Basic Principles of Doppler Ultrasound

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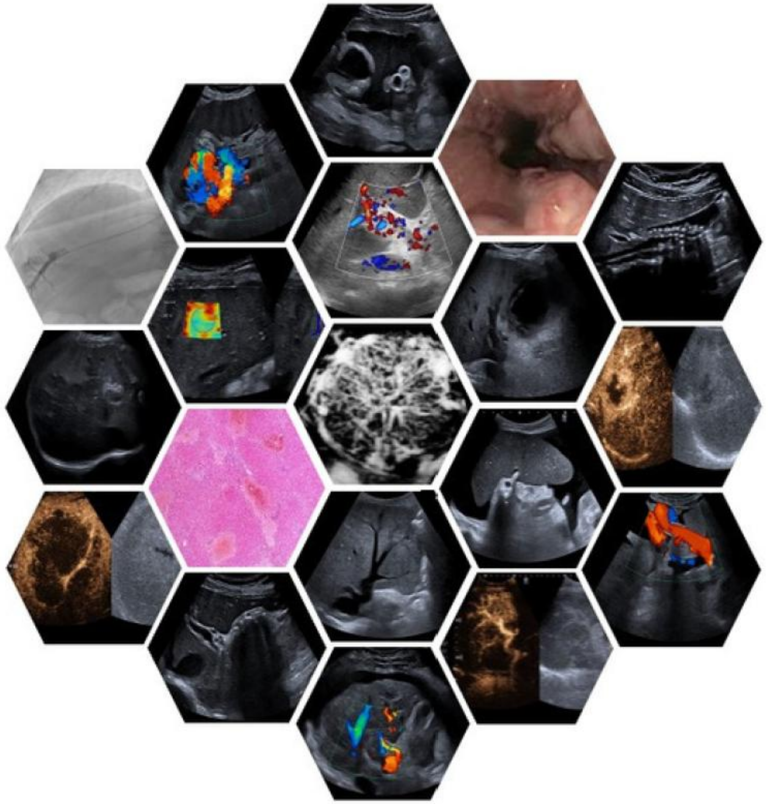

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Disclosures

Canon Medical Systems: speaker; research grant/support

Fujifilm: speaker; research grant/support

Mindray Medical: speaker

Philips Medical Systems: speaker; advisory board member

Loan of ultrasound systems for research purpose:

- Arietta 850, Fujifilm, Japan
- Aplio 800 iSeries, Canon Medical Systems, Japan
- EPIQ Elite, Philips Medical Systems, Bothell, USA
- MyLab 9, Esaote SpA, Italy

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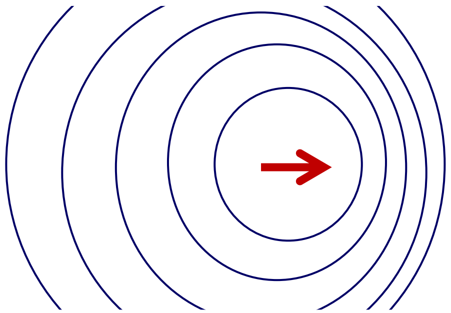
Doppler

Parameter assessed: blood flow velocity

Doppler Effect

The Doppler effect describes the change in frequency of sound, light, or other waves due to the relative motion between the source and the observer.

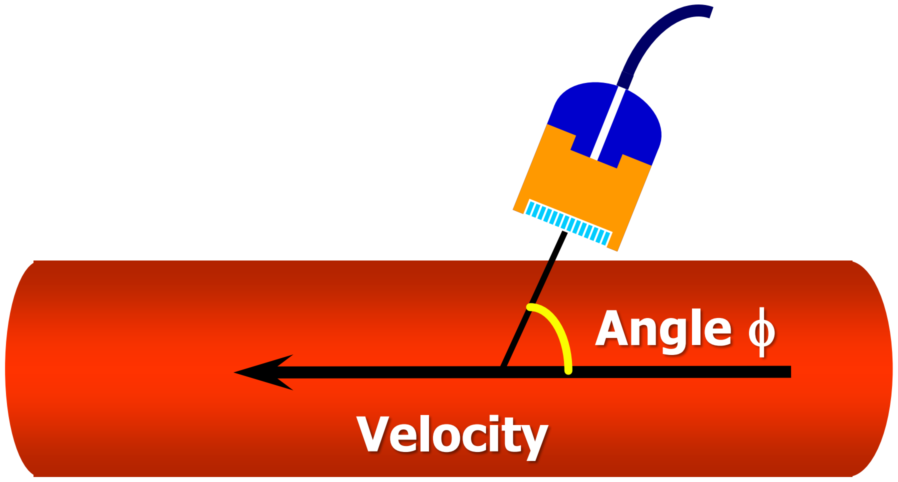


Named after the Austrian physicist Christian Doppler, who described the phenomenon in 1843. The term “Doppler” should be written with the first letter capitalized.

Doppler Frequency Shift (Ultrasound)

The difference between the transmitted and reflected ultrasound frequency is directly proportional to the velocity of the moving interface, such as red blood cells.

Doppler Equation



$$\Delta F = \frac{2\, F_i \,.\, V \,.\, \cos \phi}{C}$$

ΔF : Doppler frequency shift

F_o : Frequency of the transmitted ultrasound beam

V : Velocity of the moving interface (red blood cells)

ϕ : Insonation angle (angle between ultrasound beam axis and vessel longitudinal axis)

C : Sound velocity (1540 m/s in soft tissue)

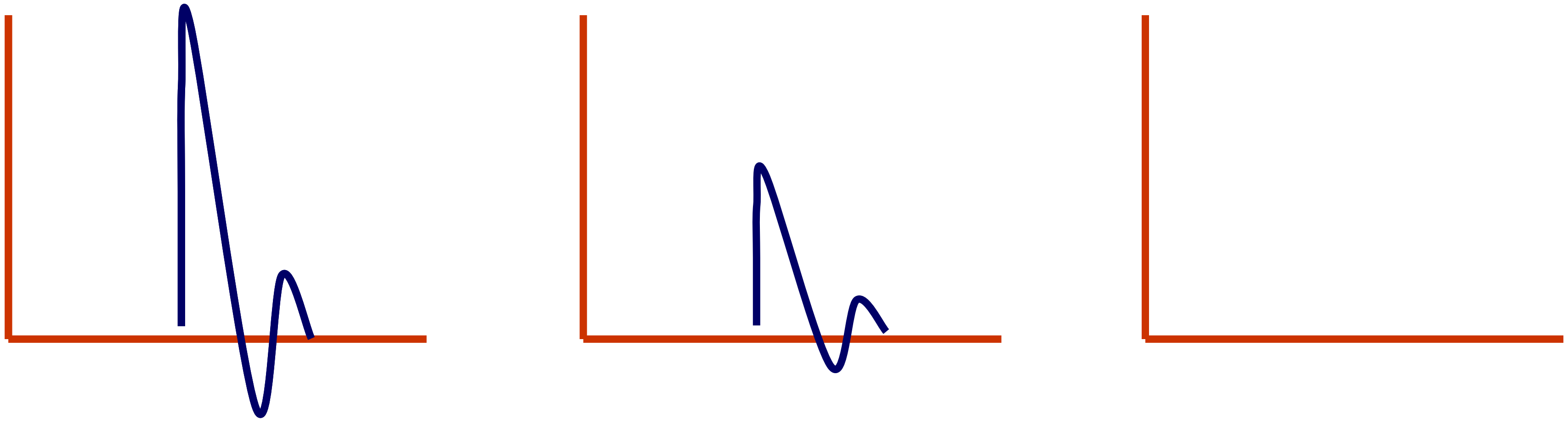
The Doppler equation converts the Doppler frequency shift to velocity

- The Doppler angle is set by the user. The estimate must be accurate.
- To correctly measure blood velocity the Doppler angle must be <60°.
- When the Doppler angle exceeds 60°, even minor adjustments in the angle lead to significant changes in its cosine value, meaning that a slight error in calculating the Doppler angle can greatly affect the accuracy of the velocity estimation.

