Concepts of Doppler and Colour Doppler Analysis

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ULTRASOUND COURSE

20TH–21ST SEPTEMBER
LONDON
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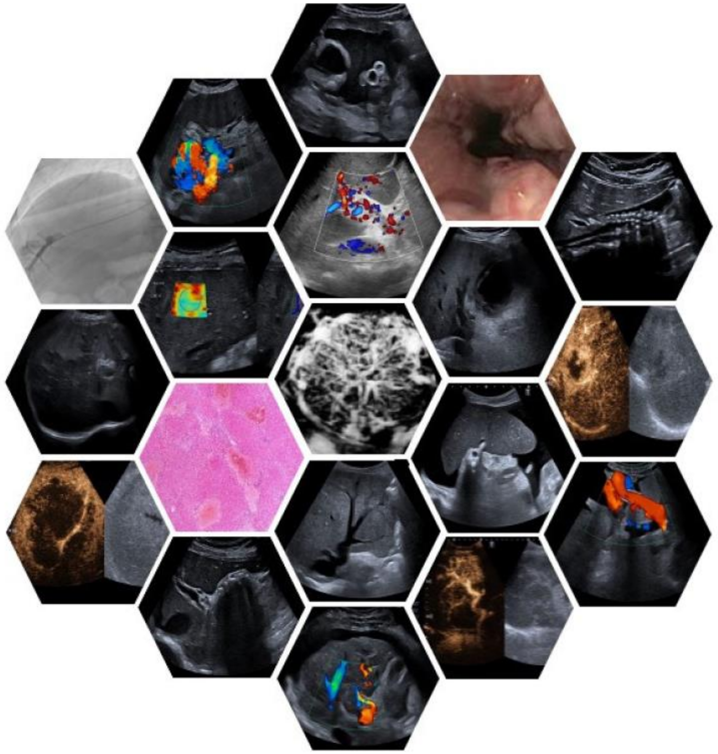


Disclosures

Canon Medical Systems: speaker; research grant/support

Fujifilm: speaker; research grant/support

Mindray Medical: speaker; research grant/support

Philips Medical Systems: speaker; advisory board member

Siemens Healthineers: speaker, advisor board panel

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
- Resona i9, Mindray Medical, China
- Sequoia, Siemens Healthineers, Germany

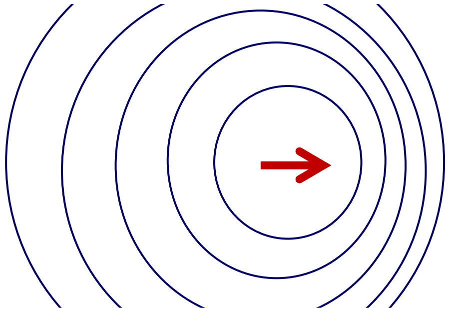
Elsevier Publishing: Royalties

Doppler

Parameter assessed: blood flow velocity

Doppler Effect

The Doppler effect is the change in frequency of waves (in our case sound waves) due to motion of either the source or the observer: the frequency increases when the distance between the two decreases and vice versa.



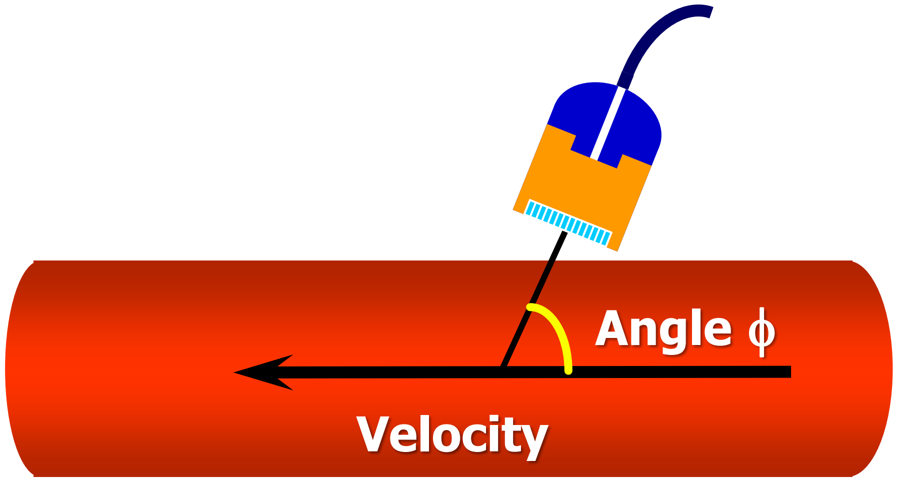
Named after the Austrian physicist Christian Doppler, who described the phenomenon in 1843.

The term “Doppler” should be written with the first letter capitalized.

Doppler Frequency Shift (Ultrasound)

The difference between the transmitted and the reflected US frequency is directly proportional to the velocity of the moving interface (red blood cells).

