DOPPLER ULTRASOUND PHYSICS

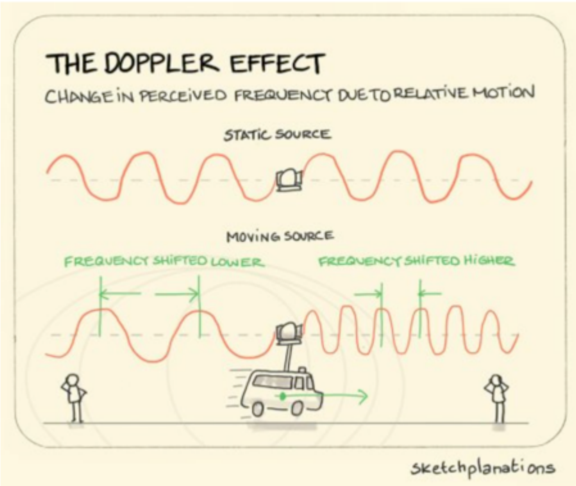
Doppler ultrasound is used to elucidate function, in particular in relation to blood flow in the heart, and in blood vessels. The principles of Doppler ultrasound are based on the Doppler effect.

There are 3 main forms of Doppler ultrasound:

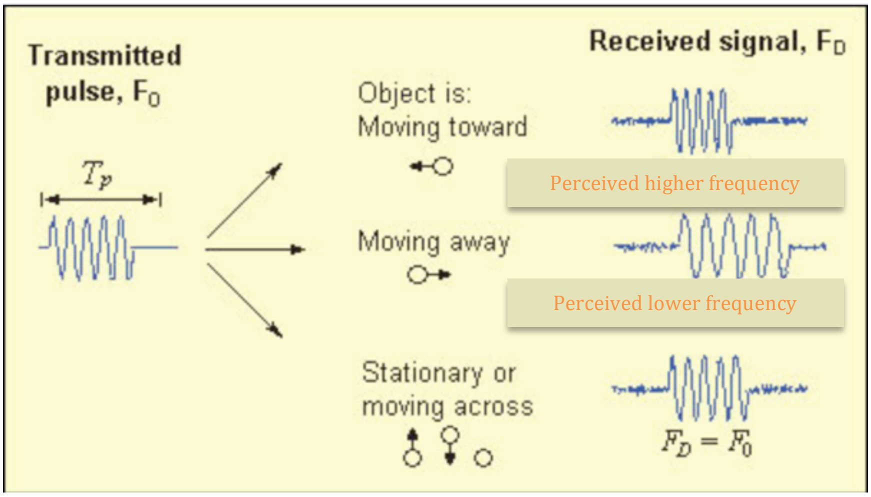
- Spectral Continuous Wave (CW) Doppler
- Spectral Pulsed Wave (PW) Doppler
- Colour Doppler

<u>DOPPLER EFFECT PRINCIPLE</u>

The Doppler effect applies to all wave energy (sound, light, radio waves etc.), the observed frequency changes depending on the direction of wave motion and relative motion of the source and or receiver location. The change in relative frequency is the Doppler shift (Hz).



Above source: Jono Hey - sketchplanations.com



Above source: Sontek (Modified)

DOPPLER EQUATION

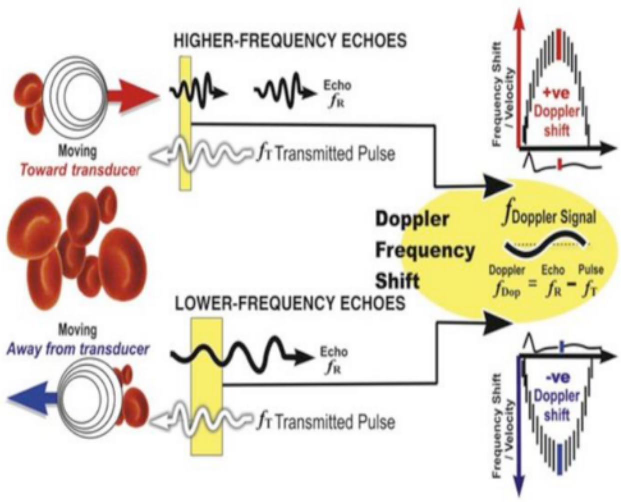
The basis of spectral and colour Doppler is the Doppler equation:

$$\text{Doppler shift (Hz)} = \frac{2f(v\cos\theta)}{c}$$

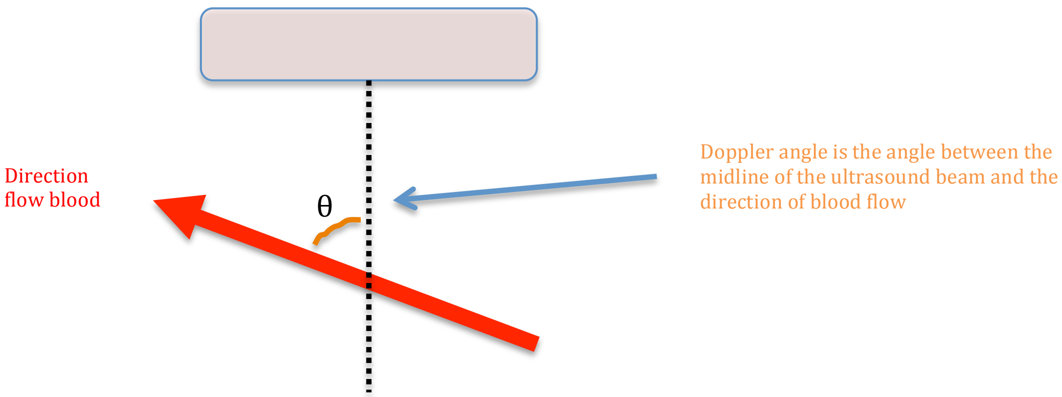
v= velocity of moving blood
f= transmitted ultrasound frequency
c= ultrasound propagation speed in soft tissue
θ= Doppler angle, or angle between ultrasound beam and direction of blood flow

The Doppler Shift:

- The transmitted ultrasound beam is reflected from moving blood and the resulting echoes received by the transducer will have a different frequency
- **The Doppler shift is directly proportional to the velocity of the moving blood away or toward the transducer**
- **The Doppler shift is directly proportional transmitted *f***
- In Spectral Doppler modes the Doppler shift is used to calculate blood velocity, which is displayed over time



Above source Thoracic Key



Rearranging equation:

[$^{2f}/_{c}$] is constant for a given probe frequency

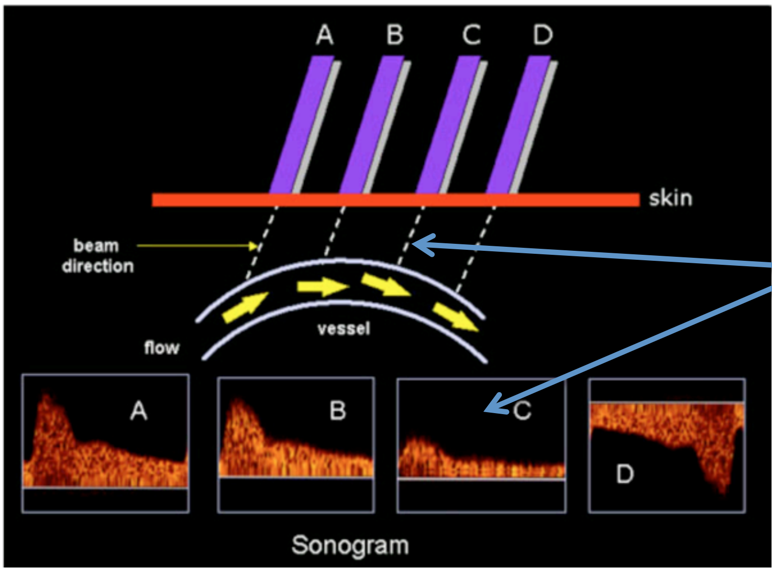
For a given transducer frequency (f) and propagation speed (c) are known

Doppler shift (Hz) = [$^{2f}/_{c}$] x (vcosθ)

- Doppler shift is dependent on the blood velocity and direction of flow relative to the beam (Doppler angle)

Cosine 90°= 0
Cosine 0°= 1

- Hence when the Doppler angle is close to 0° the greatest Doppler shift will occur.
- **As Doppler angle becomes > 60° the potential effect on error in velocity measurement becomes unacceptably high**
- Doppler effect is zero if the angle of the beam is at 90 degrees to the blood flow velocity



C: Angle ultrasound insonation near 90° showing minimal Doppler effect

Above source: Sonoworld

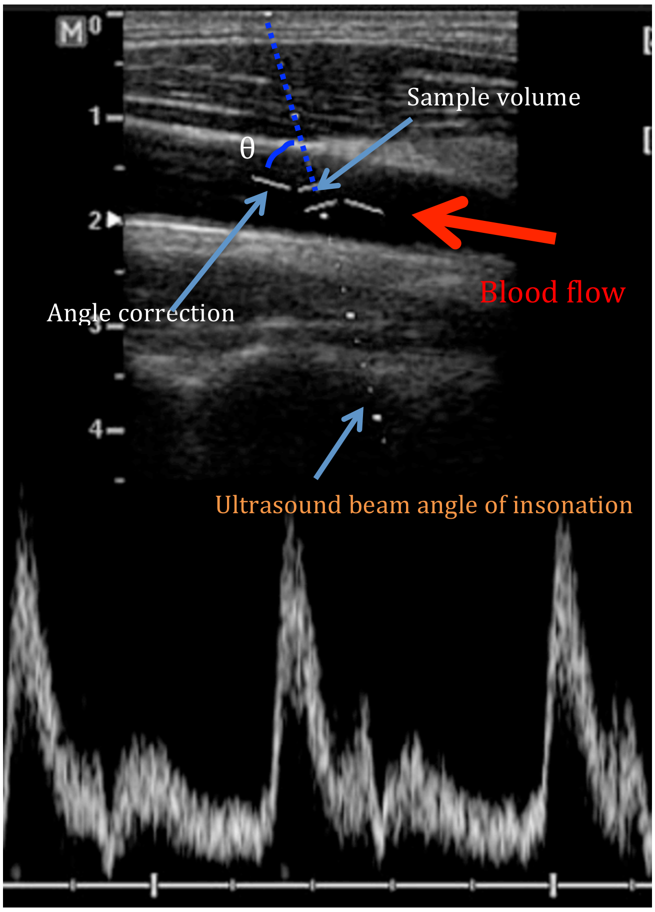
DOPPLER ANGLE θ

Doppler angle is required to measure the Doppler effect, and Doppler velocity accurately.

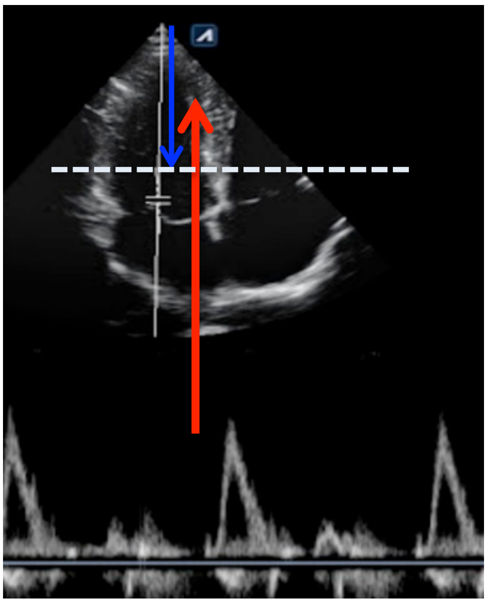
- The ultrasound machine will assume a Doppler angle of zero degrees unless the user applies an angle correction:

- The measurement will be spurious unless the true Doppler angle is near zero

- User can place a PW Doppler sample volume and angle adjustment made to give a measure of the Doppler angle (angle correction Doppler θ≈ 60°)

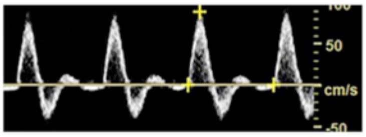


- In echo Doppler measurements are made as near parallel to blood flow direction as possible, and the Doppler angle can be assumed as near 0°.