Cosine of the Doppler angle is the most important variable

Doppler Frequency Shift:
The Cosine

$$\Delta F = \frac{2\,F_i \,.\, V \,.\, \cos\phi}{C}$$



Cos 0° = 1 | **Cos 60° = 0.5** | **Cos 90° = 0**

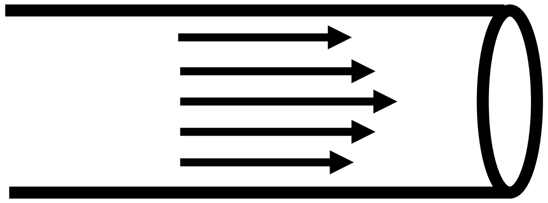
Doppler Frequency Shift

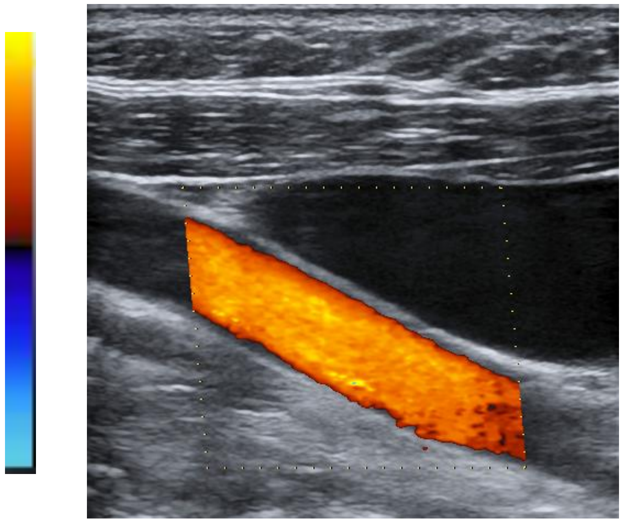
Frequency shifts in Doppler ultrasound are in the audible range (20 - 20,000 Hertz)

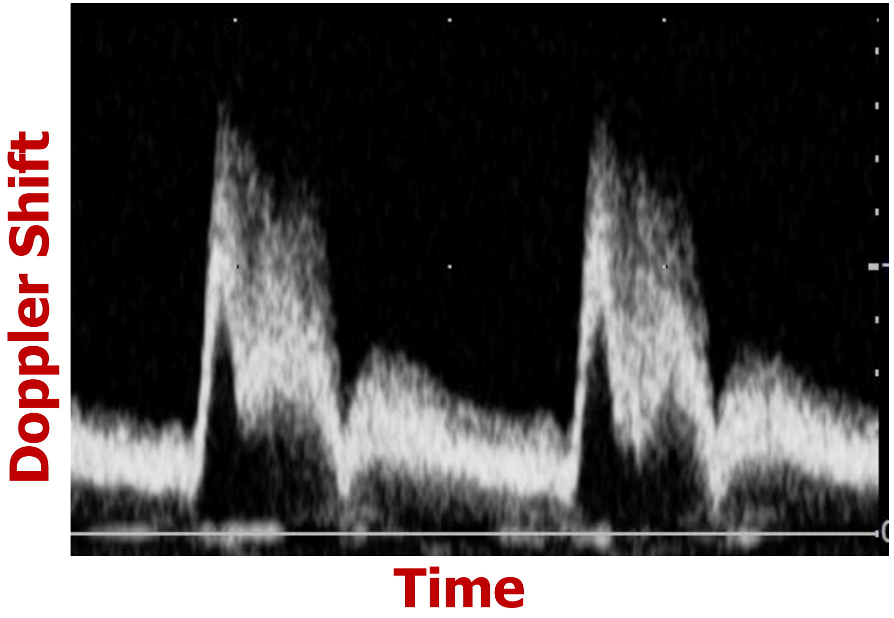
The higher the frequency, the sharper the sound.

Doppler: Laminar Flow and Spectral Analysis

In the case of blood flowing in a vessel, not all blood cells are moving at the same speed at any given time: in the center of the vessel their speed is higher than near the vessel wall due to viscosity.

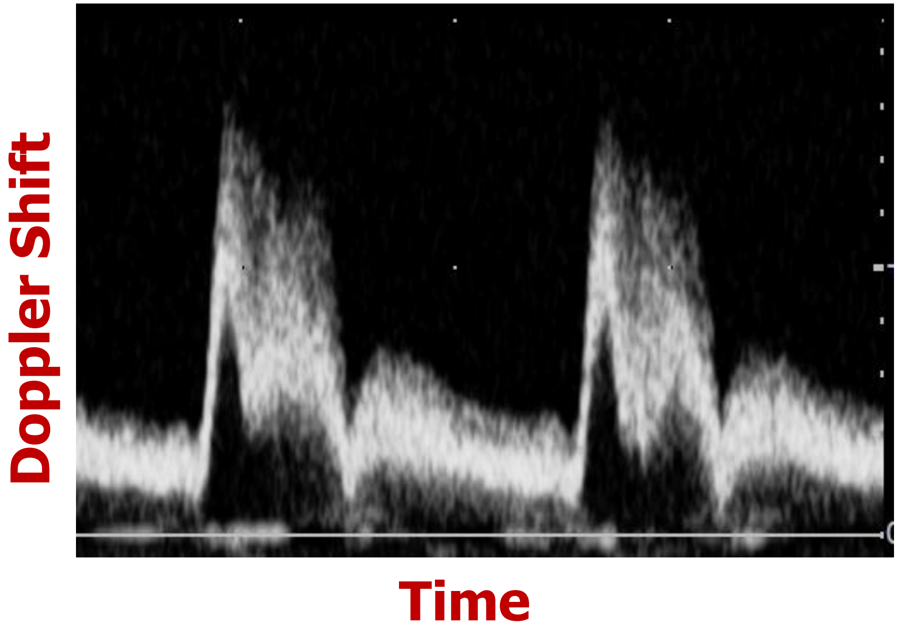






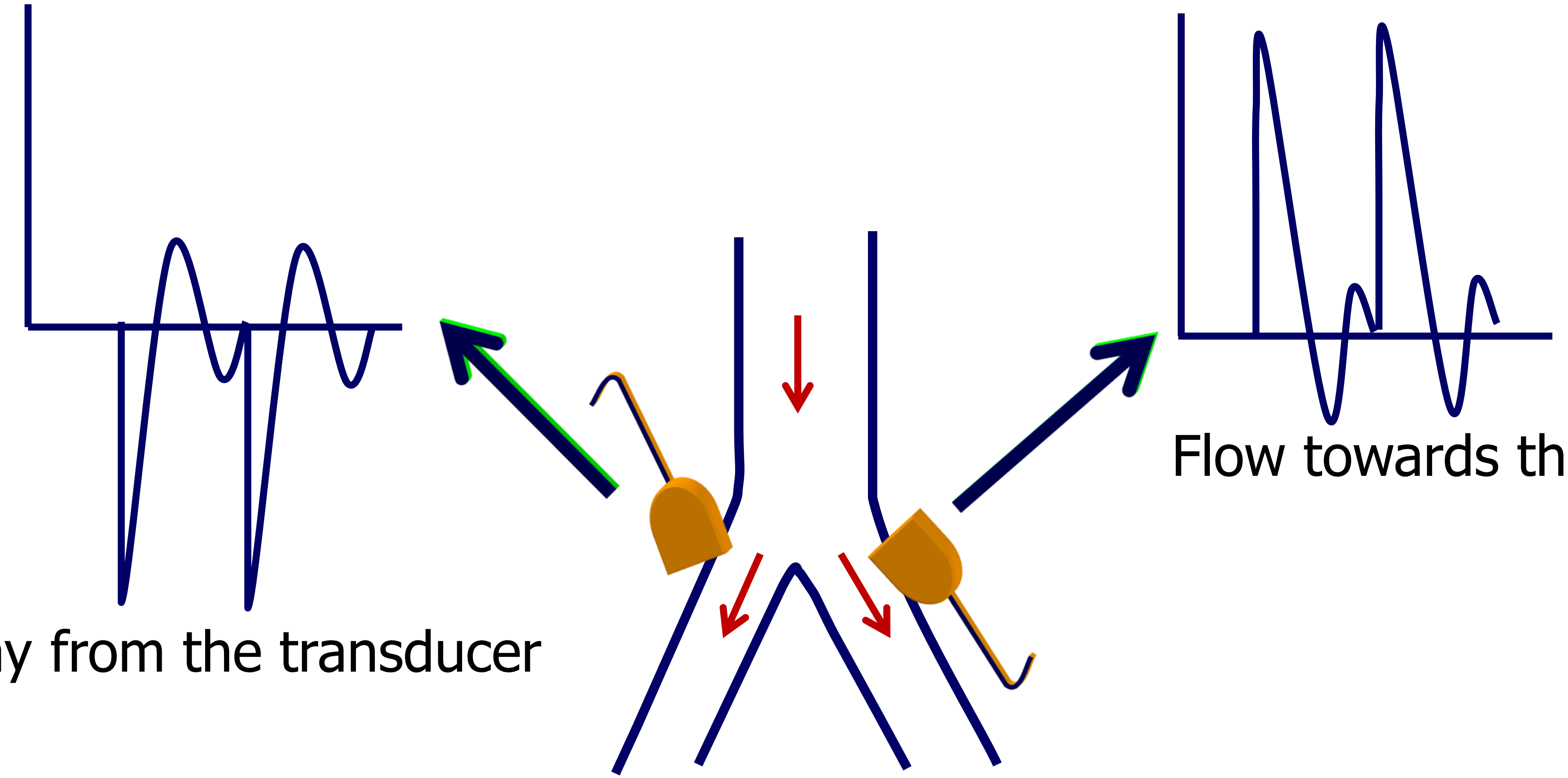
Spectral Analysis

- **Direction**: waveform above or below the baseline.
- **Distribution of velocities**: the distance from the baseline at any time point.
- **Doppler signal power**: Brightness, indicating the number of blood cells at any given velocity.