Doppler Equation



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

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

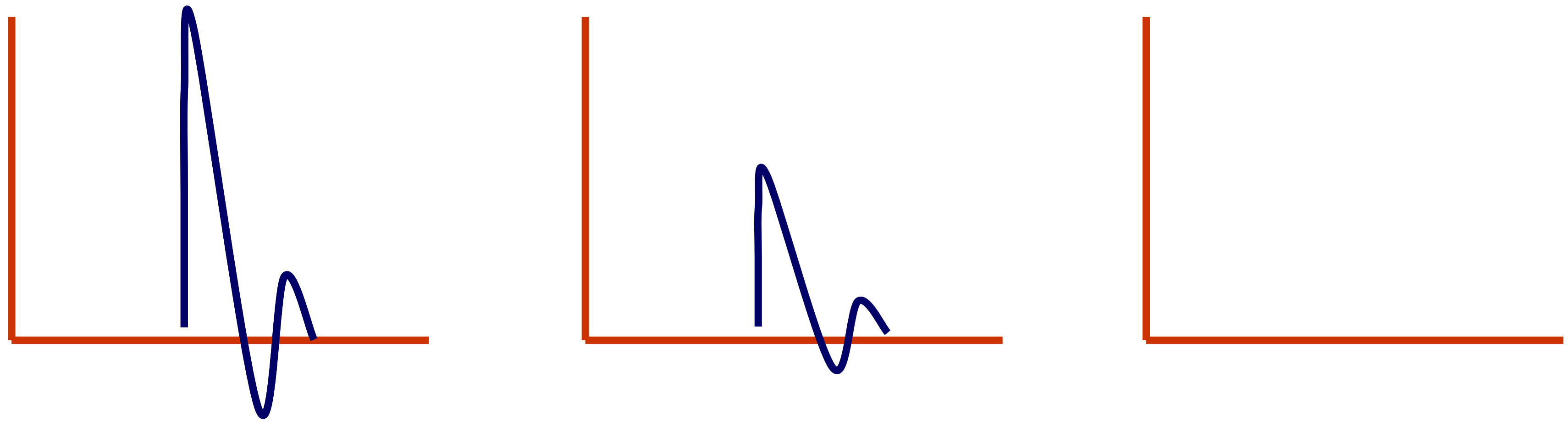
- The Doppler angle is set by the user and the estimate must be accurate.
- To correctly measure blood velocity the Doppler angle must be <60°.
- Above 60°, relatively small changes in the Doppler angle are associated with large changes in the cosine; therefore, a small error in estimating the Doppler angle can result in a large error in estimating the velocity.

Cosine of the Doppler angle is the most important variable

Doppler Frequency Shift:

The Cosine

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



Cos 0° = 1 Cos 60° = 0.5 Cos 90° = 0

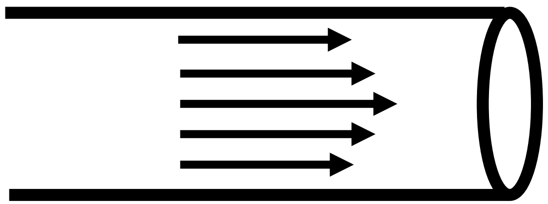
Doppler Frequency Shift

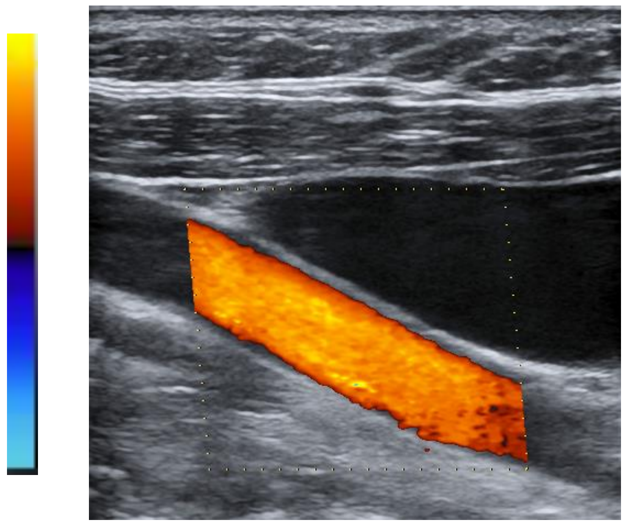
Frequency shifts in Doppler ultrasound are in the audible range (20 - 20,000 Hertz)