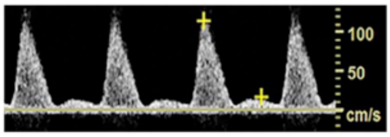


- In some scenarios Doppler cannot be determined, such as in small blood vessels.

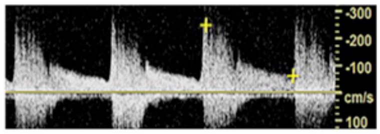
- In this case velocity measurements will not be accurate
- But spectral display (waveform) variation with time will be accurate
- These waveforms can be compared to those of an expected normal or abnormal pattern to establish useful interpretation (see below image)



Laminar triphasic arterial waveform



Disturbed waveform flow



Turbulent waveform

- CW and colour Doppler cannot be readily angle adjusted

- Doppler angle has the same effect on all modes

DOPPLER TRANSMIT FREQUENCY

At a constant Doppler angle and blood flow velocity; a 8MHz transmit frequency will have double the Doppler shift of that of 4MHz.

Doppler shift is directly proportional to transmit frequency

- For low velocity situations which produce smaller frequency shifts, a higher frequency transducer is required

- Doppler of venous flow (lower velocity) will require a higher transmit frequency to detect useful frequency shifts

<u>DOPPLER MEASUREMENT ACCURACY</u>

Spectral Doppler velocity measurements are subject to a number of errors, and hence accuracy can be limited by a number of factors:

- **Uncertainty of blood flow direction, which we assume to be parallel to the blood vessel walls (the most important)**

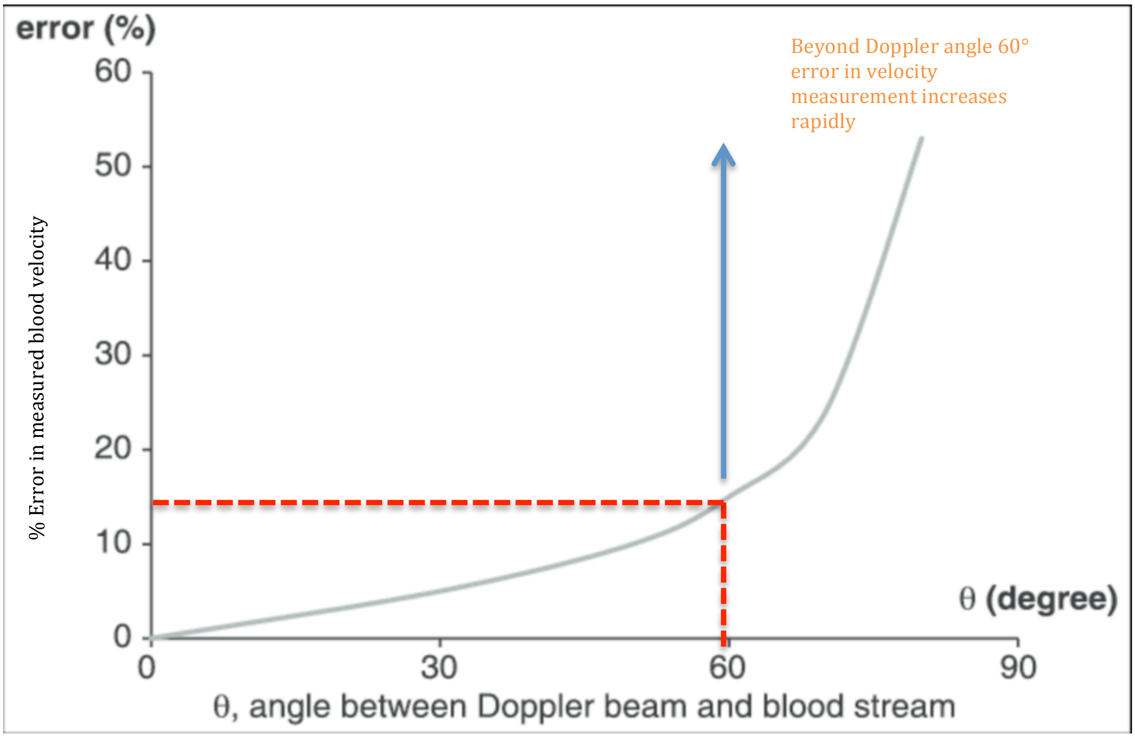
- The ability to measure the Doppler angle, and if feasible in PW Doppler to place an accurate angle correction

- Subjectivity (user dependent) of spectral waveform measurements

- Doppler artifact (intrinsic spectral broadening)

Typically angle markers are placed so they are parallel to the blood vessel walls, as we assume the flow is along this plane. The resulting Doppler angle used may be inaccurate by as much as 5-10°.

The effect of angle error on error in velocity measurement becomes marked as the Doppler angle nears 60°, and beyond this velocity error increases dramatically.



Above source: Hidemichi Imamura et al. - Journal of Endoscopic Ultrasound 2014 (Modified)

- **60° Doppler angle is considered the maximum acceptable angle for velocity measurements**

DETECTING SCATTERING FROM BLOOD

DOPPLER TRANSMIT POWER

The energy of scattered echoes from red blood cells is of low intensity as compared to surrounding tissue. Therefore to obtain useful Doppler the transmit power in Doppler is much higher then in normal Grey scale ultrasound.

- This is achieved by increasing the transmit pulse duration which increases transmit power (reduces spatial resolution)

- As a consequence of increased transmit energy, stationary beam and single line of sight (PW Doppler) potential tissue exposure to the bio effects of ultrasound is greatest in this mode of imaging

TISSUE/WALL FILTERS

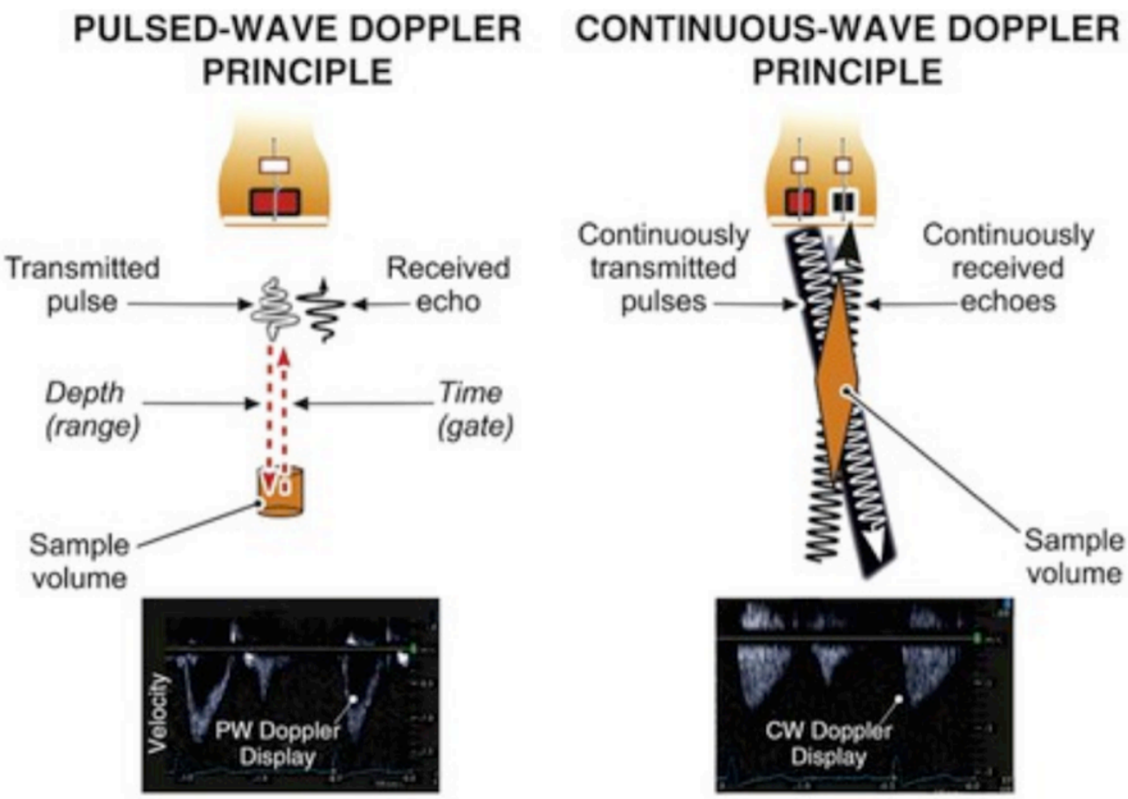
Doppler echoes will be detected from not only moving blood, but also a greater degree from moving tissue, and vessel walls. These will be of much greater amplitude, so these need to be suppressed by the machine in Doppler modes.

- Blood flow velocities are much greater than tissue movement velocity:

- Doppler shift frequencies will be lower from these low velocity tissue origins
- The low frequency Doppler signals will be suppressed by a wall filter utilized in the processing
- The frequency cutoff will be determined by the preset being used (in low velocity venous Doppler the frequency cutoff is much lower)

CONTINUOUS WAVE DOPPLER (CW)

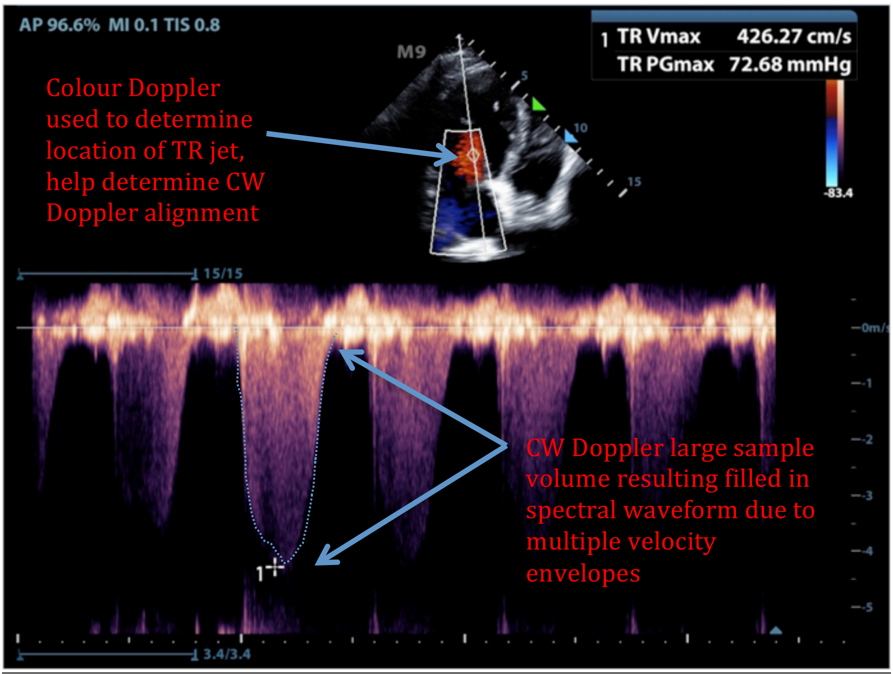
In continuous Doppler the transducer has a transmit and receive aperture with continual transmission beam and reception of echoes. The overlap of the transmit and receive beams is the sample volume.