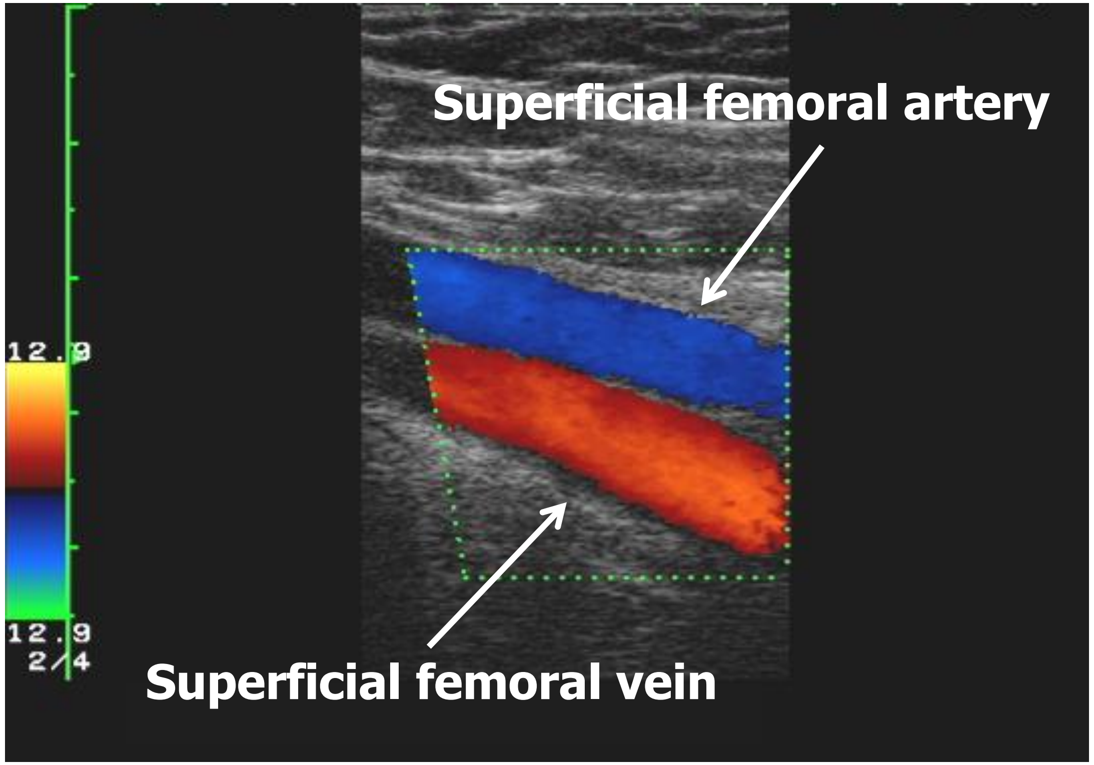
Direction of Flow

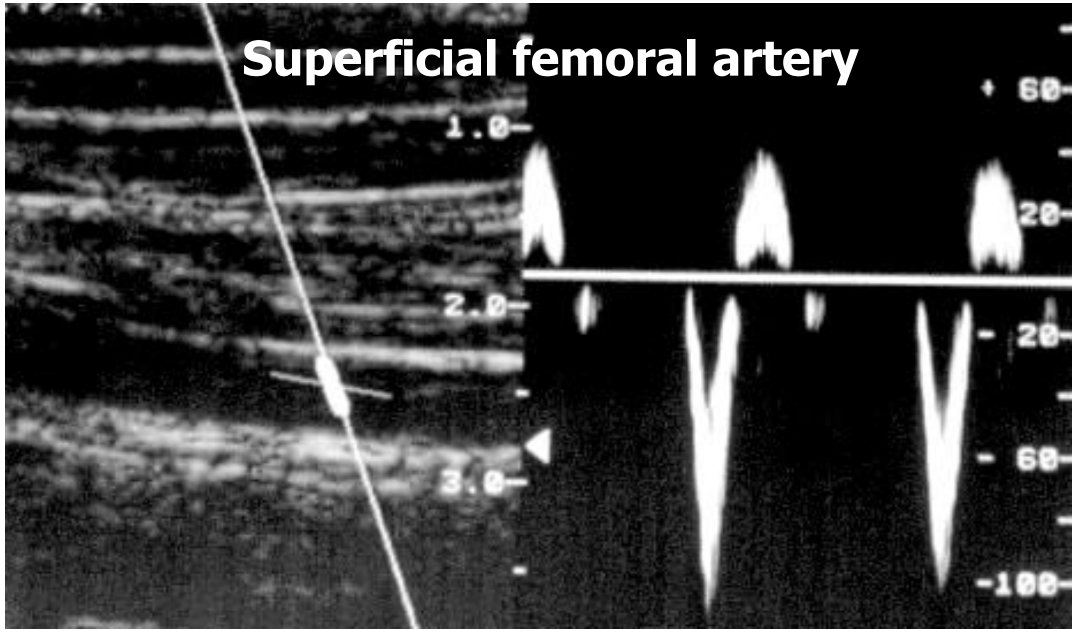
Antegrade flow can be either towards or away from the transducer, depending on the transducer position.



Flow away from the transducer

Flow towards the transducer





Antegrade flow away from the transducer

Doppler Techniques

Continuous Wave Doppler: US waves are continuously transmitted by one set of transducer's elements and received by another set. The system does not provide information where the blood flow velocity is measured but is able of correctly sampling high velocity.

Pulsed Wave Doppler: The same elements of the transducers transmit and receive back pulsed US waves. The depth and size of the region of interest (sample volume) are known and are user-adjustable, but high velocities may not be sampled correctly (aliasing).

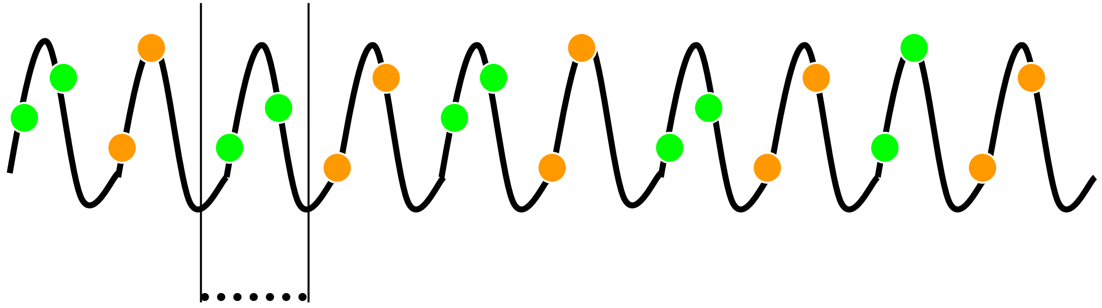
Pulsed Wave Doppler: The Pulse Repetition Frequency (PRF)

- PRF is the number of ultrasound pulses sent per second by the transducer (sampling rate).
- Since the sound speed in the body is constant (1540 m/s), the PRF depends on the distance the sound waves must travel: the greater the distance, the longer it takes for the waves to go forth and back.
- The same piezoelectric elements are used to both transmit and analyze sound waves, so there is a maximum velocity that can be accurately measured at a given depth.

The PRF is limited by the speed of sound for a specific imaging depth

Shannon-Nyquist Theorem and Nyquist Limit

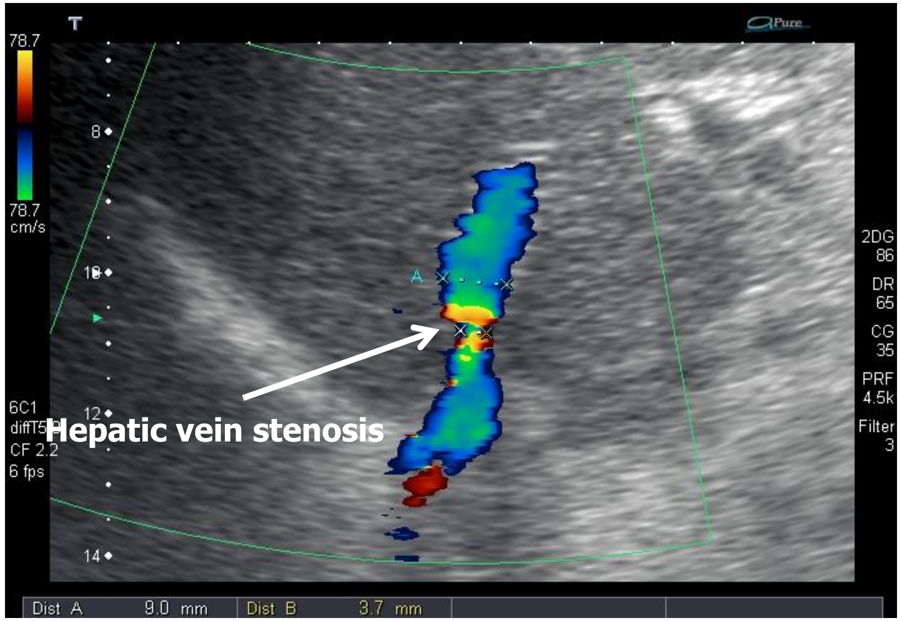
Shannon-Nyquist theorem: To accurately measure a waveform, it is necessary to randomly sample it at least twice per cycle.