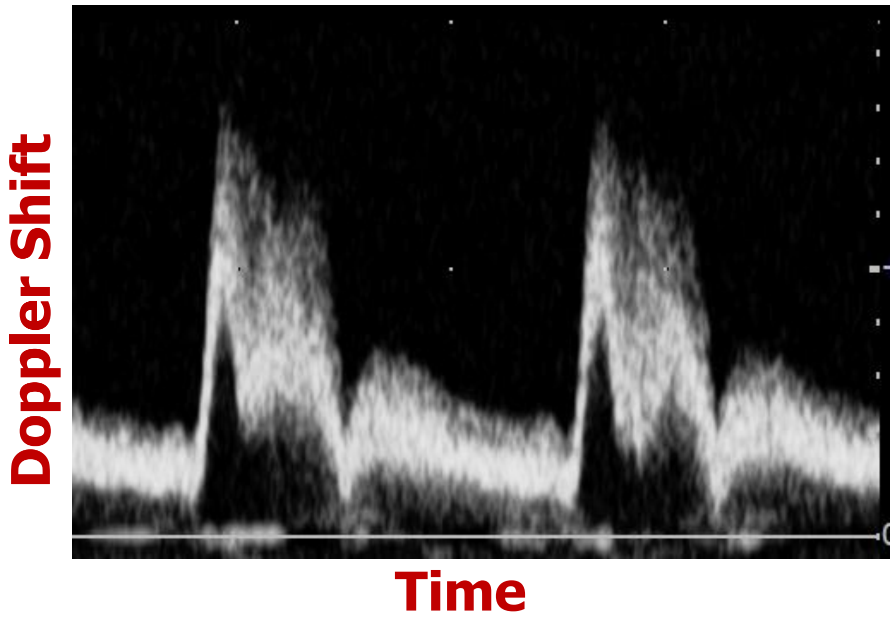
The higher the frequency, the sharper the sound.

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.

