The Doppler effect in medical ultrasound
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1. The Doppler effect in medical ultrasound

*Understanding the physics and properties of sound waves is fundamental to getting the best out of an ultrasound machine.*

In medical ultrasound the Doppler effect is used to measure the velocity of blood in blood vessels, especially arteries to determine if a stenosis is present. The Doppler equation is modified when used for medical ultrasound to take into account the pulse-echo cycle, as each part produces a Doppler shift.

The transmitted pulse interacting with a moving reflector results in a Doppler shift with the transducer acting as the stationary source. The reflector then acts as a moving source, generating an echo which returns to the transducer, now acting as a stationary receiver (refer figure 1).

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**Figure 1:** Pictorial representation of Doppler signals being detected from within a vessel.

To take into account the double Doppler shift, a factor of two figures in the equation:

$$f_d = \frac{f_i 2u \cos \theta}{c}$$

The Doppler shift increases with transmitted frequency, increasing velocity of blood cells and with a decreased angle of approach.

The goal is to determine the velocity of blood within the vessel so the equation is rewritten as:

$$u = \frac{f_d c}{f_i 2\cos \theta}$$

**Important note**

In practical applications, direction of blood flow is relative to the transducer, that is, either towards or away from the transducer.

The angle of insonation is very important. Cos 0° = 1 with the cos 90° = 0. Angles between 0° and 60° are acceptable. The velocity measurements become unreliable with angles more than 60°. If a normal non-occluded blood vessel is scanned with an angle of insonation of 90°, no trace will register. This will give the impression that the blood vessel is occluded.

To accurately determine the Doppler frequency shift, the transmitted frequency must be known and constant so that it can be compared to the returning signal.

Identifying and maintaining the transmitted frequency would appear to be relatively straightforward; however, most modern transducers are capable of transmitting many different frequencies. The different manufacturers of ultrasound machines achieve the transmission of different frequencies through the application of two technologies:

- **Defined frequency technology**: defined frequency technology lets the operator choose the specified frequency transmitted by the receiver and the whole ultrasound beam operates at the same frequency. A 4 MHz to 7 MHz transducer will send and receive all of the ultrasound beam at either 4 MHz, 5 MHz, 6 MHz or 7 MHz.

- **Broadband technology**: Broadband transducers use a pre-defined range of frequencies to form an ultrasound image. A 4 MHz to 7 MHz broadband transducer will send and receive some of the ultrasound beam at 4 MHz, 5 MHz, 6 MHz and 7 MHz.

It should be noted that the utilisation of multiple frequencies creates a number of problems for calculating the Doppler shift and corresponding velocities in Doppler imaging. The processing required to calculate numerous velocities and accurately depict the individual Doppler shift for each transmitted frequency is too complex to allow real-time imaging. As a result, rather than using a range of frequencies to determine the Doppler shift only one centre frequency is used as the transmitted frequency. For example, a 4 MHz to 7.5 MHz transducer used for B-mode imaging will use 5 MHz as the Doppler centre frequency. The centre frequency will usually be lower than the highest frequency available on the transducer because the best Doppler signal is usually obtained using a lower centre frequency.
Colour flow Doppler (CFD)

Colour flow Doppler (CFD) imaging colour codes Doppler shift information and superimposes that information over a B-mode image. The colour information overlay provides a global depiction of the presence and direction of blood flow.

CFD is useful for highlighting gross circulation anomalies. It is also useful for providing beam/vessel angle correction for velocity measurements. The size, position and shape of the colour coded area (or colour box) that is colour coded is determined by the operator.

Once determined, the image within the colour coded area is divided into pixels by the ultrasound machine. Each pixel can only display one colour at a time. Due to this limitation the ultrasound machine calculates an average Doppler shift value for each pixel. Each pixel requires that the ultrasound transducer record a minimum of eight pulses to provide the average Doppler shift. Lower Doppler frequency shifts are deeper in colour or hue whereas lighter colour hues represent a higher Doppler frequency shift. As there is no angle information captured, the colour display only depicts Doppler frequency shift values rather than specific velocity information.

Important note

It is important to note that the differences between PW and CFD are that:

- PW Doppler uses a specific angle to calculate specific velocity information in a defined sample volume which is typically only a couple of millimetres in size.
- CFD can only give averaged Doppler shift information within the defined colour box. The Doppler shift information is therefore possible over a larger sample area. The colour box size can be set to give a global assessment of the vessel over a much larger area.