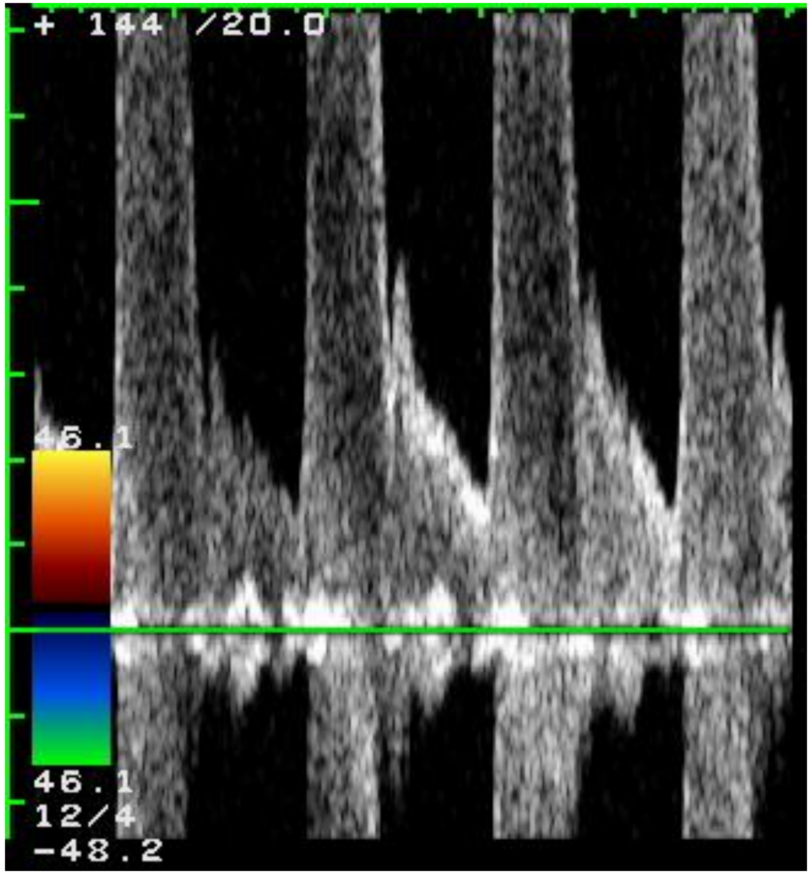
The maximum Doppler shift frequency that can be correctly measured is determined by the Nyquist limit (PRF/2).

Aliasing

Aliasing occurs when the PRF is less than twice the maximum frequency shift



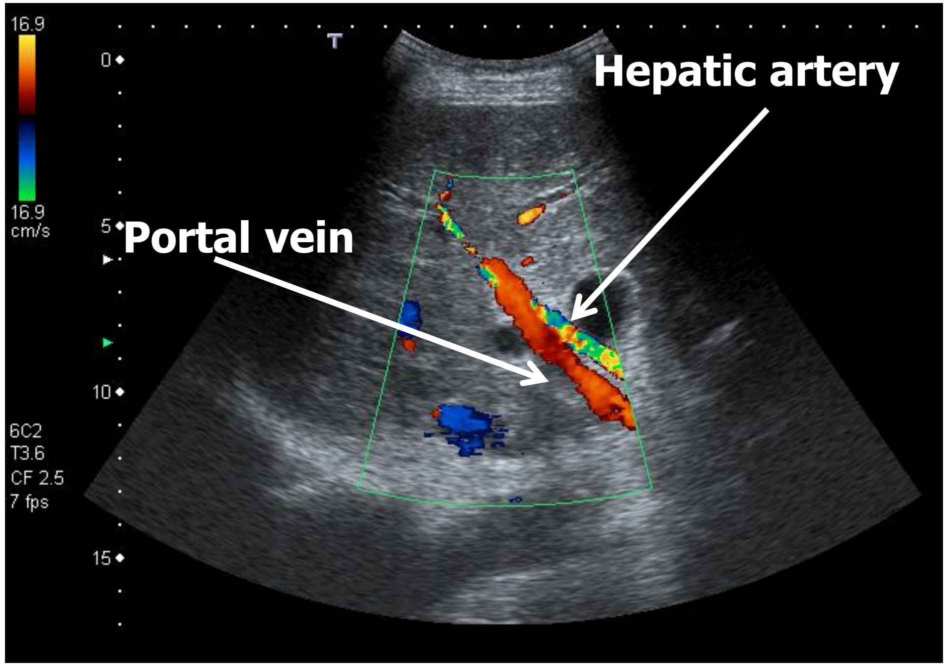
(Courtesy of Dr. Roccarina)

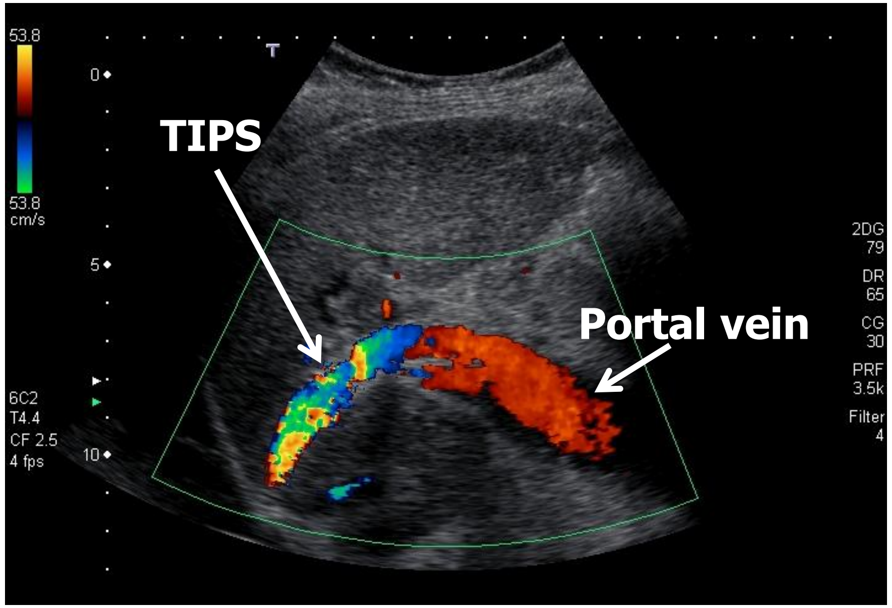


Velocities that exceed the Nyquist limit are represented as reverse flow.

Aliasing: How to mitigate it

Aliasing can be mitigated by increasing the PRF, adjusting the baseline, or using a lower frequency transducer.





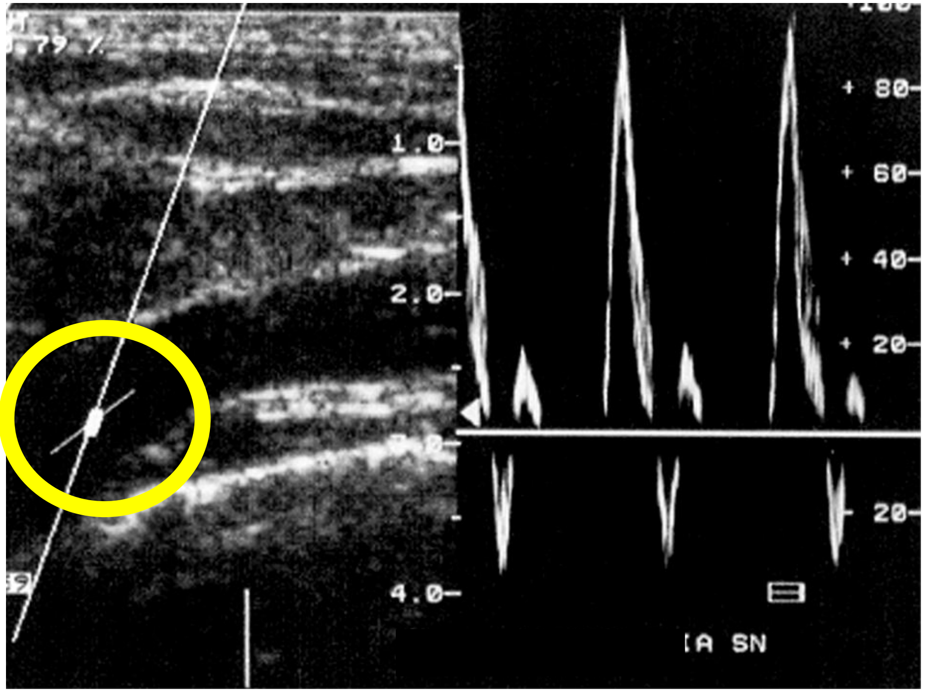
(Courtesy of Dr. Roccarina)

Types of Pulsed Wave Doppler Imaging

- Spectral Doppler
- Colour Doppler
- Power Doppler

Spectral Doppler

By time-gating the returning signals, the blood flow velocity is assessed at a specific location.