Above source: Thoracic Key

- The Doppler shift is determined from measuring the difference between the transmitted frequency and the received frequency i.e. Doppler shift.

- The Doppler shift is displayed as a spectral waveform of velocity versus time and also as an audible Doppler signal



Above source: Sonoguide - ACEP (Modified)

- **CW Doppler is excellent for detection of high velocity flows** e.g. TR Vmax (above)

- The **continuous nature also means this mode of Doppler does not suffer aliasing (discussed later)**

- There is however **no range resolution** i.e. cannot determine where along the sample volume the velocities arise from

- CW Doppler waveforms also suffer spectral broadening (filled in waveform)

<u>PULSED WAVE DOPPLER (PW)</u>

This mode of Doppler uses short transmit pulses utilizing the Pulse Echo Principle as in normal grey scale imaging.

- A small sample volume can be positioned within the grey scale image in a required location (Stationary line of sight)

- Angle correction can be applied if the direction of blood flow is known

- As long as the Doppler angle is ≤ 60°, and this has been accurately placed then velocity can be accurately measured from the spectral display produced

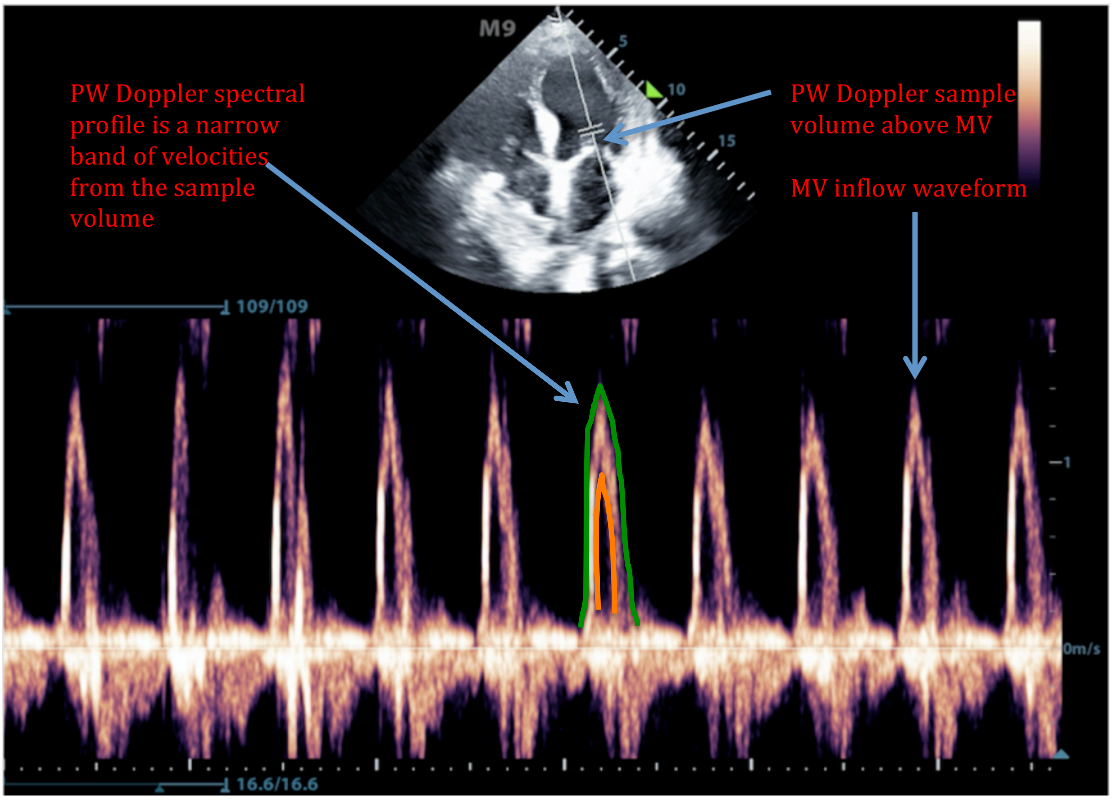
- Sample depth along the line of sight is determined by the machine using range-gating

- After a transmit pulse, a fixed time occurs before a short sample of the echoes is acquired

- The delay to the range gate is calculated by the machine to ensure echoes sampled come from the required sample volume

Time to range gate= 2x depth/ propagation speed

- As with CW Doppler, PW Doppler is presented as a spectral waveform and also in an audible manner



Above source: Sonoguide - ACEP (Modified)

- PW Doppler **can provide accurate quantitative measurement of velocity from a specified sample location**

- PW Doppler has **accurate range resolution**

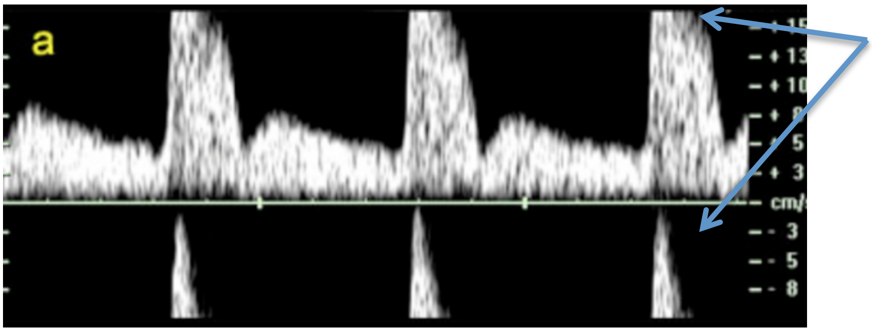
- **Cannot measure very high velocities due to aliasing**, which is dependent on the Doppler PRF

PW DOPPLER PULSE REPETITION REQUENCY (PRF)

The number of transmit-receive cycles each second is the Doppler PRF. The upper limit of the Doppler shifts detectable (**Nyquist Limit**) by the ultrasound machine will be ½ the PRF i.e. if the PRF is 1500Hz the maximum Doppler shift detectable = 750Hz.

Nyquist Limit = PRF/2

- Beyond the Nyquist Limit aliasing will occur
- Higher Doppler PRF enables higher Doppler shift detection



Aliasing of spectral waveform of positive velocities wrapped above and below the baseline

This can be overcome to a point by dropping the baseline, and increasing the PRF depending on the severity of aliasing

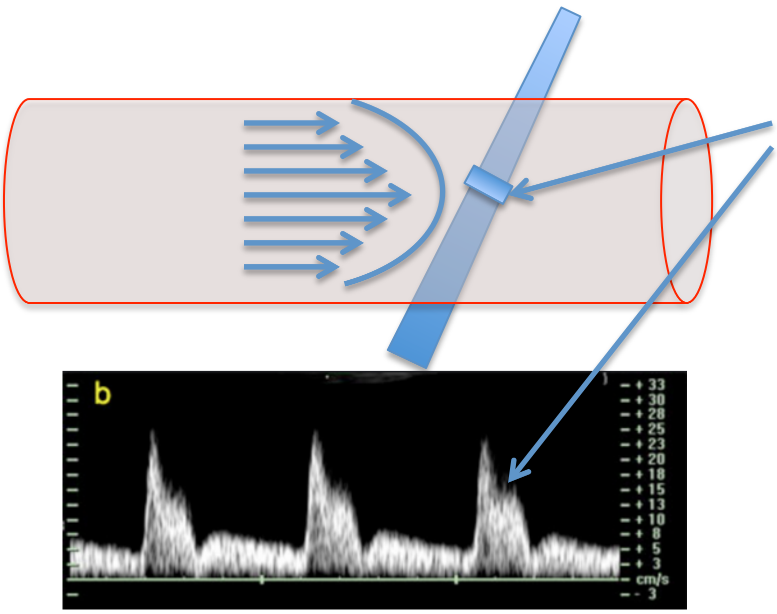
Above credit: Sonoguide - ACEP

HIGH PRF PW DOPPLER (MULTI-GATED)

This is a form of PW Doppler that as additional sample volumes, where multiple range gates are sampled simultaneously by different elements of the transducer along the same line of sight.

- The higher PRF means a higher Nyquist Limit for high velocity large Doppler shifts
- The downside is that the spectral waveform losses spatial resolution (a more blurred waveform is displayed)

<u>SPECTRAL WAVEFORM</u>



Sample volume contains blood flowing at different velocities; this is displayed on the spectral waveform

- By convention blood flow travelling toward the probe is displayed above the baseline, and that travelling away below the baseline.

  - This can be inverted by the user for particular applications

  - It is important to determine the expected direction of flow when using Doppler

- In PW Doppler the velocity scale can be adjusted up or down, this simply increases or decreases the PRF to enable large or small Doppler shifts to be detected

<u>COLOUR DOPPLER</u>

Colour Doppler provides qualitative information about Doppler shifts; this depends on the Doppler angle and the velocities encountered. Doppler shifts are measured at a large number of sample points (each pixel is a sample point) within the colour box.

- Transducer elements a switched rapidly between grey-scale imaging and colour to give a dynamic overlay.

- Information collected is combined to give three variables:

  - Mean Doppler shift frequency
  - Variance (measure of spectral broadening)
  - Doppler signal power (intensity – used in power Doppler modes)

COLOUR DOPPLER ACQUISITION

A colour box is placed over the area of interest; the colour box can be adjusted in height and width depending on the application.

- Multiple lines of sight are taken across the colour box, with a large number of sample points per line of sight

  - Only a small number of transmit pulses are generated per line of sight sample point

  - For each transmit pulse multiple range gates are taken at varying time intervals (compared to one for PW Doppler)

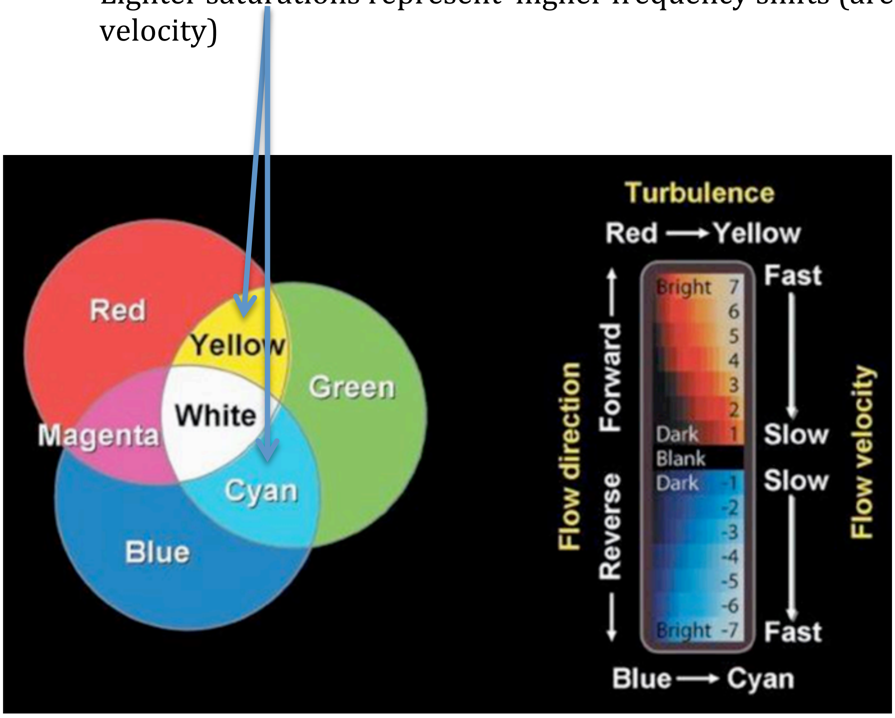
- Frequency shift data obtained from these multiple sample volumes is analysed for mean frequency, variance, and signal power.