Using a large colour box slows the frame rate as a wide colour box has more lines of sight and therefore requires that more pulses be generated to determine the Doppler shift information. The additional information generated requires more computer processing power, which in turn slows the frame rate and the temporal resolution.

Once the information is received by the ultrasound machine, colour is assigned on the basis of the direction of flow. Bloodflow that is moving toward the transducer is displayed in one colour (for example red) and blood flow away from the transducer is displayed as another colour (for example blue). This contextual information is graphically represented on the ultrasound image as a colour bar. The colour bar has a baseline which is denoted by a black gap between the two bars. This baseline can be varied just like the baseline in a spectral trace. Darker colour hues (such as deep red or deep blue) represent areas of low Doppler frequency shifts, with lighter shades representing areas of higher Doppler frequency shift. Some colour maps use a range of colours to represent the frequency shifts. As the frequency increases the colours can range from deep red to orange and yellow. In the reverse channel or negative spectrum which represents flow away from the transducer, the colours might range from blue to green (refer figure 2).
Changing the frequency range or the angle of approach to the vessel will change the frequency shift represented by a particular hue of colour. This has the potential to misrepresent the degree of stenosis. Decreasing the frequency range is likely to produce colour aliasing (refer to aliasing, page 7).

Flow direction can be confusing when using a linear array because in many instances the blood vessel is interrogated by an incident beam 90° to the transducer. No blood flow should therefore be represented. However colour coding is based on flow relative to the active aperture, and not the entire transducer face. At any instance in time flow in the vessel within the colour box will be travelling towards or away from the active aperture (refer figure 3).

Figure 2: colour image of portal vein.

Figure 3: representation of spectral trace.
The spectral trace in this diagram illustrates flow towards and away from the transducer. In colour flow Doppler imaging the flow within the vessel is coloured differently eg red (towards) and blue (away) from the transducer. Source: http://www.centrus.com.br/DiplomaFMF/SeriesFMF/doppler/capitulos-html/chapter_01.htm (accessed 25 September 2008).
The angle of approach is especially important when using sector or curved transducers as the radial alignment of the lines of sight are not parallel. These wide angles of approach will colour code the flow from some lines of sight as going towards the transducer and some away from the transducer. At the point where the lines of sight are perpendicular to the vessel, there will be an abrupt change of colour with an area of black in between, representing the baseline (refer figure 4).

![Figure 4: wide angle approach.](image)

(l) schematic representation of wide angle of approach (Gent (1997), p. 275)) and (r) CFD image of wide angle of approach (Pozniak et. al. (1992), p. 42).

In a linear transducer, the lines of sight are perpendicular to the face of the transducer (i.e. at 90°) making the interrogation of a vessel parallel to the transducer face unfavourable. For this reason ultrasound systems allow the colour box to be steered at a fixed angle in either direction (usually about 20°). The disadvantage is a reduction of the B-mode field of view that can be colour coded and a reduction in the sensitivity of Doppler shift detection. If optimum sensitivity is required to detect low flow a straight colour box should be used. With all other colour parameters are constant colour detection is more sensitive with a straight colour box.

![Figure 5: carotid artery with (l) a steered colour box and (r) a straight colour box.](image)

**Advantages of colour flow Doppler**

- Overall view of flow in a region.
- Rapid assessment of flow direction.
- Rapid assessment of estimates of velocity information (high velocity or low velocity).
- Illustrates areas of turbulence.
Disadvantages of colour flow Doppler

- Limited flow information. The velocity information is not specific as colour coding indicates averaged Doppler shift information and not specific velocities.
- Poorer temporal resolution especially at increased depth.

Colour flow Doppler artifacts

**Poor spatial resolution**

Poor spatial resolution is an inherent colour flow Doppler limitation. This is particularly true for curved or sector transducers when vessels under examination lie deep within the body. In such instances colour representation can extend beyond the margins of the vessel by as much as four times the actual size of the vessel. It is important to recognise this limitation; however little can be done to remedy the situation.

**Angle of approach**

As described above, the colour presented on the monitor will abruptly switch from one colour to another to denote a change in flow direction relative to the transducer. To lessen this effect the transducer can be moved in a heel–toe action so that the angle of approach to the vessel is altered. This minimises the presentation of this type of artifact by enabling the flow direction to be more easily determined. This technique is also helpful when using a linear transducer with a steered colour box (refer figure 6).

