is used to derive cross-sectional area. As with velocity measurements, it is prudent to be aware of possible errors and to conduct repeatability tests.

Flow waveform analysis

Non-dimensional analysis of the flow waveform shape and spectrum has proved to be a useful technique in the investigation of many vascular beds. It has the advantage that derived indices are independent of the beam / flow angle.

Changes in flow waveform shape have been used to investigate both proximal disease (e.g. in the adult peripheral arterial circulation) and distal changes (in the fetal circulation and uterine arteries). While the breadth of possible uses shows the technique to be versatile, it also serves as a reminder of the range of factors which cause changes to the local Doppler spectrum. If waveform analysis is to be used to observe changes in one component of the proximal or distal vasculature, consideration must be given to what effects other components may have on the waveform.

Flow waveform shape: indices of measurement

Many different indices have been used to describe the shape of flow waveforms in a quantitative way (Figure 14). In general, they are a compromise between simplicity and the amount of information obtained. Commonly used indices are:

- Systolic / diastolic ratio: (S/D);
- Resistance index: (S-D) / D, also called Pourcelot's index;
- Pulsatility index: (S-D) / Vm.

The PI is the only useful index when there is no end-diastolic flow.

In addition to these indices, the flow waveform may be described or categorized by the presence or absence of a particular feature, for example the absence of end-diastolic flow and the presence of a post-systolic notch.

Generally, a low pulsatility waveform is indicative of low distal resistance and high pulsatility waveforms occur in high-resistance vascular beds, although the presence of proximal stenosis, vascular steal or arteriovenous fistulas can modify waveform shape. Care should be taken when trying to interpret indices as absolute measurements of either upstream or downstream factors. For example, alterations in heart rate can alter the flow waveform shape and cause significant changes in the value of indices.

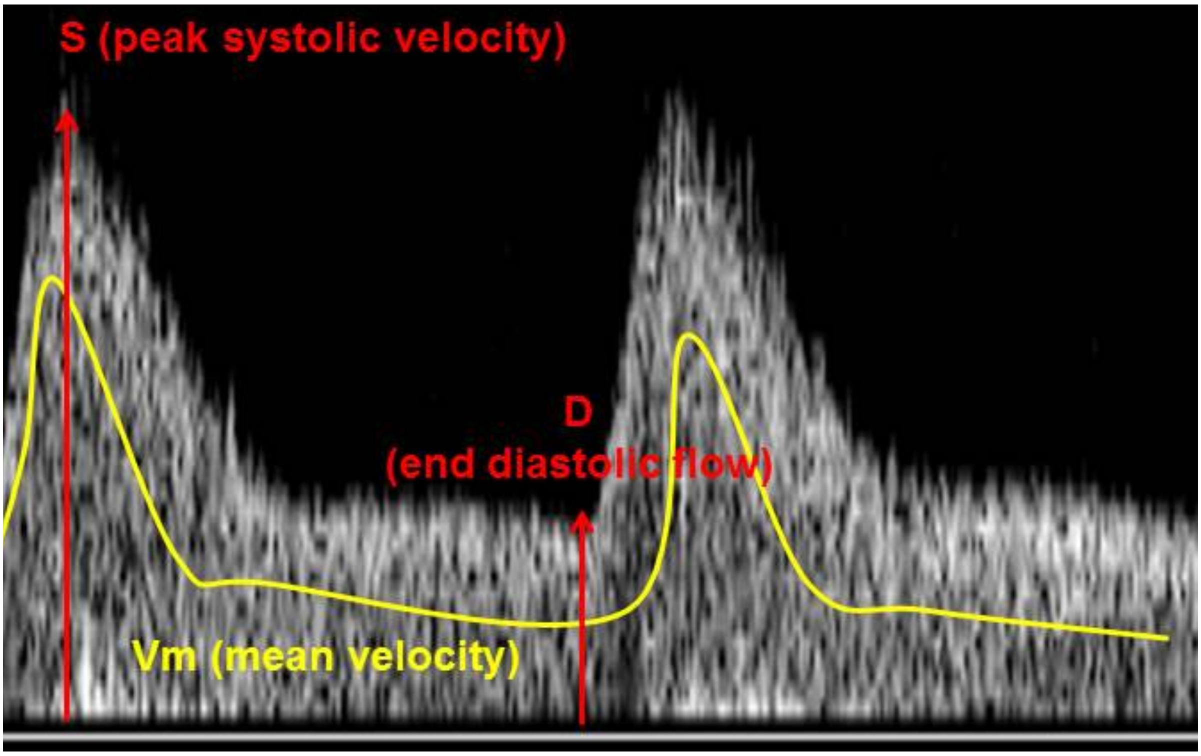

Figure 14: Flow velocity indices