- Rapid acquisition is possible by using a defined colour box, using a small number of transmit pulses per line of sight, having multiple range gates, and having a relatively narrow colour box.

COLOUR DISPLAY

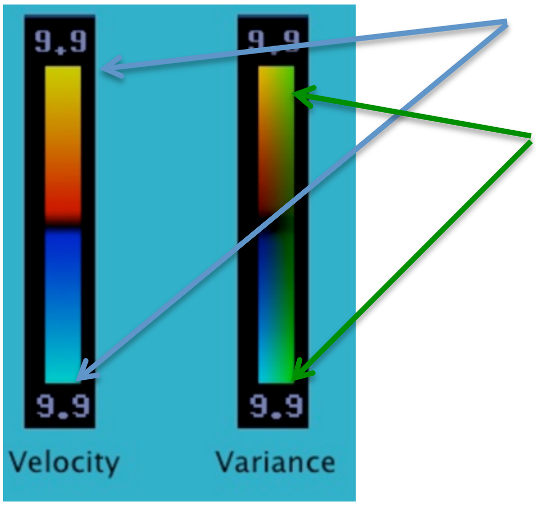
Assignment of color to frequency shifts is based on direction and magnitude of the shift:

- Red for Doppler shifts towards the ultrasound beam/probe and blue for shifts away from it (This can be reversed by the operator)
- Lighter saturations represent higher frequency shifts (areas of higher velocity)



- Variance of Doppler signal is a measure of spectral broadening and essentially represents areas of turbulent flow

- This is generally represented by green on the colour map
- Bright green represents the most severe turbulance

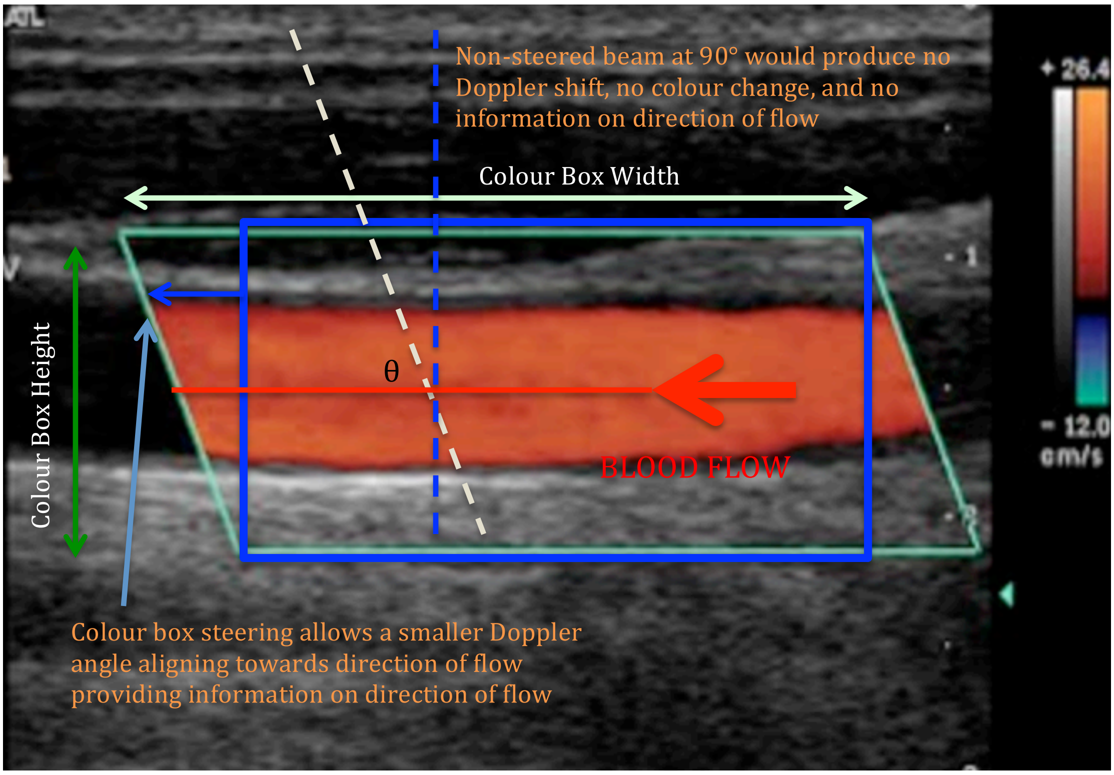


The tops of the colour bar represents the velocities at the Nyquist Limit (= PRF/2) assuming the Doppler angle is 0°

Variance of Doppler signal (Green colour bar)

COLOUR BOX

The size of the colour box is adjusted to required position but also to optimise the frame rate (FR)



- Reducing the colour box width reduces the number of colour lines of sight and therefore the number of transmit pulses required, resulting in improved FR (increased PRF)

- Reducing the colour box height will have minimal effect on FR as the same number of lines of sight are required

- Reducing the depth of the colour box will increase FR as time delay to reception of echoes is reduced, improving PRF (required pulse transit delay is less)

In vascular applications the colour box can be steered using a linear array to optimise the angle of insonation to give information on direction of flow

COLOUR DOPPLER APPLICATION AND UTILITY

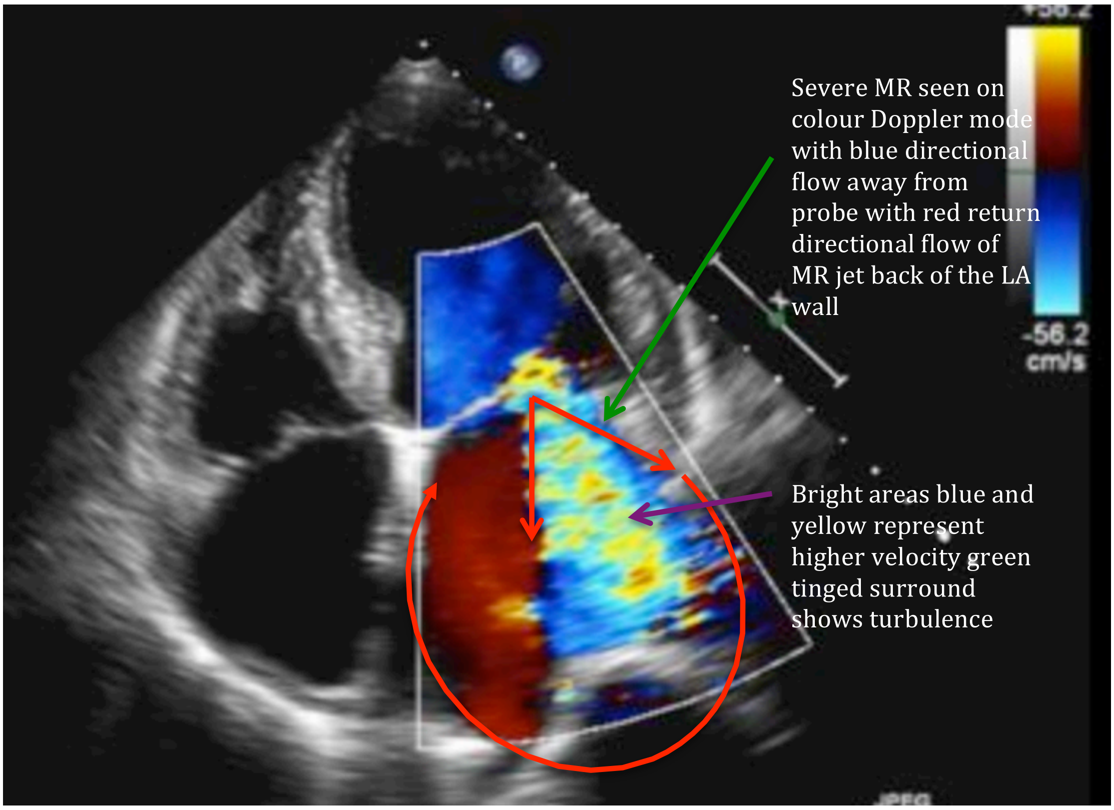
Colour Doppler has a number of limitations due to the inability to angle correct at points within the colour box, and requirement for rapid acquisition/processing of echo information:

- Does not detect small Doppler shift/low velocity well; the scale/PRF needs to be optimised depending on application

- Less effective tissue filters
- Less accurate measures of Doppler shifts

Colour Doppler has important applications in a variety of areas including:

- Echo (e.g. qualitative assessment of valvular regurgitation, turbulence)
- Placement of PW Doppler sample location
- Identifying vessels and vascularity, areas of flow
- Helping establish directionality of flow



Source: MYHEART.net (Modified)

POWER COLOUR DOPPLER

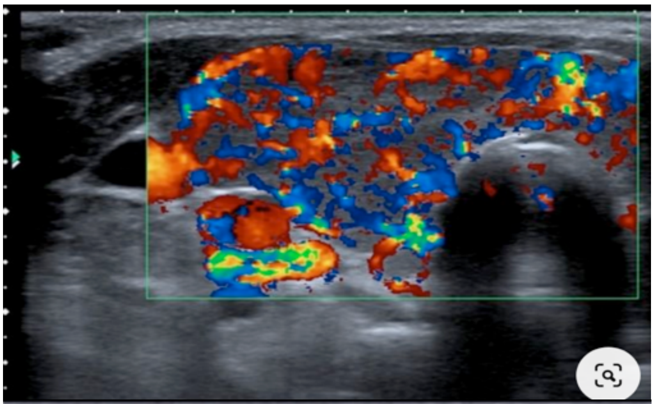
This is a simplified mode of colour Doppler where only the Doppler signal power is used to display a single colour of varying brightness depending on signal intensity.

- This is useful in applications where the normal colour Doppler display variation can be hard to interpret.

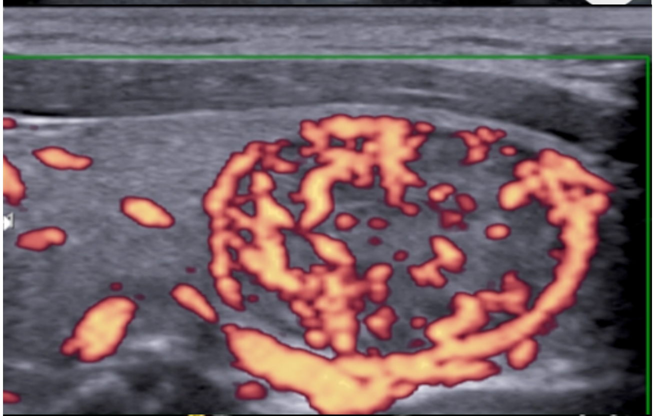
- Uses include superficial structures; like thyroid, testis, renal grafts and subcutaneous lesions.

- It may be used to look for tumor vessels

- To evaluate tiny low-flow vessels and detect subtle ischemic areas.