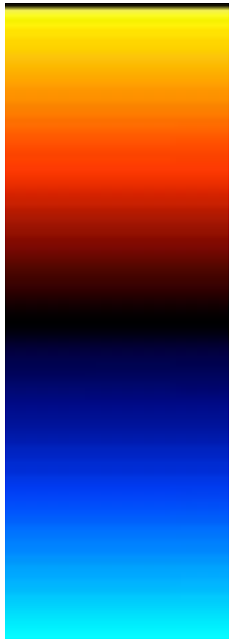


Quantitative estimate of blood flow velocity.

Spectrum of blood flow velocities at any given time.

Angle information is mandatory to convert frequency shifts in blood velocities

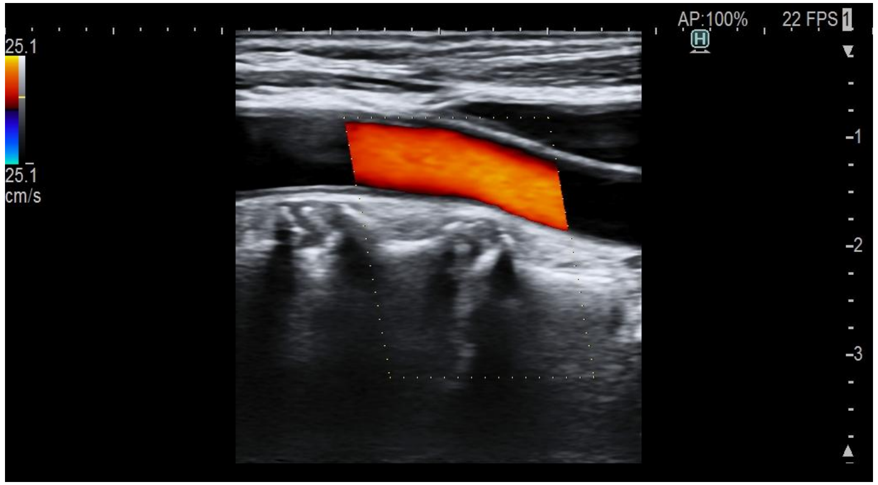
Colour-Doppler



Mean blood flow velocities are color-coded and shown in a user-adjustable box overlaid on the B-mode image.

Red: blood flow toward the transducer

Blue: blood flow away from the transducer



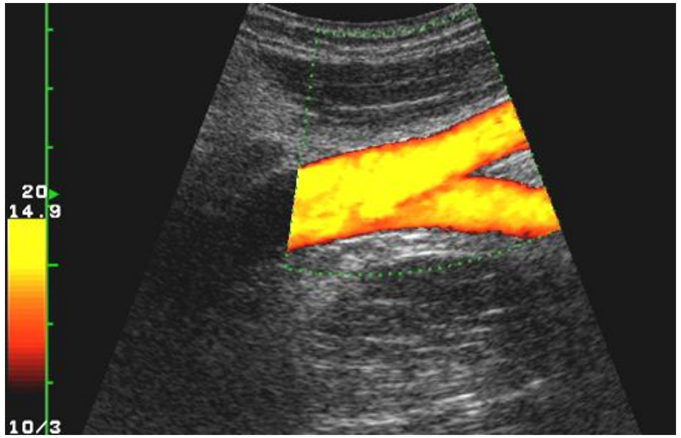
Angle dependency is less critical than in spectral Doppler if the color box is properly steered.

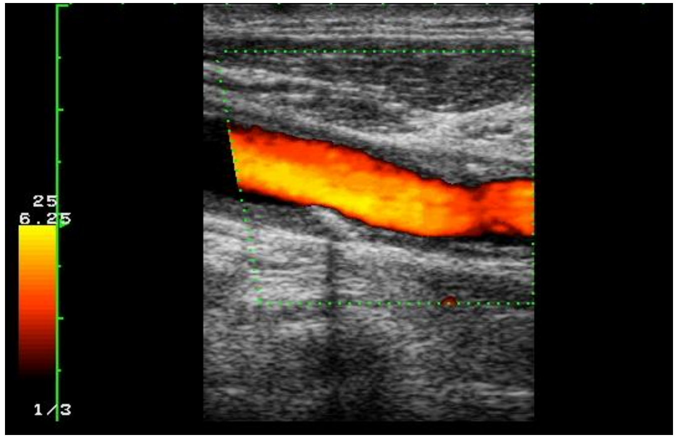
Power-Doppler

It shows the strength of blood flow signals, which reflects red blood cell quantity.

While it lacks blood flow velocity data, it has high sensitivity for visualizing vessel morphology.

The influence of the angle is minimal, except when the angle between the flow and the beam direction reaches 90°.





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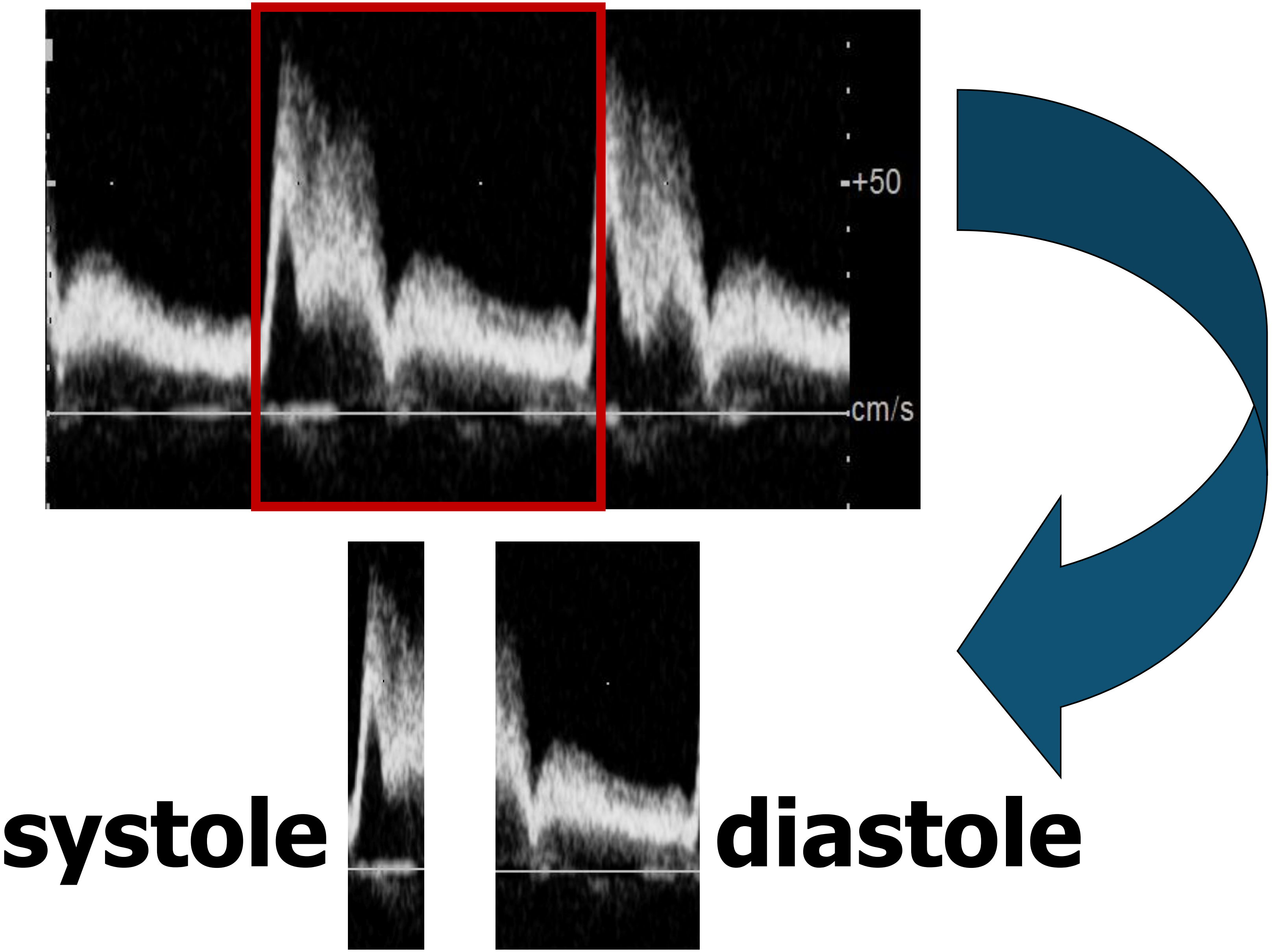
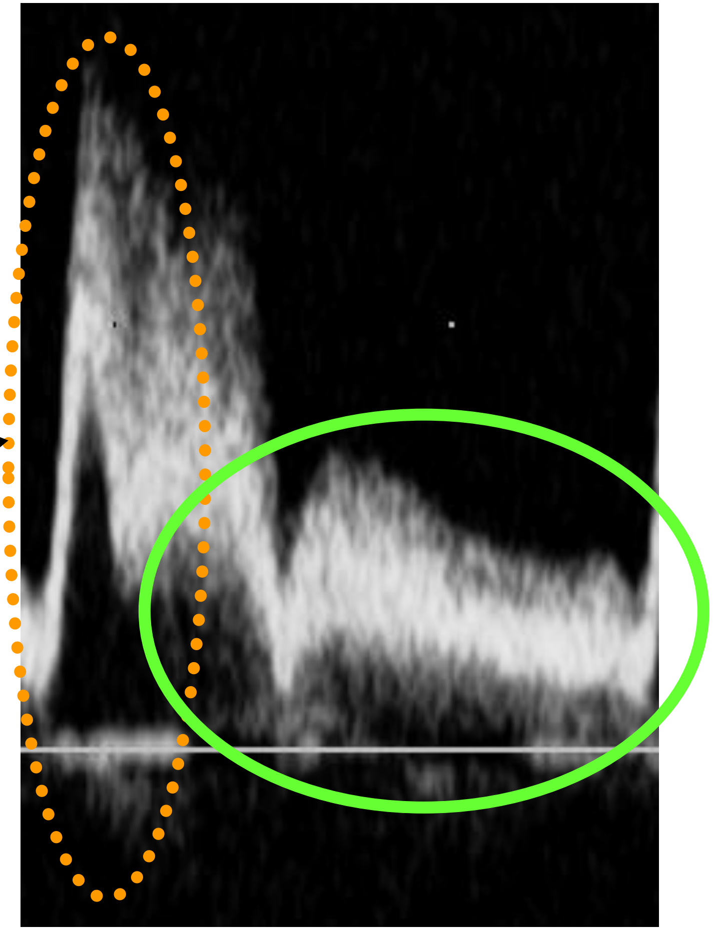