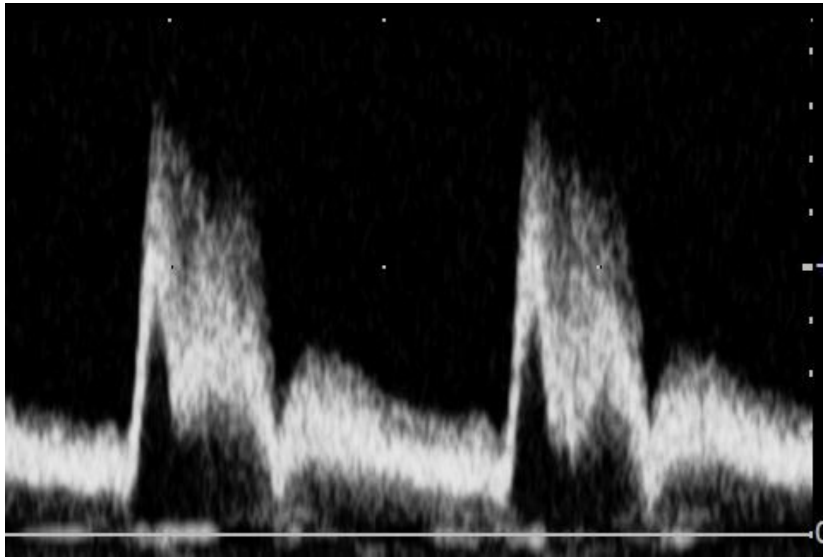






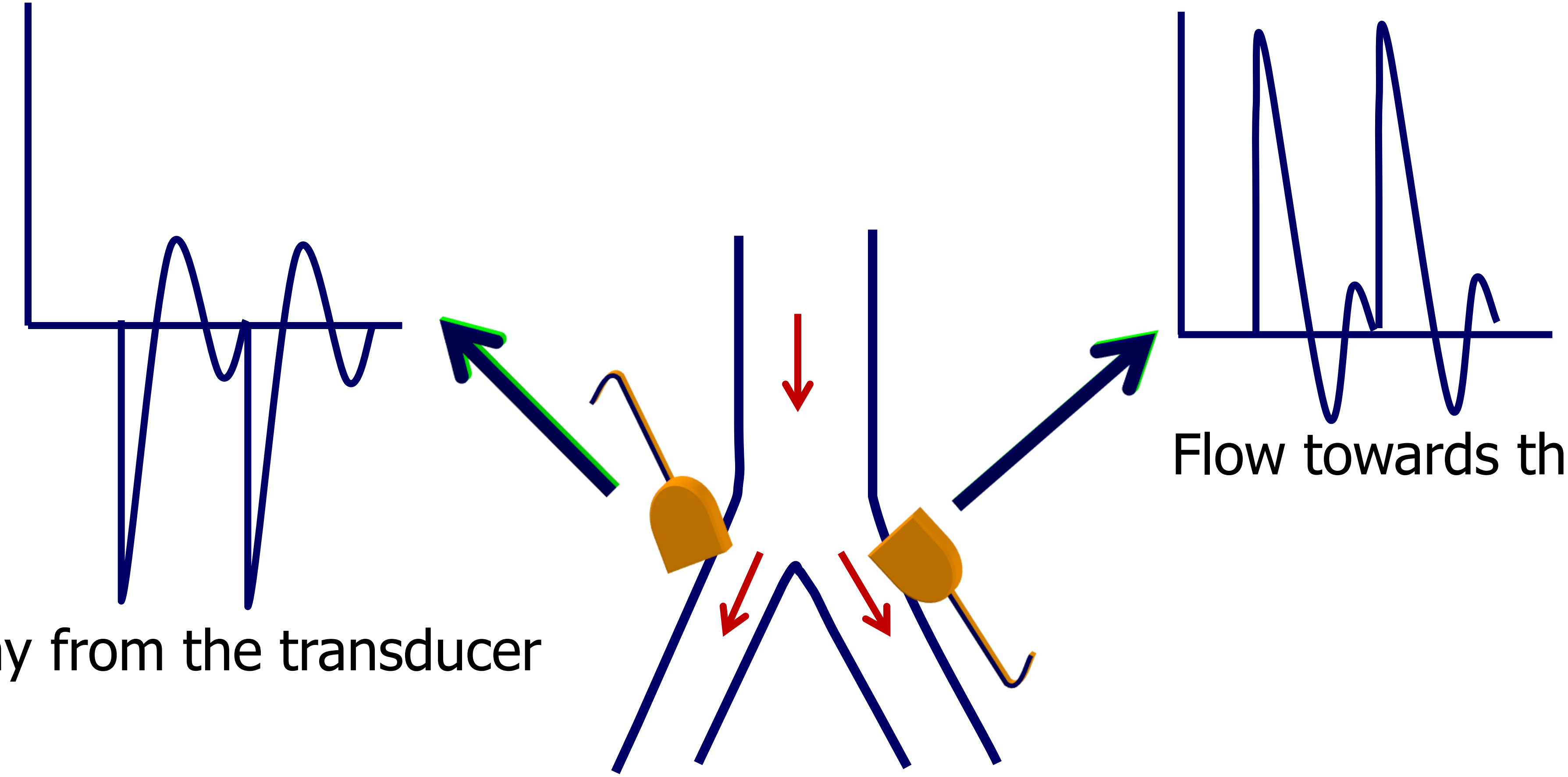
Spectral Analysis

- 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.