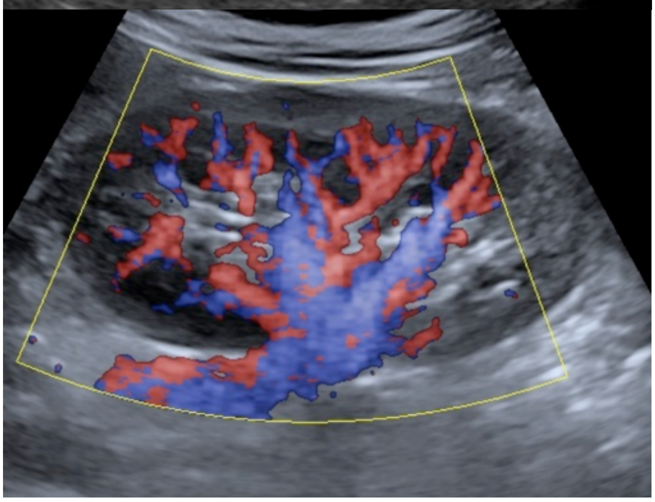


Colour Doppler of Thyroid Gland



Power Doppler of Thyroid showing vascular adenoma

Power Doppler of Kidney



Directional Power Doppler of Kidney

Directional power Doppler retains information on flow direction (red towards probe, blue away from probe)

ADVANTAGES OF POWER COLOUR DOPPLER

- The variable Doppler power signal is easier to detect than the Doppler shift for weak echoes

- Useful for detection of weak echoes, small vessels and low velocity states

- Also power Doppler signal is detected even when the Doppler angle is 90° (i.e. no Doppler shift detected), this is due to spectral mirror artifact. Normal colour Doppler will display no flow at a Doppler angle of 90°.

- Power Doppler is not affected by aliasing artifact unless a directional mode is used

DOPPLER ARTIFACTS

SPECTRAL DOPPLER ARTIFACTS

ALIASING

This is the most common spectral Doppler artifact and occurs with PW Doppler at high velocities when the Doppler shifts are above the Nyquist limt which is =PRF/2.

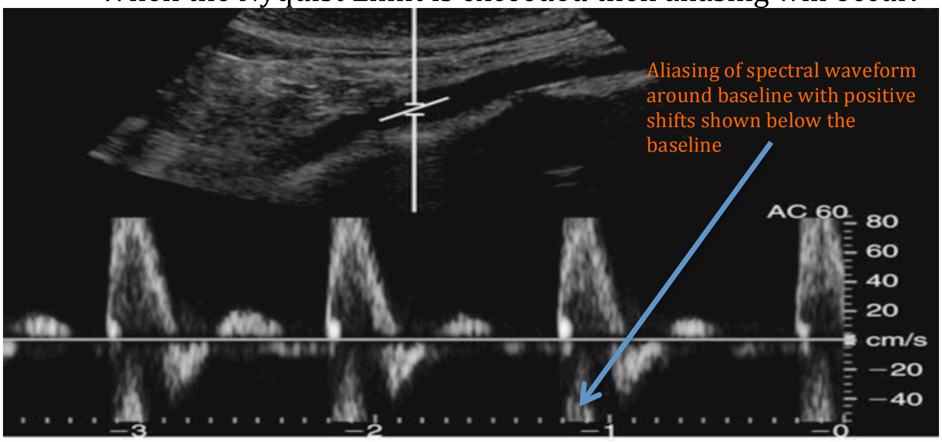
- Aliasing generally does not indicate abnormal physiology, but instead the velocities are exceeding the set parameters.

To detect the Doppler shifts correctly the Doppler PRF must be greater than two times the Doppler shift frequency ($f_{Doppler\ shift}$)

$$\mathbf{PRF > 2}f_{Doppler\ shift}$$

Rearranging this to: $f_{Doppler\ shift} < PRF/2$ (this is the Nyquist Limit)

- When the Nyquist Limit is exceeded then aliasing will occur.

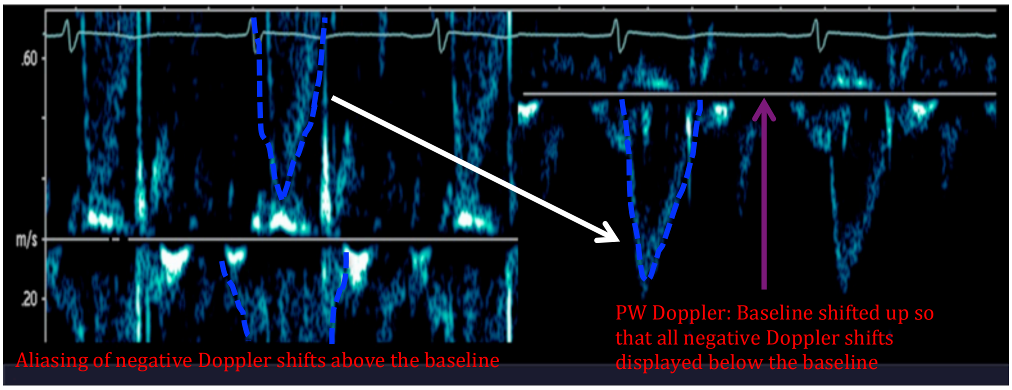


Source: Radiology Key (Modified) 1

OVERCOMING ALIASING

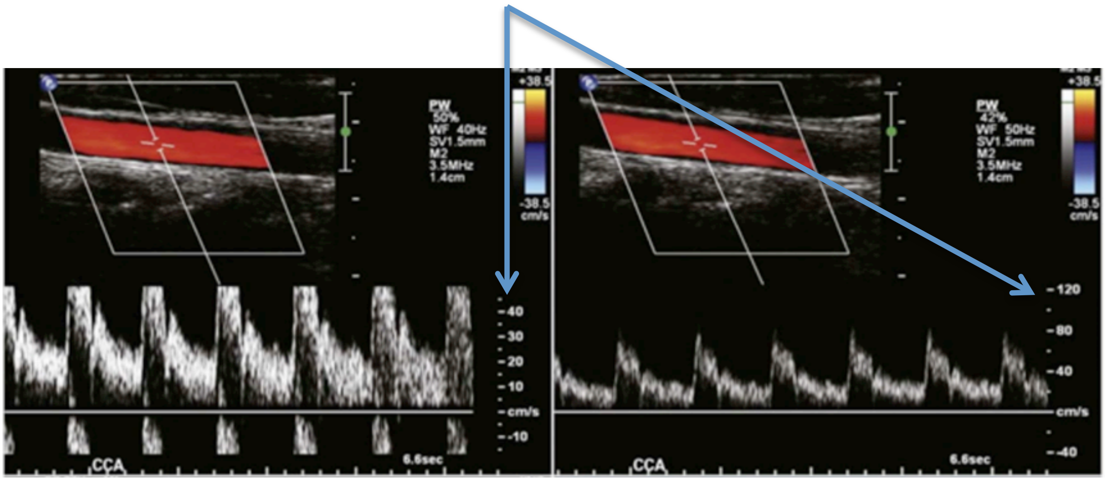
- The first method is to **shift the baseline**, this can be moved up or down so that the majority of the spectral display is either above or below depending on the direction of Doppler shift.

- The consequence is reduced display in the opposite direction, but this is usually not an issue as the largest shifts will be unidirectional



- When aliasing is severe altering the baseline will not be able to overcome the aliasing alone, so other methods can be employed:

- **Increasing the velocity scale**, this increases the Doppler PRF), which is limited by depth of penetration (PRF inversely proportional to depth)



Source: Kasia's E-portfolio

- **Reducing the Probe frequency of transmission** will reduce the Doppler shift magnitude (Doppler shift is directly proportional to frequency of transmission)
- **Increase the Doppler angle** (acceptable angle limited to ≤60°), but often not possible due to anatomy and practical reasons

- CW Doppler is not affected by aliasing; **using CW Doppler** instead of PW will allow interrogation of areas of higher velocities that may be of interest

INTRINSIC SPECTRAL BROADENING

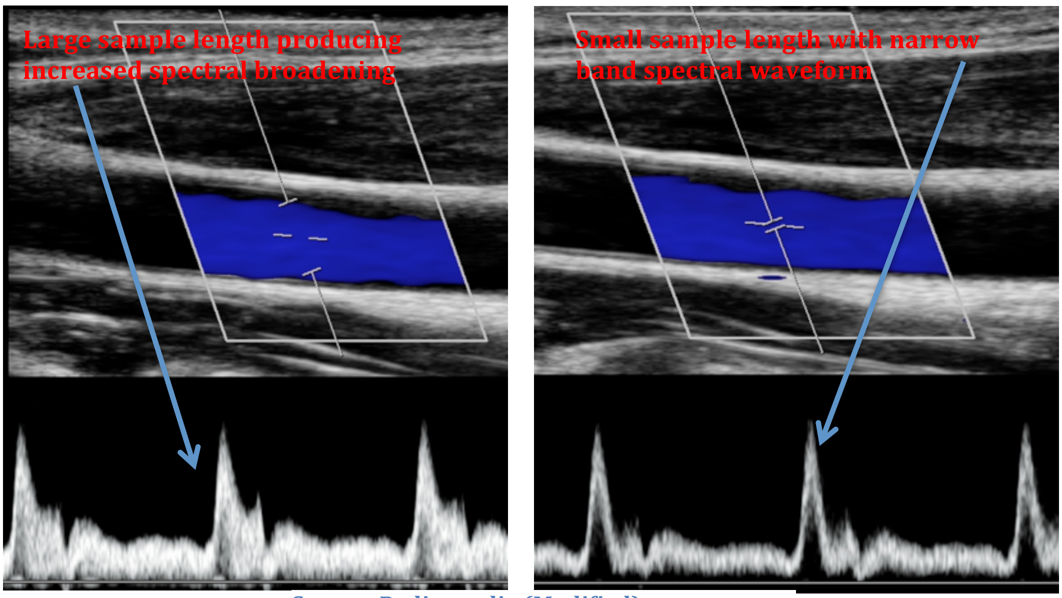
This occurs as the aperture on the transducer used to create the transmitted beam produces paths for transmission and reception at a variety of Doppler angles, which in turn produce different Doppler shifts from within the sample volume.

- The larger the aperture the greater the intrinsic broadening, so generally the aperture is kept small for PW Doppler

  ➢ The consequence of a small aperture is a larger beamwidth and reduced spatial resolution in this mode

- More superficial vessels will have greater intrinsic broadening.

- Doppler angles closer to 0° (in line with beam) will have reduced spectrum of Doppler shifts, hence reduced intrinsic broadening.



Source: Radiopaedia (Modified)

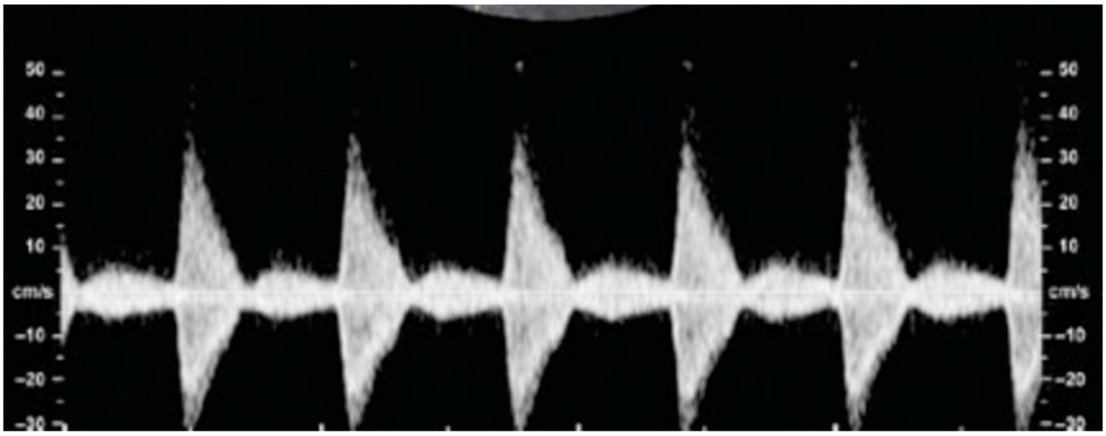
- The importance of intrinsic spectral broadening is that it has an influence on accuracy of spectral waveform measurements, but also can mimic or mask true pathologic spectral broadening which occurs in turbulent blood flow (e.g. stenotic blood vessel)

SPECTRAL MIRROR ARTIFACT

This presents as a mirrored spectral waveform on both sides of the baseline, and occurs usually when the Doppler angle is close to 90° and you would expect no Doppler shift.