+50
cm/s
systole
diastole



Steep rise to peak systole

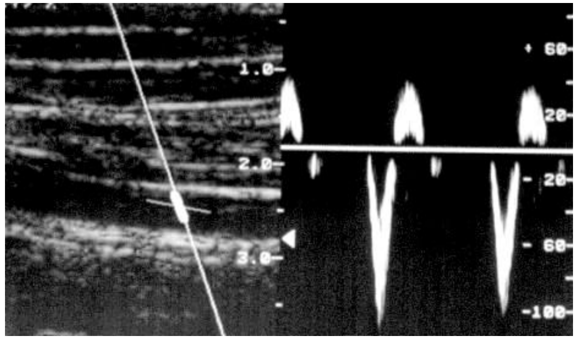
Systolic component:
Upstream vascular bed

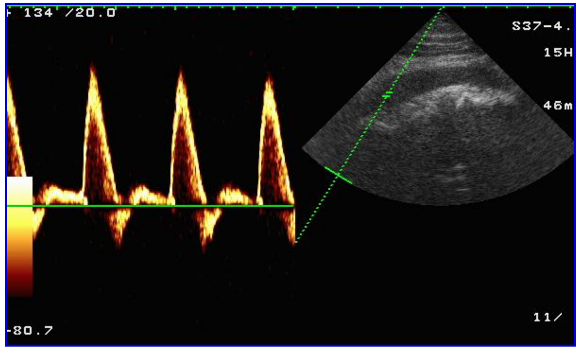
Diastolic component:
Downstream vascular bed

Doppler Waveforms: Arteries

Multiphasic pattern

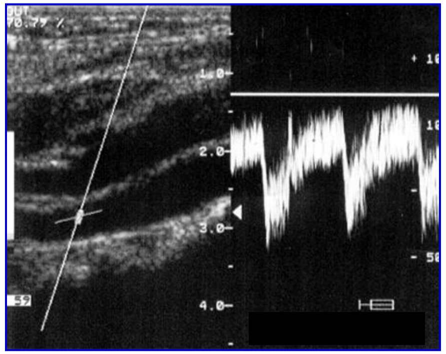
High resistance





Intermediate resistance

Waveform crosses the zero-flow baseline and contains both forward and reverse velocity components.



Monophasic and low resistance pattern

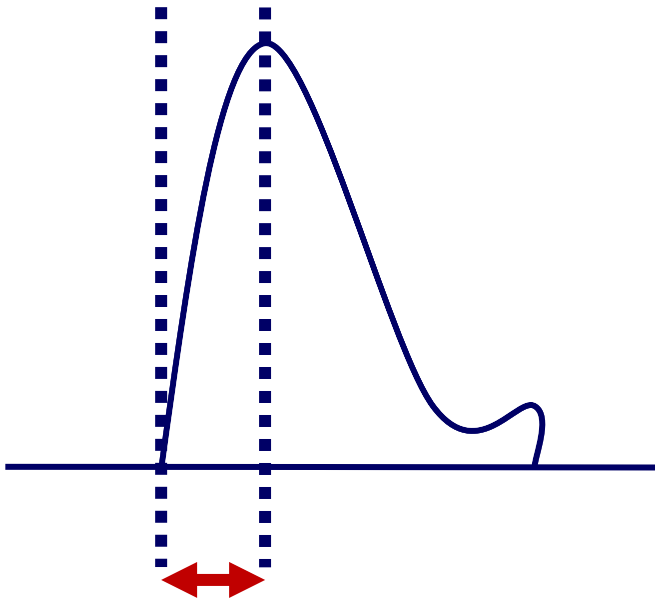
Waveform does not cross the zero-flow baseline throughout any part of the cardiac cycle; blood flows in a single direction.

Kim ES et al. Interpretation of peripheral arterial and venous Doppler waveforms: A consensus statement from the Society for Vascular Medicine and Society for Vascular Ultrasound. Vasc Med. 2020 Oct;25(5):484-506

Upstream Vascular Bed

Acceleration time (AT)

It evaluates the slope of the ascending Doppler curve to help identify possible upstream stenosis.



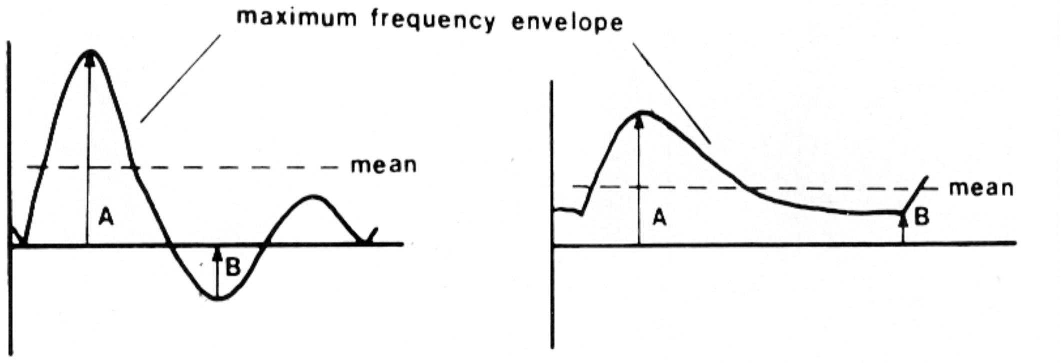
Normal values ≤ 70-140 msec

Downstream Vascular Bed

Resistive Index (RI)

$$\frac{\text{Peak Systolic Velocity} - \text{End Diastolic Velocity}}{\text{Peak Systolic Velocity}}$$

Low resistance arteries: upper limit 0.70



Velocity ratios remain unaffected by the Doppler angle.

Pulsatility Index (PI)

$$\frac{\text{Peak Systolic Velocity} - \text{End Diastolic Velocity}}{\text{Mean Velocity}}$$

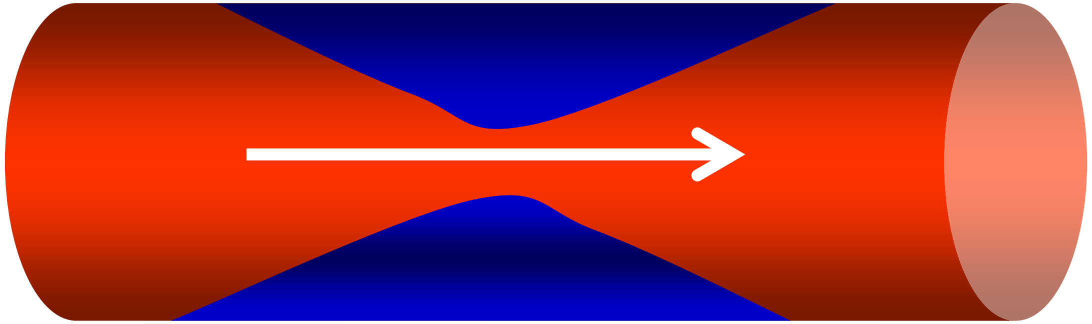
Volume of blood flow in an artery

$$F = Vm \cdot A$$

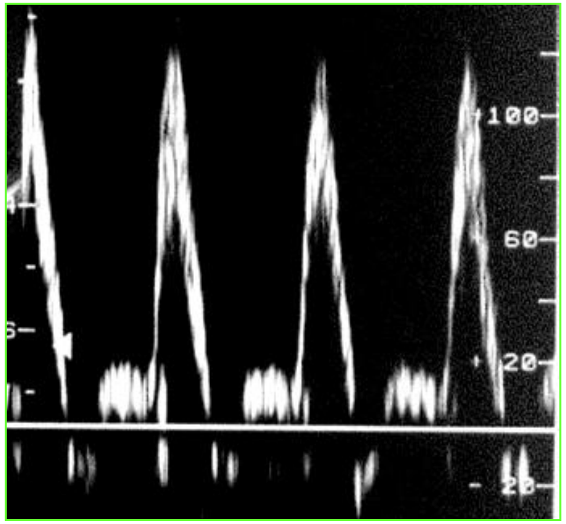
F = Blood flow volume
Vm = Mean velocity
A = cross sectional area of the vessel