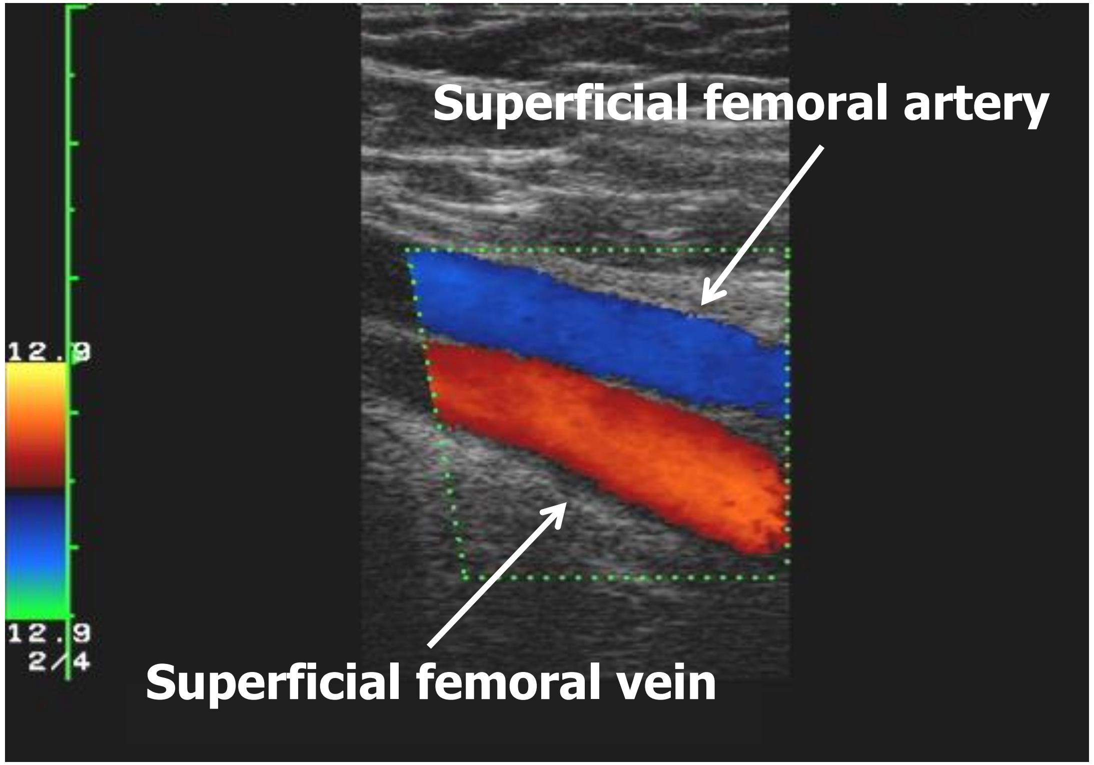
Direction of Flow

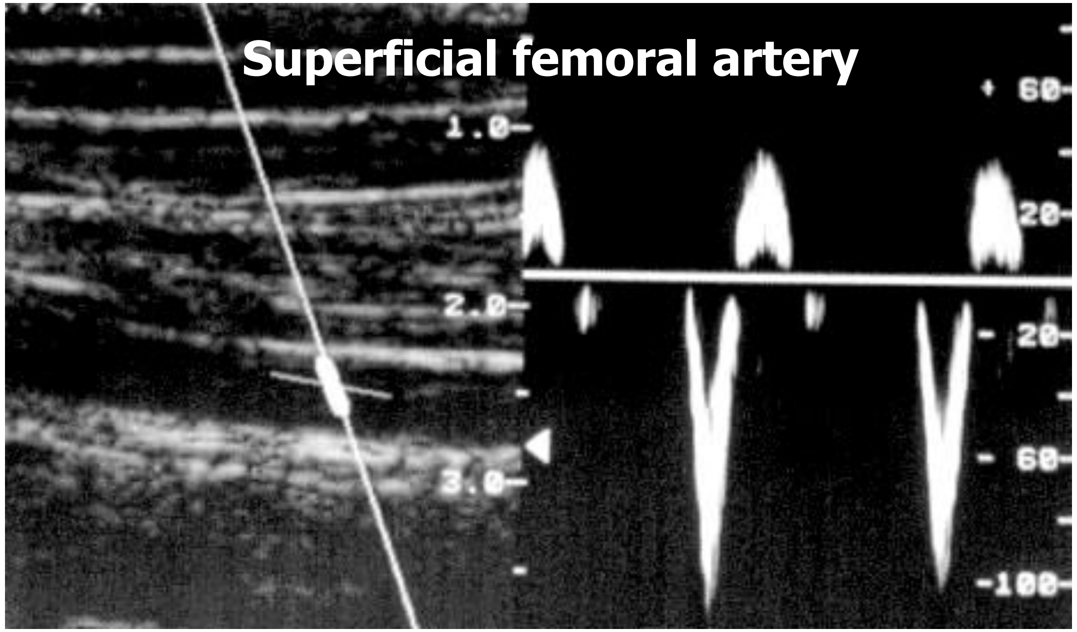
Antegrade flow can be either towards or away from the transducer, depending on the transducer position.



Flow towards the transducer

Flow away from the transducer





Antegrade flow away from the transducer

Doppler Systems

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, but high velocities may not be sampled correctly (aliasing).

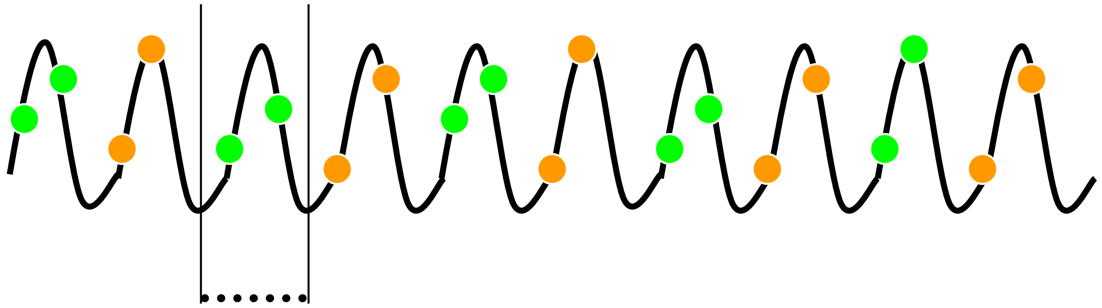
Pulsed Wave Doppler: The Pulse Repetition Frequency (PRF)

- PRF is the number of ultrasound pulses sent per second by the transducer (sampling rate).
- The PRF is determined by the sound speed and the distance it must travel.
- Since the sound speed in the body is constant (1540 m/s), the PRF depends on the distance the sound waves must travel: the longer the distance, the more time required to travel forth and back.
- Because the same piezoelectric elements are used to send and analize sound waves, there is a maximum velocity that can be correctly measured at any given depth.

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

Shannon-Nyquist Theorem and Nyquist Limit

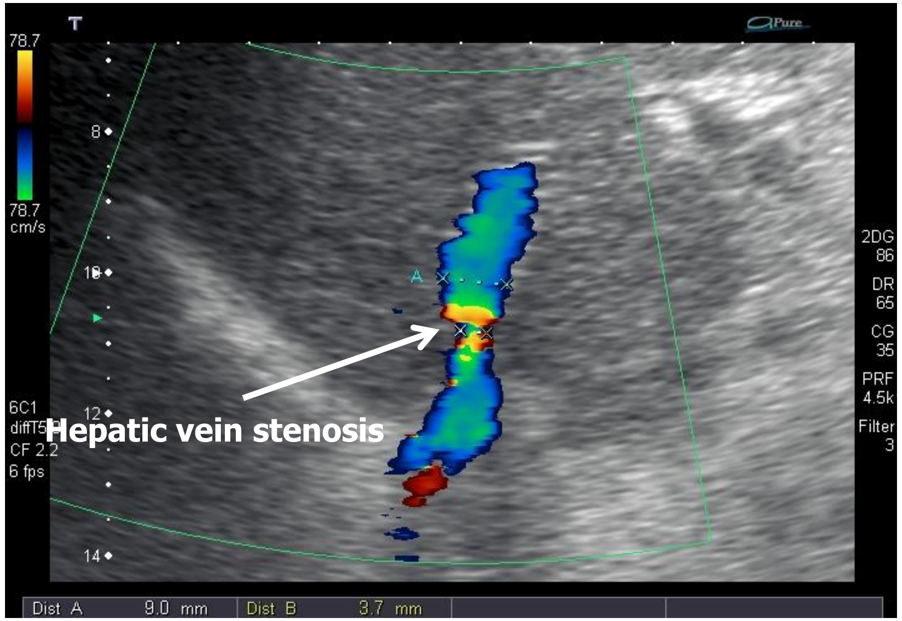
Shannon-Nyquist theorem: A wave must be sampled at least twice per cycle in order to be correctly measured.