- The mirrored waveform is a result of intrinsic spectral broadening. This will increase as the Doppler angle is closer to 90°. The effect is magnified by the high Doppler angle interrogating the sample volume at a multitude of slightly different angles

- The spectral waveform is entirely artifactual



Source Jaypeedigital.com

- It is more common when Doppler gain is too high and the PW Doppler cursor is close to the midline of the transducer (closer to 90° incidence)

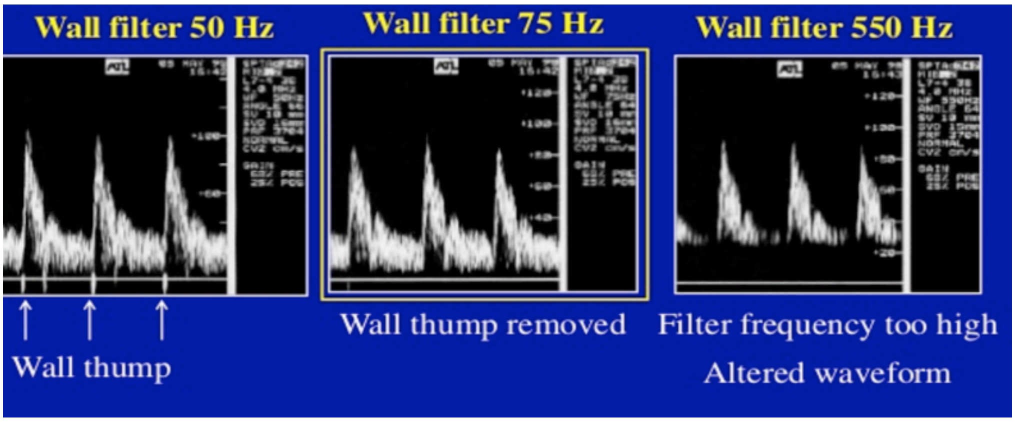
MIRROR ARTIFACT

If grey-scale mirror artifact is created, mirroring of a blood vessel/vascular structure occurs. Then this mirror image will also be able to be interrogated by Doppler producing a similar spectral waveform to the true image. The waveform is often reduced in intensity due to effects of attenuation.

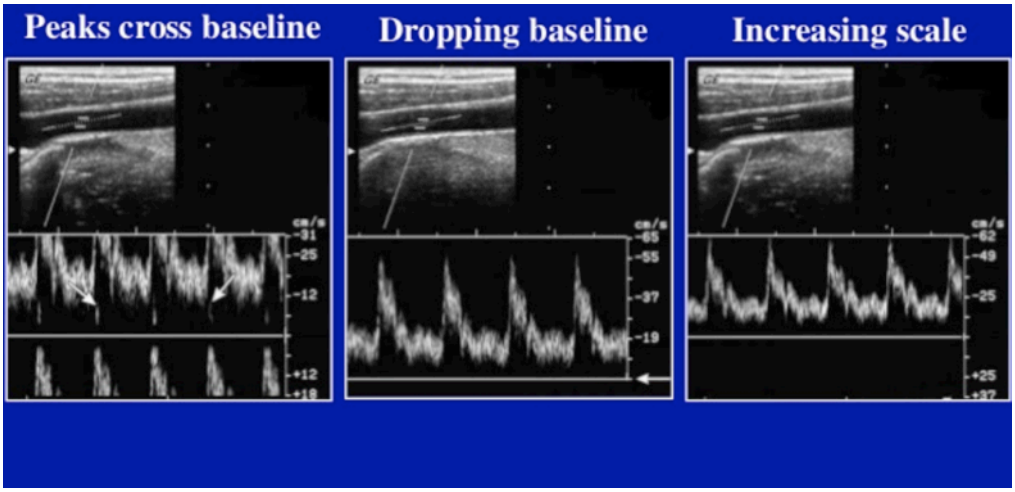
INSTRUMENTATION DOPPLER ARTIFACT

Adjusting certain machine settings will affect the clarity of the spectral Doppler waveform shown and potential artifacts, these include:

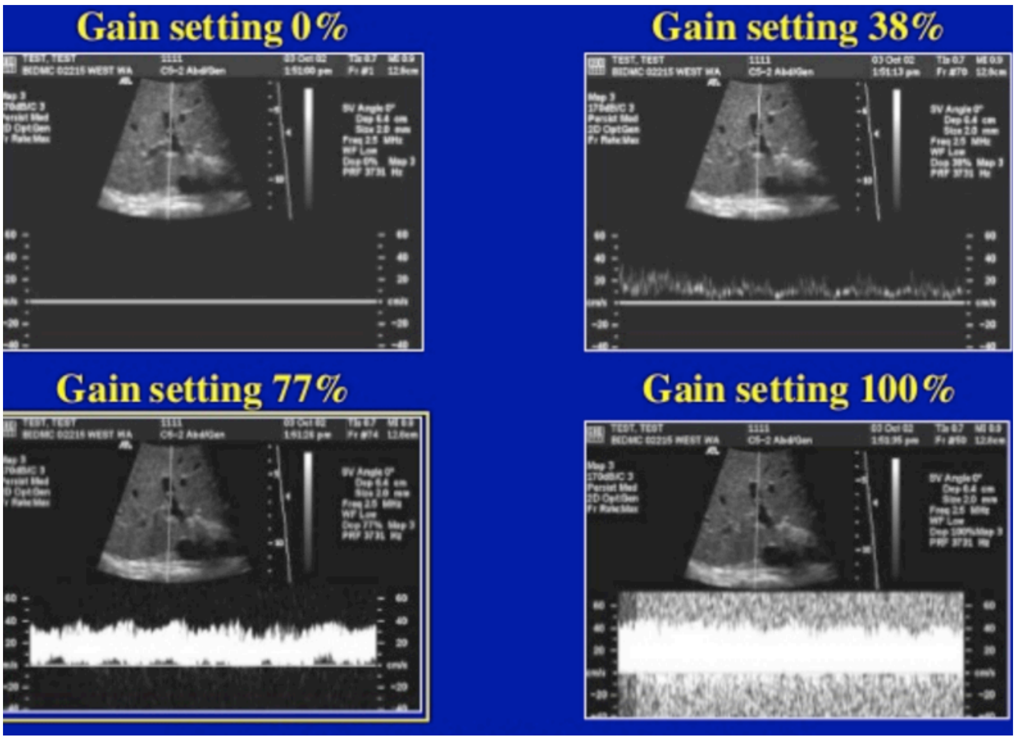
- Wall filter cut off
- Baseline adjust and scale
- Doppler gain
- Doppler Sample volume size (see spectral broadening image above)



Source: Samir Haffar- Principles Doppler



Source: Samir Haffar- Principles Doppler



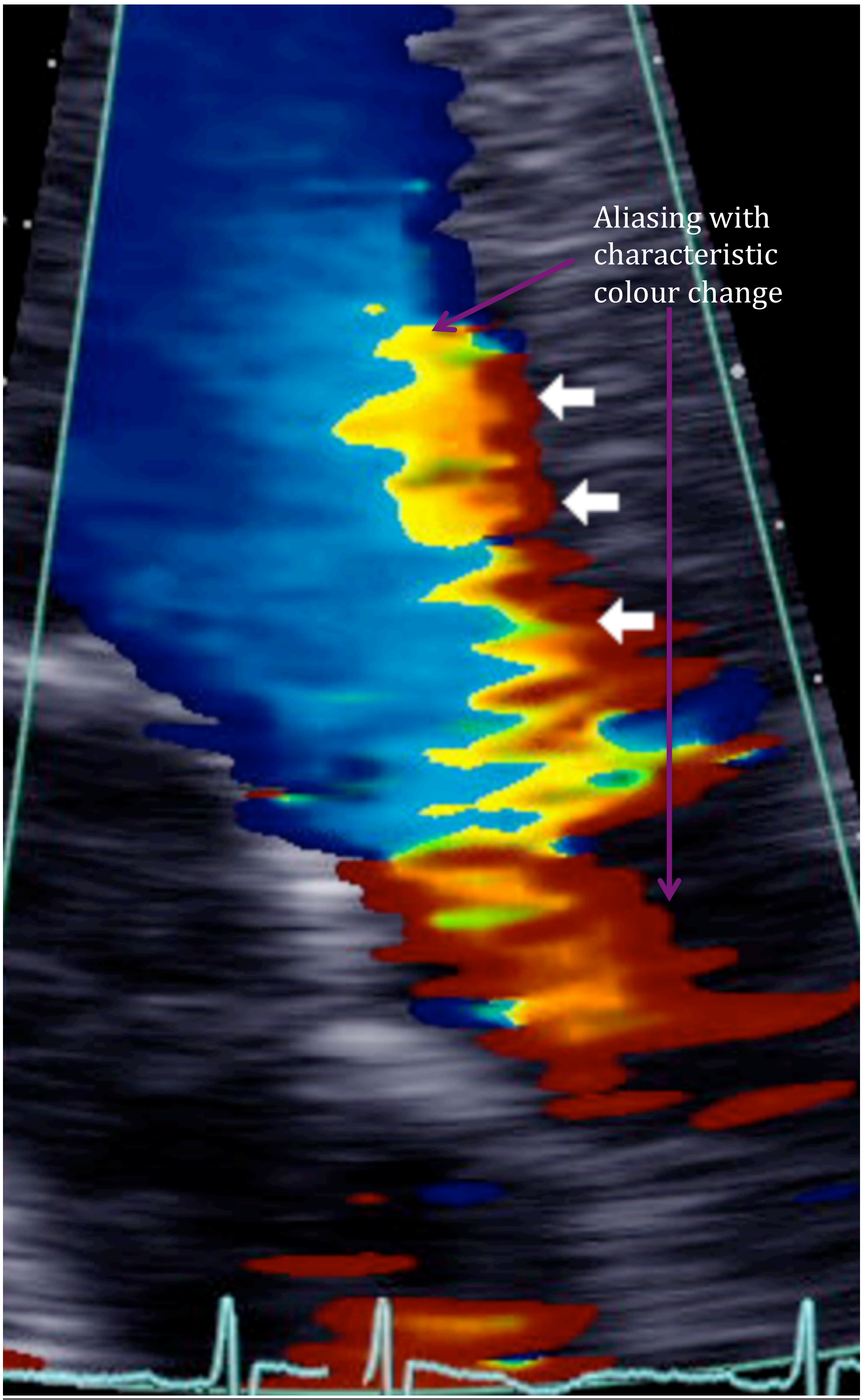
Source: Samir Haffar- Principles Doppler