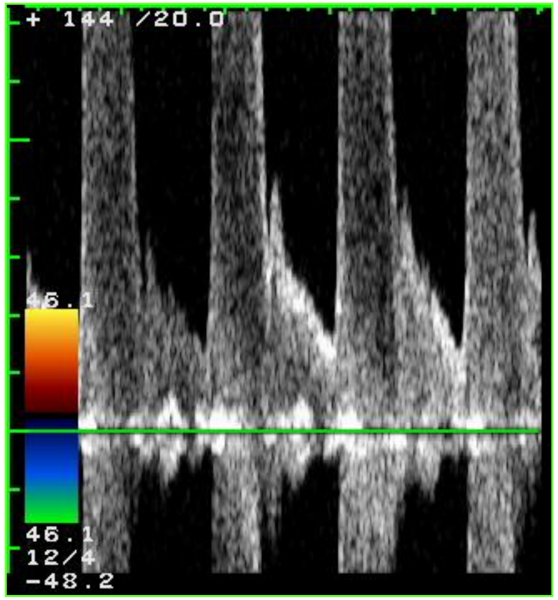
Normal

(F = Vm . A)

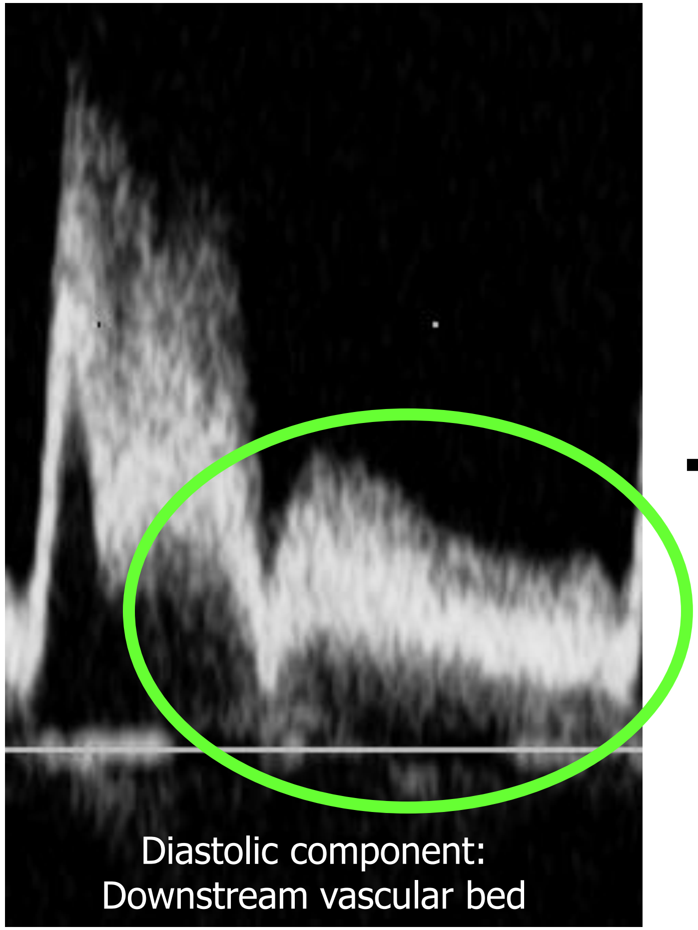


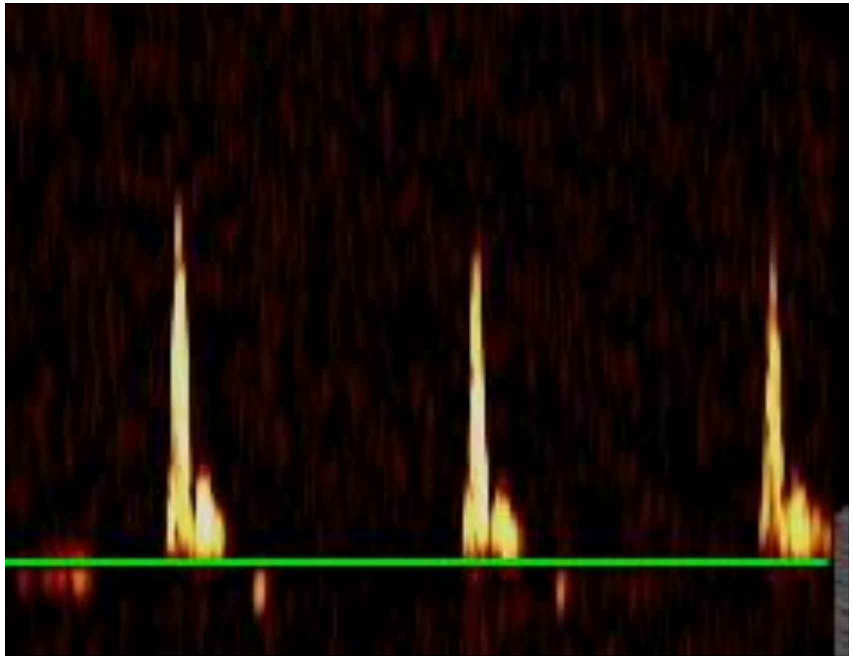
Stenosis

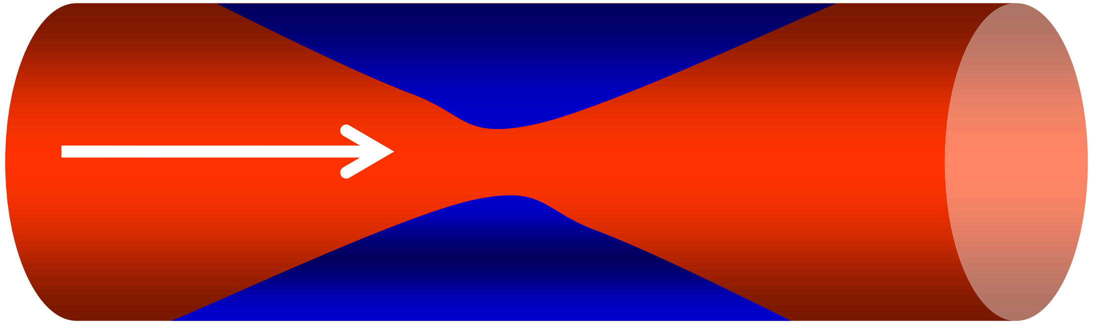




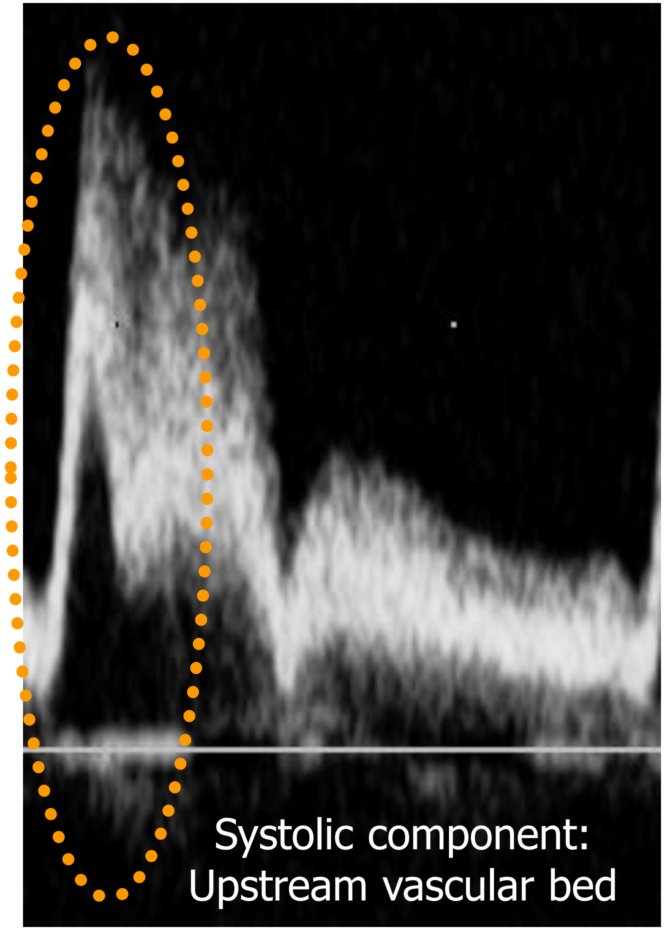
Indirect Criterion for Downstream Stenosis: Increased Resistance