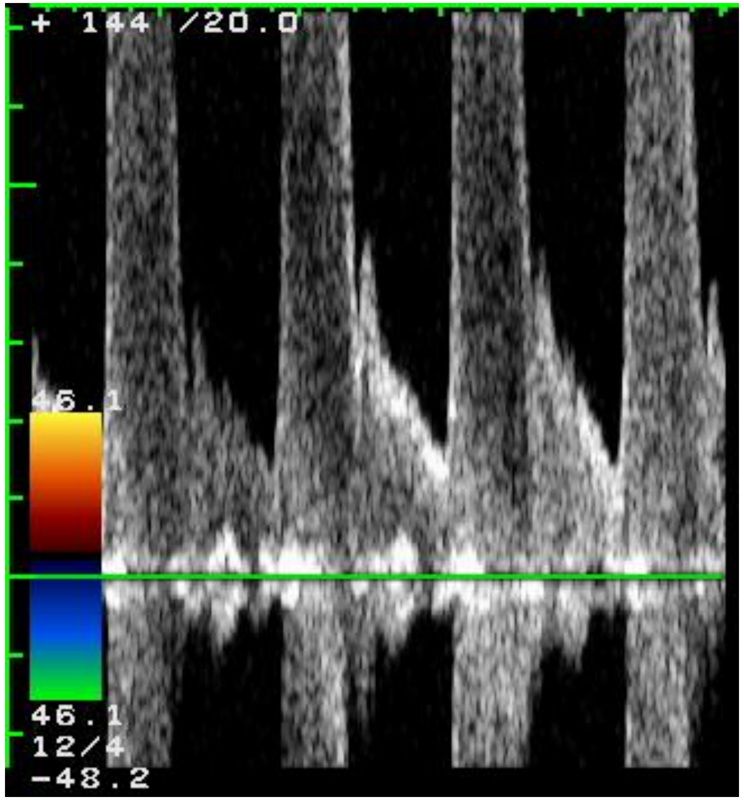
The maximum Doppler shift frequency that can be correctly detected is determined by the Nyquist limit (PRF/2).

Aliasing

Velocities higher than the Nyquist limit are shown as flow in the opposite direction.



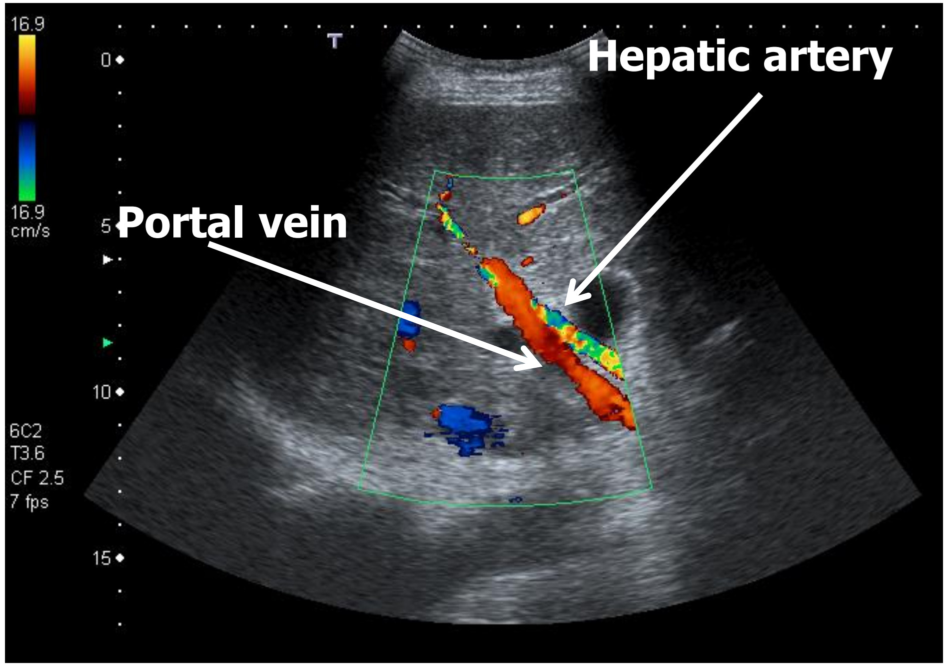
(Courtesy of Dr. Roccarina)