COLOUR DOPPLER ARTIFACT

COLOUR ALIASING

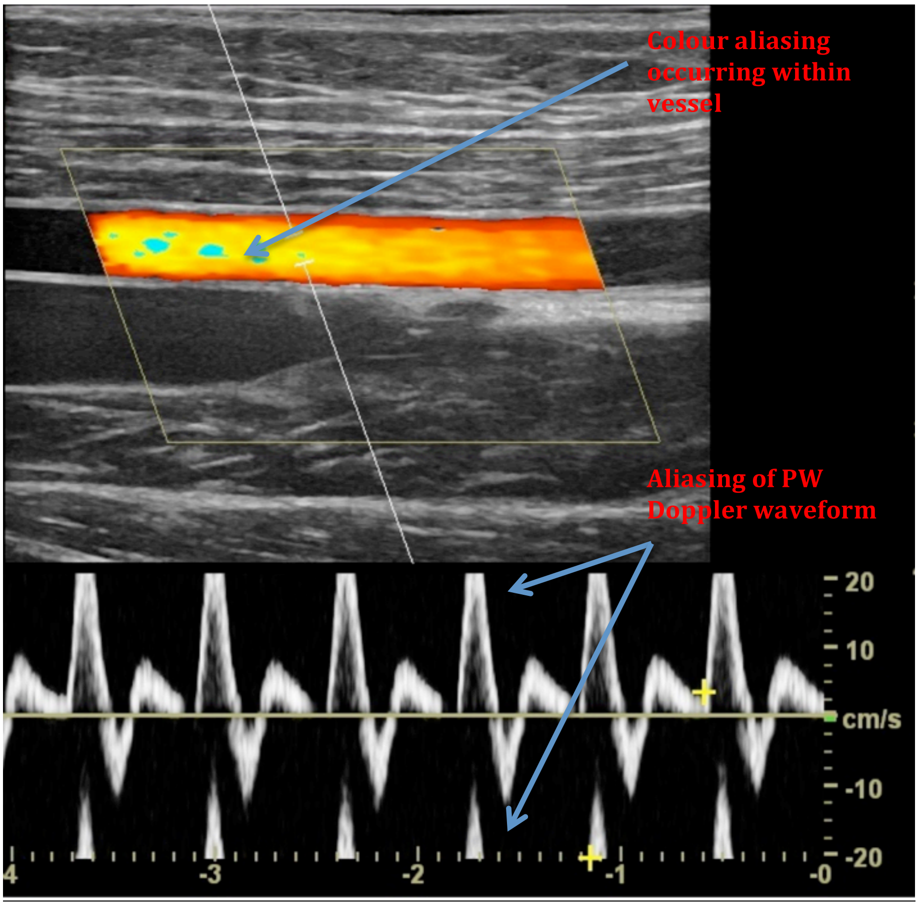
- Colour aliasing will occur as a change in colour from red to yellow to green to blue artifactually suggesting change in flow direction.

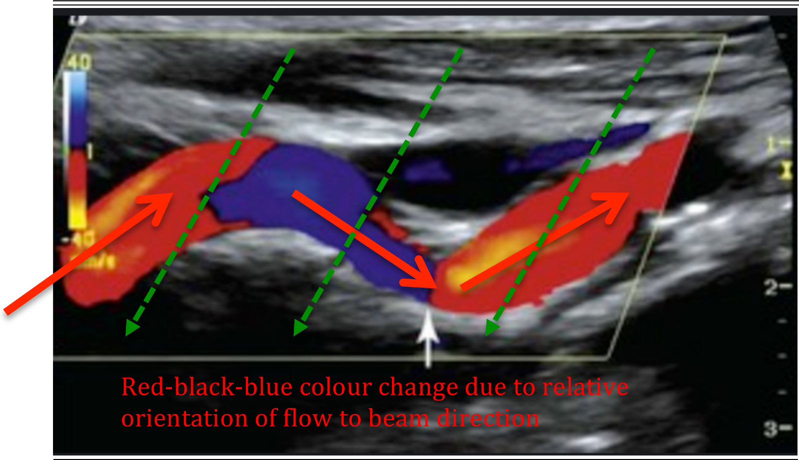
➢ True directional change is represented by colour change from red, through black, to blue.



Source: Echo.Guru

Below source: Thoracic Key



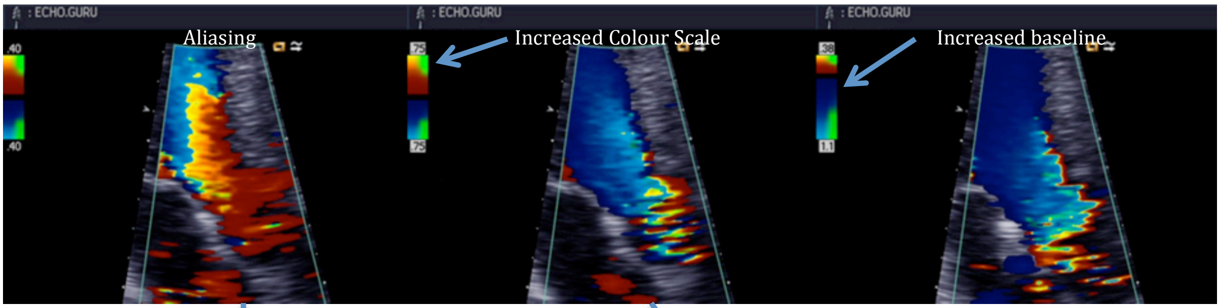


Above source: EPOS - European Society of Radiology (Modified)

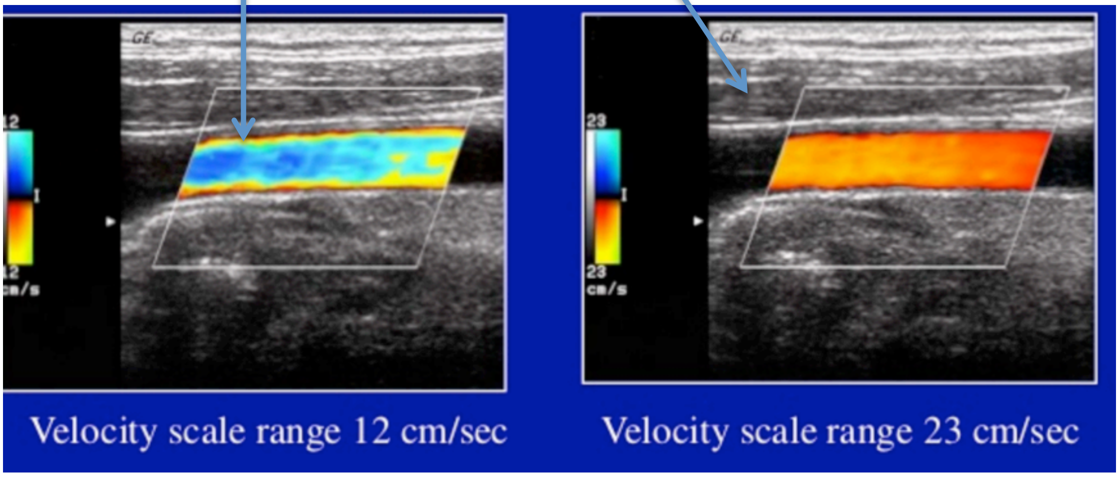
- In situation when blood flowing in a vessel is at a constant angle to the transducer. Colour aliasing can be useful as a sign of high velocity/high Doppler shift representing turbulence and potential pathology

To determine if aliasing is occurring the user needs to look at the nature of colour change as discussed above.

- ➢ Change from red/yellow to green/blue is aliasing
- ➢ Adjusting the colour baseline (as with PW Doppler) can reduce and may eliminate aliasing, or similarly increasing the colour velocity scale



Source: Echo.Guru

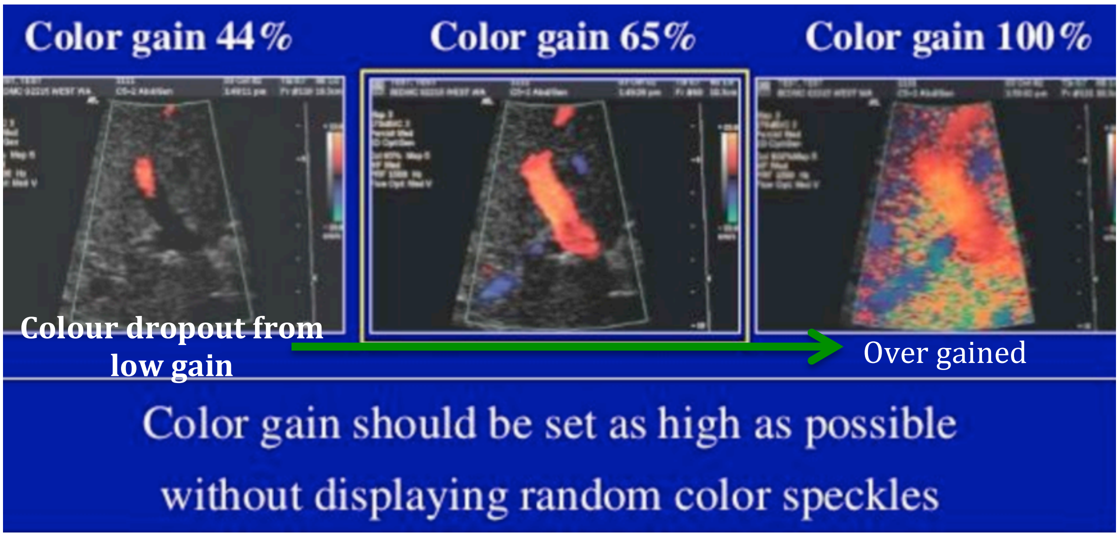


Source: Samir Haffar- Principles Doppler

COLOUR DROPOUT

This may be related to a number of issues due to settings, depth of the imaged vessel (attenuation), Doppler angle, low velocity of flow (small Doppler shifts):

- Colour Gain



Source: Samir Haffar- Principles Doppler (Modified)

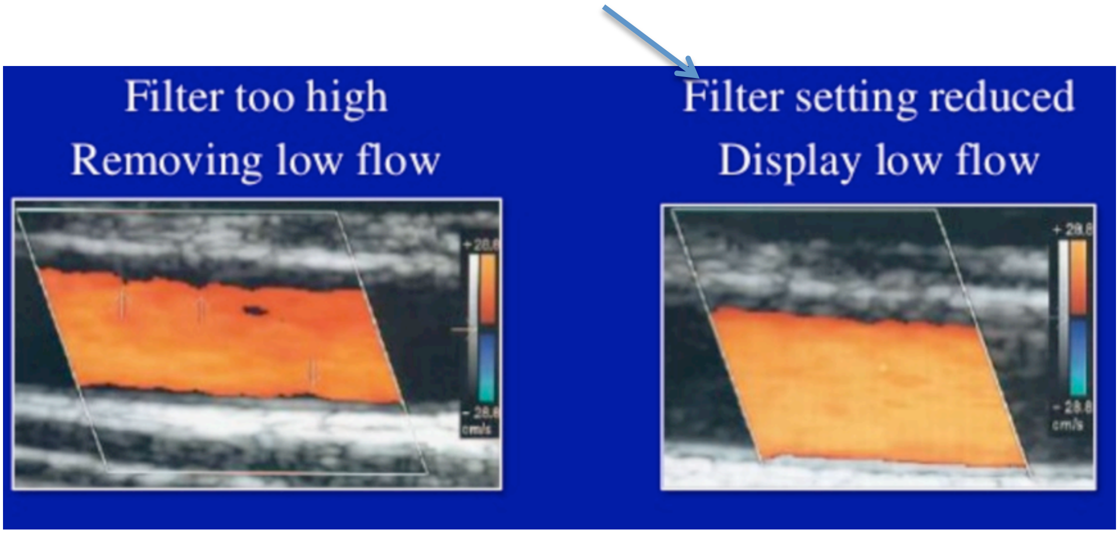
- Orientation of the probe to the vessel – Doppler angle should be < 60°