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Figure 6: angle of approach.

(a) linear transducer with steered colour box with the vessel parallel (or flat) to the transducer (b) heel – toeing of transducer improves colour (c) curved transducer with colour box interrogating the aorta which is perpendicular to the ultrasound beam (d) curved transducer with heel – toeing of transducer changes the angle of approach to the aorta making colour coding of flow direction unambiguous.
Aliasing
Aliasing occurs when abnormally high velocities exceed the rate at which the system can record the velocity correctly – that is the Nyquist Limit. Just as the Nyquist Limit affects spectral Doppler, a frequency shift of greater than PRF/2 will be displayed in the colour of the opposite directional blood flow (or opposite channel). True blood flow reversal presents as a colour change, with a distinct area of black between the colours. The presence of black identifies that blood flow is crossing the baseline, and therefore actually changing direction.

The manifestation of colour aliasing can most simply be represented on a colourwheel (refer figure 7). As the blood flow velocity increases in either direction, increasingly bright colours are presented until the aliasing point is reached; this results in a reversal of colour which misrepresents the blood flow as a change in direction. At the point of aliasing the brightest hues of red and blue (in figure 7 represented as pale yellow and pale blue) are adjacent to each other; this phenomenon allows the operator to be wary of where aliasing may be occurring in the final display.

The techniques that are used to eliminate aliasing in spectral Doppler are equally applicable to CFD:

- Increase the PRF or velocity scale;
- Shift the baseline;
- Increase the angle of approach; and/or
- Decrease transducer frequency (refer figure 8).
High colour gain
High colour gain produces colour noise and obscures the true Doppler signal. In order to mitigate this problem, the gain should be set just below the introduction of random colour or speckle (refer figure 9).

Figure 9: colour image indicating excessive gain.

Flash artifact
A flash artifact occurs when there is sudden marked movement of the transducer or the tissue within the field of view such as bowel peristalsis, heart motion, patient movement or sudden transducer movement. The sudden movement produces Doppler shifts everywhere and fills the entire colour box with colour (refer figure 10). To eliminate this artifact the transducer must be held still and the patient must lie still.

Figure 10: flash artifact.
Mirror image artifact
A mirror image artifact can also occur in CFD imaging in a manner similar to that seen in B-mode imaging. This occurs where a blood vessel is located very close to a large, highly reflective surface such as the lung. The subdiaphragmatic region of the liver and the supraclavicular region are common sites for colour mirror artefact (refer figure 11). To eliminate this artifact the operator must change transducer position or alter the sonographic window.

![Image of the supraclavicular region](image.png)

*Figure 11: image of the supraclavicular region shows two subclavian veins. The more anterior vessel is the true vessel with the deeper vessel below the pleura the mirror image, reflecting off the lung apex. Source: Pozniak et al. (1992), p.39.*

Colour Doppler Knobology

**Colour mode**
Colour mode uses Doppler principles to generate a colour image of the mean flow velocity, power or velocity variance. A colour box is overlaid on the 2D image. Its size and position can be adjusted within the 2D field of view by the operator. The velocity and direction of flow in the colour box are represented with different colours for direction and different shades for velocity. The colours used in the colour box are demonstrated on the screen display usually in the top left or top right hand corner of the image. The colours displayed depend on the colour map selected however the colour map is usually defined within the preset.

**Using colour Doppler**
- The trackball/touchpad changes the position of the colour box
- The select key will change the function of the trackball so that it now changes the size of the colour box
- Hitting the select key again will revert the trackball function back to the position of the colour box.
- Some systems will illuminate the colour box with dotted lines to indicate that the trackball changes the size of the box whereas a solid outline means that the trackball changes the position of the colour box.
The colour gain can be adjusted.

To exit colour mode press the colour button again or press the 2D imaging button.

**Advantages of colour Doppler**

- Colour Doppler allows for quick assessment of speed and direction of blood flow.

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**Figure 12**: colour Doppler image – red and blue indicate speed and direction of flow.

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**Colour Doppler controls**

**Box Size**

The depth and width of the colour box can be set by the operator. The depth of the colour box directly influences the pulse repetition frequency (PRF). The higher the pulse repetition frequency the higher the frame rates achievable. Increased frame rates are also achievable by decreasing the width of the box as this decreases the number of Doppler lines required to be calculated. A box that is position superficially in the tissue also increases the frame rate as the signals have less distance to travel and therefore the computing time required to process the information is less resulting in a higher frame rate.