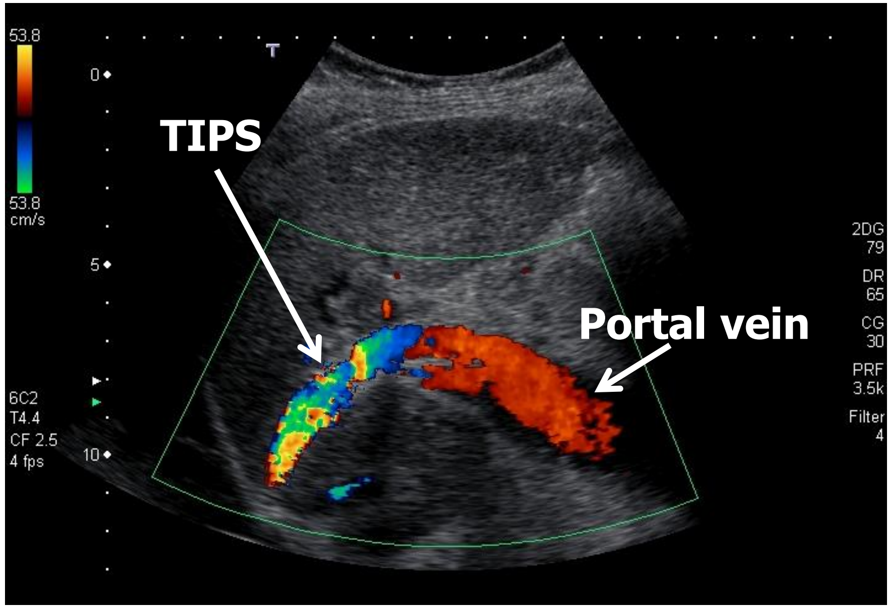


Aliasing occurs when the PRF is less than twice the maximum frequency shift

Aliasing: How to mitigate it

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





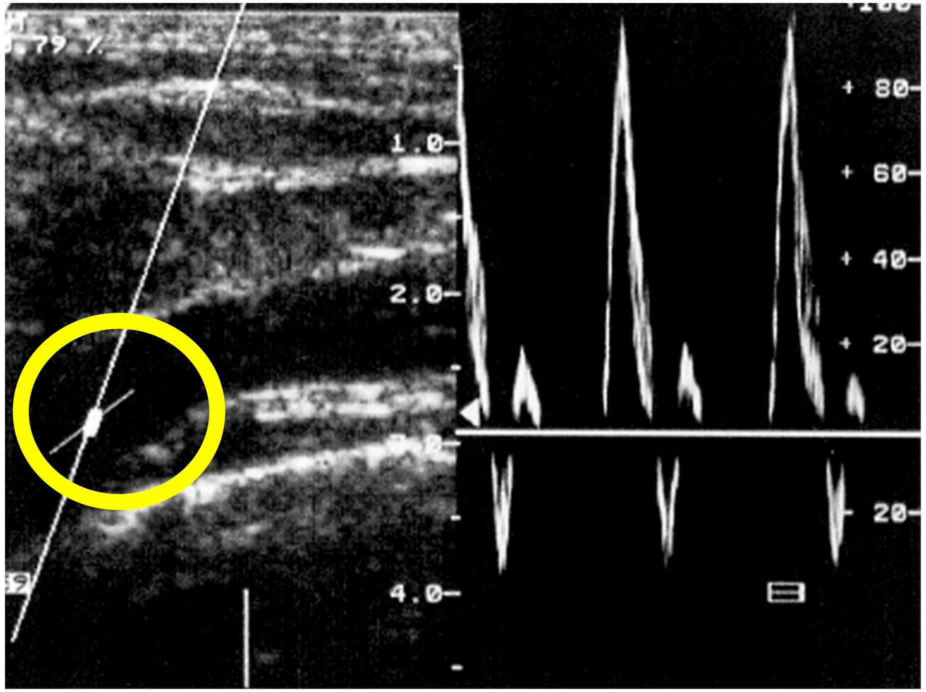
(Courtesy of Dr. Roccarina)

Modes 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.

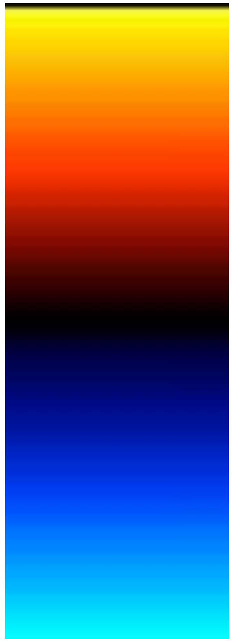


Quantitative estimate of blood flow velocity.

Spectrum of blood flow velocities at any given time.