- Use a lower frequency probe for deep applications, increasing penetration depth

- Ensure appropriate vascular preset (i.e. venous for low velocity flow)

- Reduce colour velocity scale (if over scaled wont detect low velocity Doppler shifts)

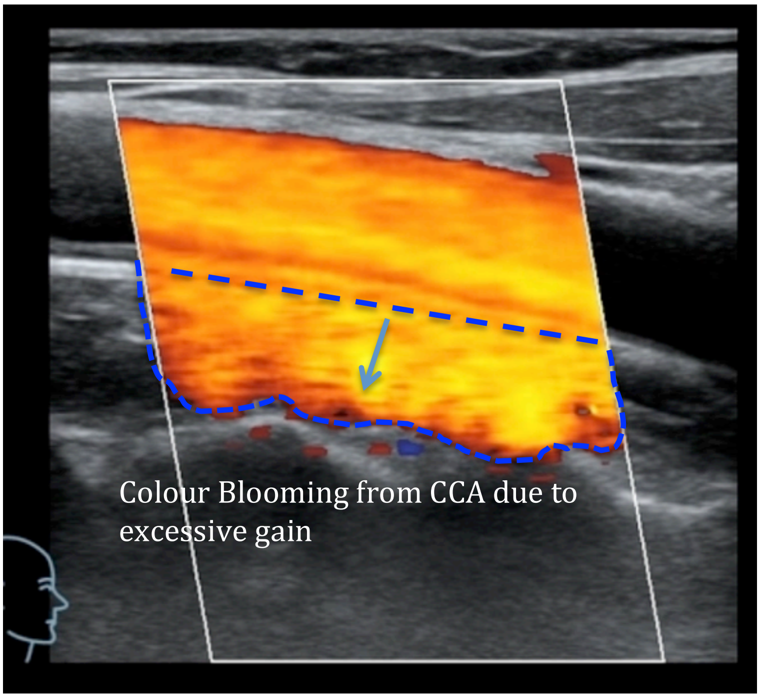
- Reduce wall filters (these cut out low frequency Doppler shifts)



Source: Samir Haffar- Principles Doppler

COLOUR BLEEDING OR BLOOMING

This is usually related to excessive gain



Source: Radiopaedia (Modified)

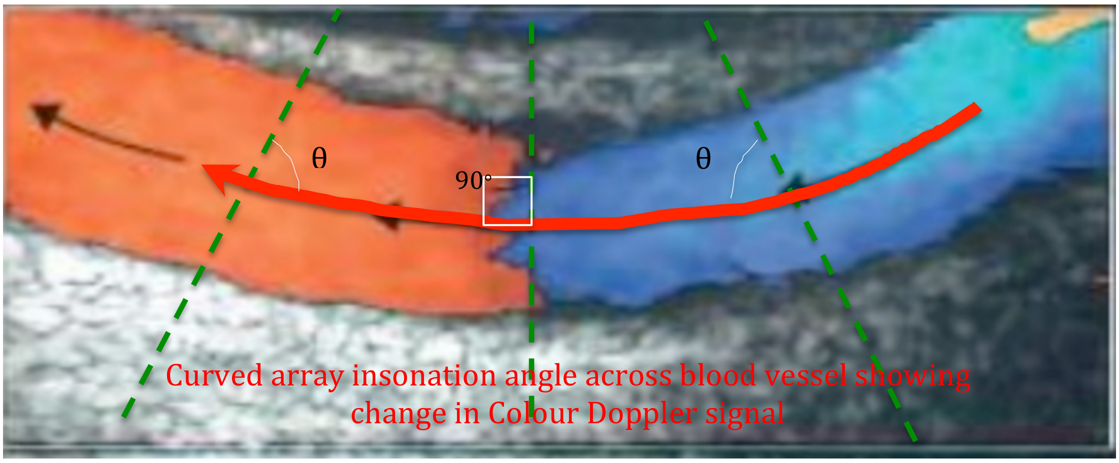
Source: Samir Haffar- Principles Doppler

- Other causes of colour bleed may be the Colour velocity scale being too low, wall filter set too low

ANGLE OF INSONATION EFFECT

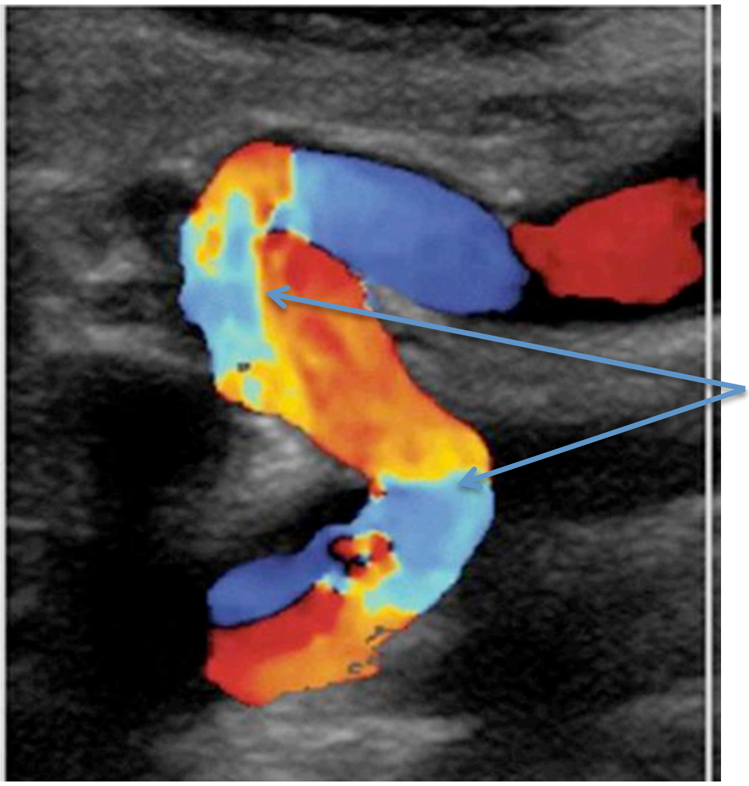
Using phased or curvilinear arrays the beams differ in direction meaning different Doppler angles will occur.

- The Doppler shifts detected depend on the velocity of the blood, but also the Doppler angle
- The Doppler angle has obvious effect on display of colour across a vessel



Source: Samir Haffar- Principles Doppler (Modified)

Curved and tortuous vessels may present a more complicated Doppler colour display. As the angle of incidence nears 0° the Doppler shifts produced may be very large resulting in aliasing. This may be misinterpreted as increased velocity and turbulence when it is artifact.

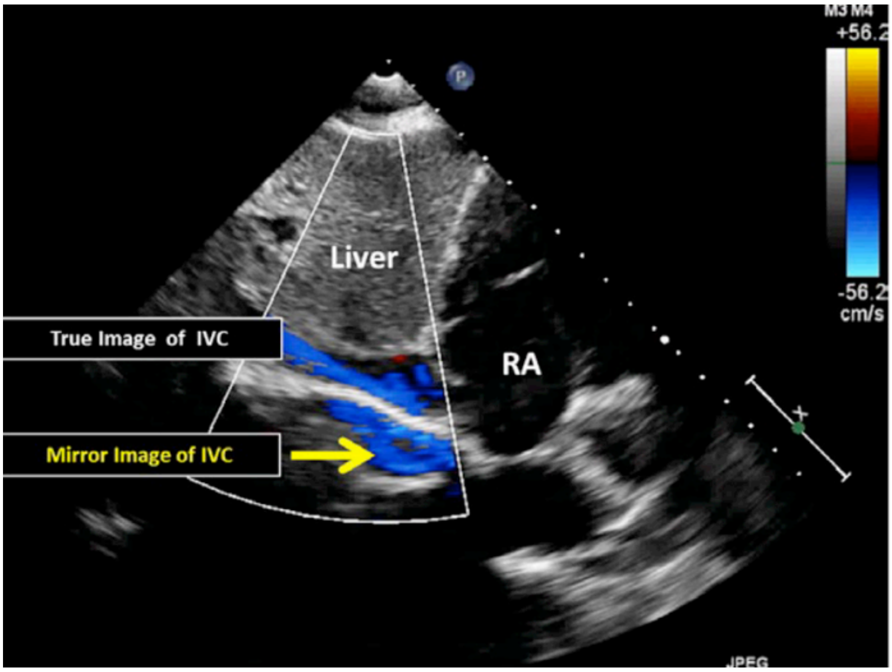


Source: doctorlib.info (Modified)

MIRROR IMAGE COLOUR DOPPLER

Mirror imaging occurs in colour Doppler, as in spectral Doppler, when vessels or heart mirror images are created in grey-scale.

- Depending on the orientation to the reflector the mirror image may have flow in the same direction or in opposite direction to the true image



Source: saric.com

TWINKLE ARTIFACT

This is caused by small calcified or crystalline structures producing colour Doppler echoes.

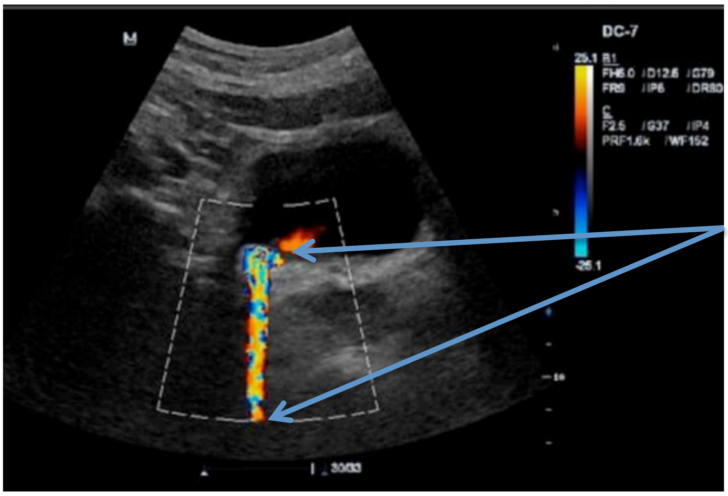
- It occurs as a focus of alternating colors on Doppler signal behind a reflective object, which gives the appearance of turbulent blood flow

- It appears with or without an associated color comet-tail artifact

It is a highly useful sign of small calcifications such as ureteric stones or renal stones.

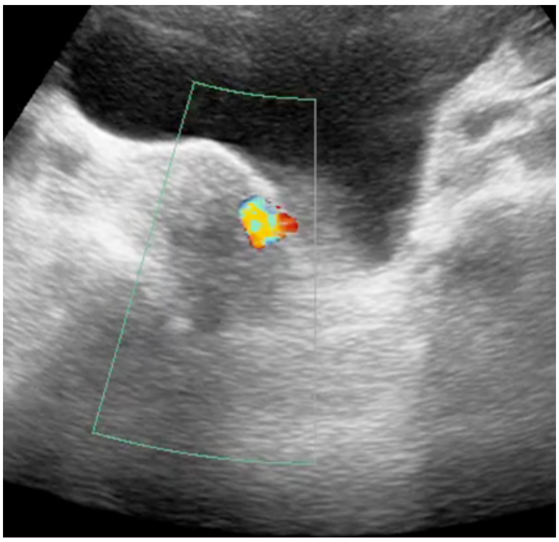
Twinkle artifact is increased:

- When the focal zone is located below reflecting surface
- A lower PRF facilitates better visualization of the artifact



Twinkle artifact from VUJ stone with associated comet-tail

Source: Radiopaedia



VUJ twinkle artifact

Source: theempulse.org

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