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**Figure 13**: The size of the colour box can be changed. A smaller colour box allows for faster frame rates and increased resolution.
Persistence or frame averaging
Persistence refers to the averaging of Doppler shift estimates from current and previous frames. The persistence controls are used to select the level of smoothing or frame averaging for the image display.

High persistence is used for slow moving organs or objects of interest whereas low persistence is required for fast moving regions of interest such as the heart or fetal heart.

Steering angle
Steering the colour box is necessary when the vessel runs parallel with the skin surface to achieve an optimum Doppler angle. Optimum B-mode imaging is at 90° to the vessel whereas the optimum angle of incidence for colour filling is at 60° to the vessel. A combination of beam steering and probe angulation makes it possible to achieve a beam to vessel angle of around 40° - 70° which is sufficient for adequate colour flow image production and good B-mode visualization. At 90° beam to vessel angle of insonation, there is colour dropout due to the low Doppler shifts at 90°.

The steering angle is applicable to linear arrays only. It is possible to steer the colour beam in a variety of directions with respect to the B-mode scan lines. Most systems provide three standard angles - +20°, 0° and -20°.

![Colour steering](image)

Figure 14: Colour steering – (a) +20°, (b) 0°, (c) -20°.

Note the changes in the representation of the colour display when the steering angle is reversed. Also note the effect of a straight colour box with 0° angle has on the degree of colour filling of the vessel.

Colour gain
Colour gain amplifies or decreases the Doppler shift signal. Too much gain results in excessive noise and detracts from image quality. Too little gain diminishes the sensitivity of the system to detect small flow disturbances.

The colour gain is adjusted to achieve maximum colour filling of the vessel without inducing noise or colour speckle in the surrounding tissue. To achieve the best gain settings the operator needs to...
increase the gain until a little bit of speckle artifact is introduced, then wind the gain down slightly to only just eliminate the speckle artifact.

![Figure 15](image)

(a) set correctly, (b) set too high, (c) set too low and resulting loss of information.

**Colour scale or Pulse Repetition Frequency (PRF)**

Colour scale or PRF is an important control as it increases or decreases the maximum velocity that can be displayed without aliasing. The scale should be chosen to accommodate the range of velocities thought to be present. Too low a scale setting will cause aliasing, whereas a scale setting too high results in a lack of colour filling in the vessel.

- The scale is limited by the maximum depth of field of view. The transmit-receive time for smaller depths is less and therefore higher PRF values are possible.
- The value of the PRF selected in the system preset is broadly defined as arterial or venous, depending on the expected velocities present in the region of interest. Higher velocities are expected in an arterial signal and therefore higher PRF values are required. Low velocities are expected in a venous signal therefore lower PRF values are needed.

The PRF can be altered by the operator to prevent aliasing or to detect low blood flow. As a general rule the PRF should be ideally set at approximately half of the expected velocity of the blood flow in the region of interest.

For example, the carotid artery blood flow is at approximately 70 – 80cm/s in the normal adult. The PRF is therefore set at a velocity range of between 30-40cm/s. Blood flow in the vertebral artery is much slower at approximately 40-50cm/s. The PRF is therefore set lower at a velocity range of approximately 20cm/s. If the PRF is left at 30-40cm/s then colour filling of the vessel will be reduced allowing for poor visualization of the vessel and the spectral trace will be illustrated as a very small trace in a large field of view.
The PRF is determined by various controls such as colour box size and velocity range. The total number of pulses transmitted is divided between the B-mode image, the colour and spectral Doppler image therefore the maximum colour PRF is achieved when spectral Doppler is switched off and the colour box width is decreased as much as possible.

Figure 16: colour scale settings.
(a) too low and resulting aliasing of the colour flow (7.2cm/s), (b) correct for imaging of the carotid artery (43.3cm/s), (c) too high and resulting loss of vessel filling (77.0cm/s).

**Imaging tips**

To eliminate aliasing:
- Increase the velocity scale or increase the PRF; and
- Adjust the baseline.

To increase sensitivity:
- Decrease the velocity scale or PRF;
- Move focal position to the region of interest; and
- Increase the colour gain.

To decrease flash artifact:
- Decrease the colour gain;
- Decrease the depth of field of view;
- Use the zoom function; and
- Decrease the sector size.
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