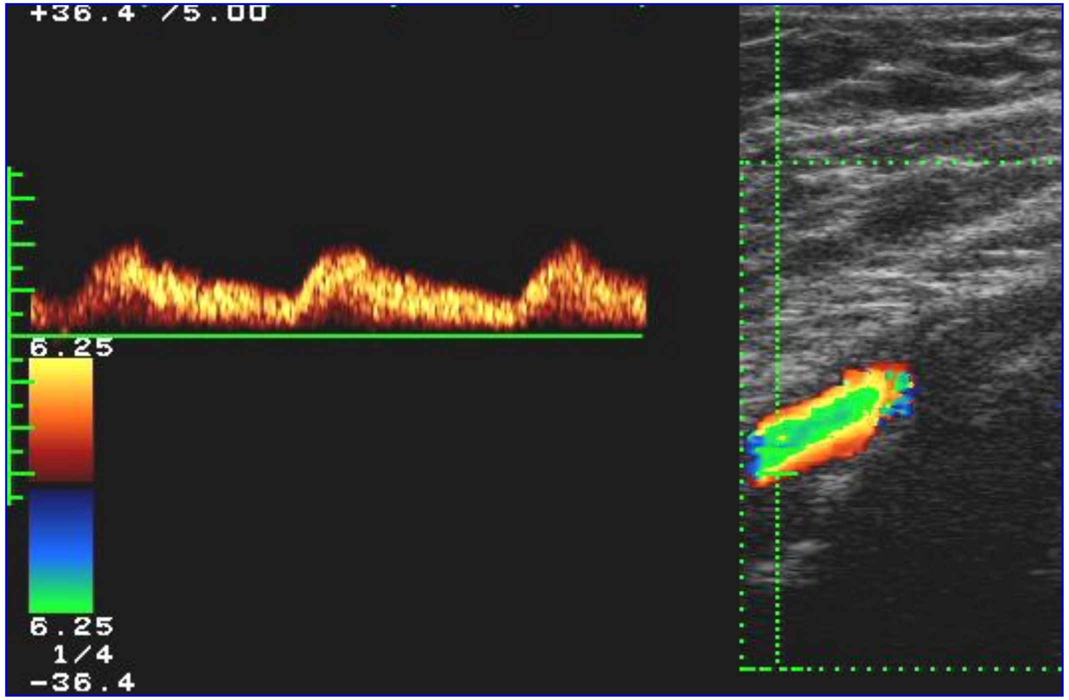




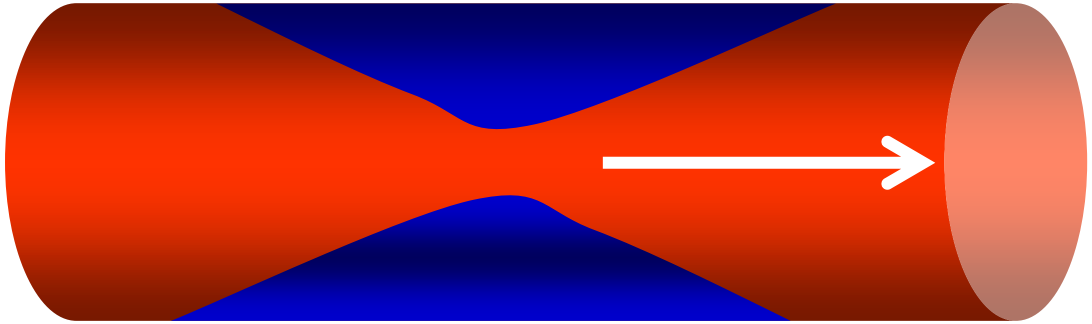


Indirect Criterion for Upstream Stenosis: Prolonged Upstroke



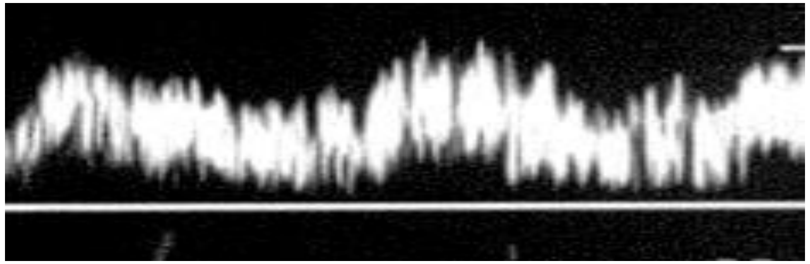


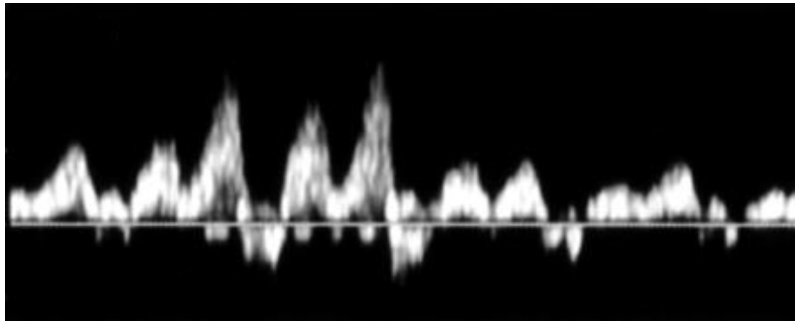
Delayed rise to peak systole



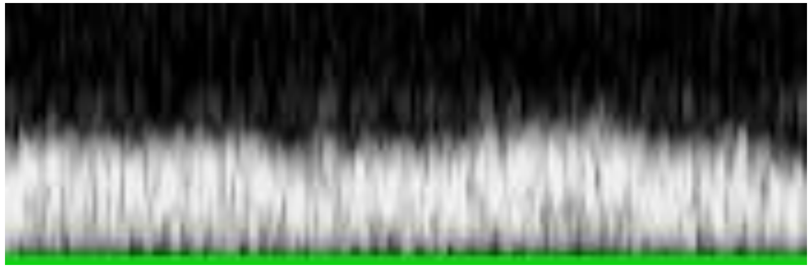
Doppler Waveforms: Veins

Phasic flow (respiratory or cardiac influence on blood flow velocity)

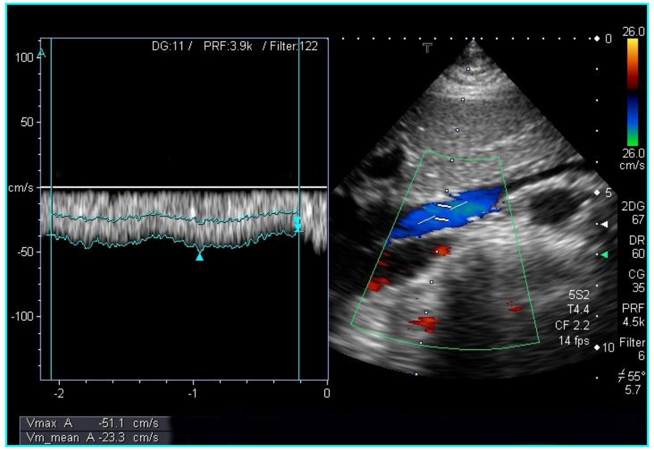




Continuous flow

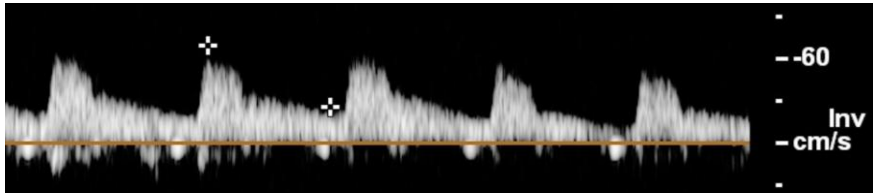


Doppler and Hepatic Circulation: Normal Findings



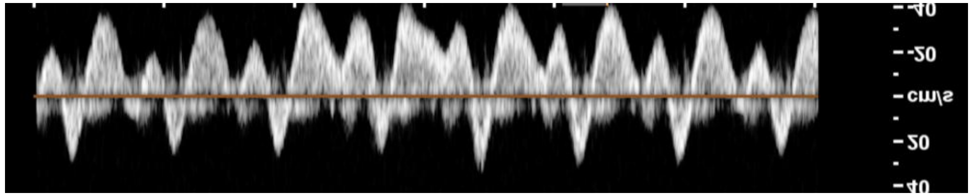
Portal venous system:

Portal flow is typically monophasic and low-velocity, with minor respiratory changes. Normal time-averaged peak velocity ranges from 30 to 40 cm/sec.



Hepatic artery:

Blood flow is in the same direction as the PV (hepatopetal) and shows a low-resistance waveform (resistive index, RI<0.70) with forward flow throughout the cardiac cycle.



Hepatic veins:

The normal Doppler waveform is triphasic.

Take Home Message

- **Frequency Shift =** $\dfrac{2\ F_i\ .\ V\ .\ \cos\phi}{C}$

- **Pulse Repetition Frequency and Nyquist limit**