Angle information is mandatory to convert frequency shifts in blood velocities

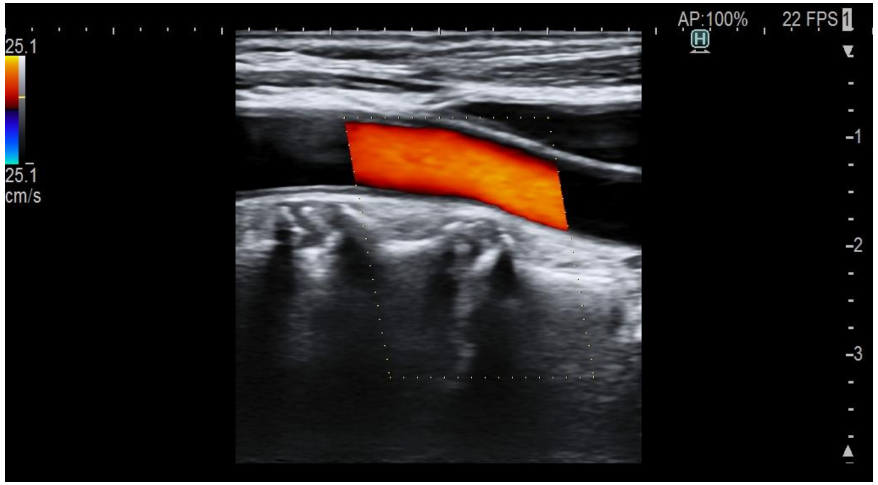
Colour-Doppler



The mean blood flow velocities are color-coded and displayed in a large sample box user-adjustable and superimposed on the B-mode image.

Red: blood flow towards the transducer

Blue: blood flow away from the transducer



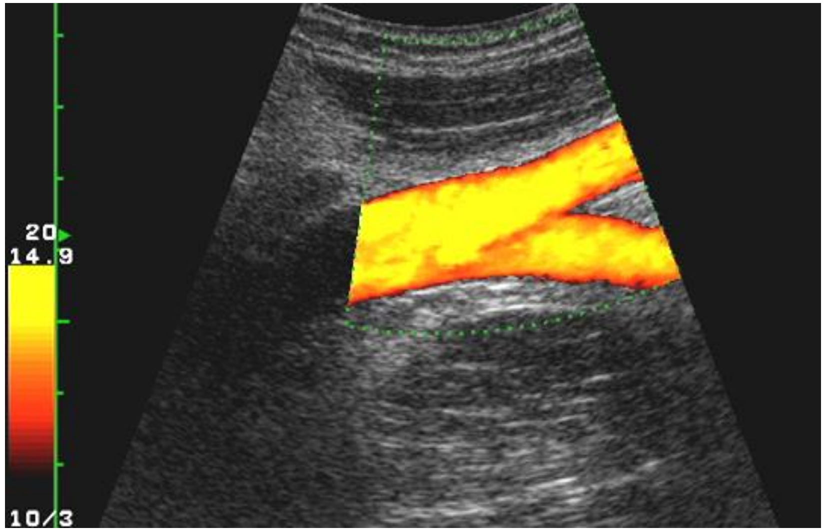
The angle dependency is not as important as with spectral Doppler, as long as the color box is steered correctly.

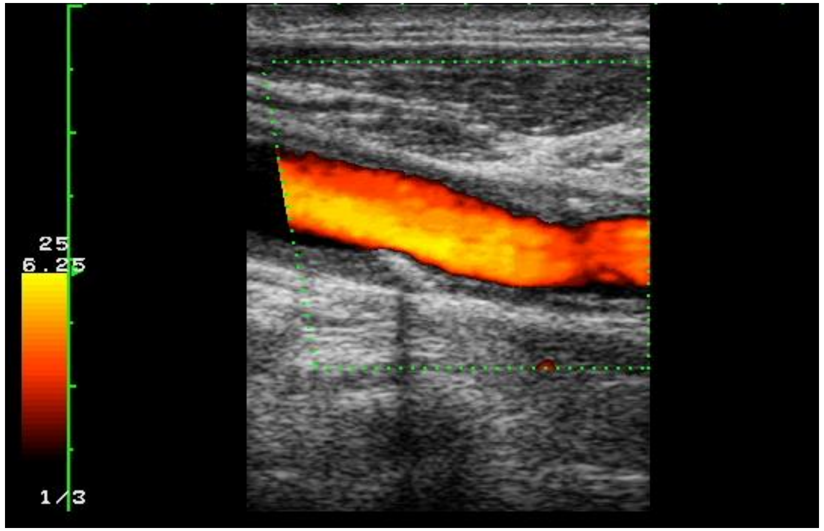
Power-Doppler

It displays the power of the blood flow signals which is related to the amount of red blood cells.

It does not provide blood flow velocity information but has a high sensitivity for visualizing vessel morphology.

The angle dependence has little influence, unless the angle between the flow and the beam direction is 90°.



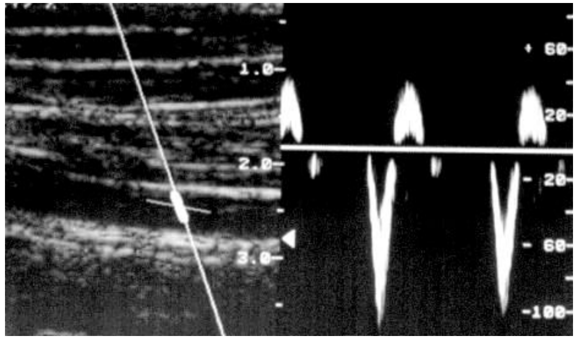


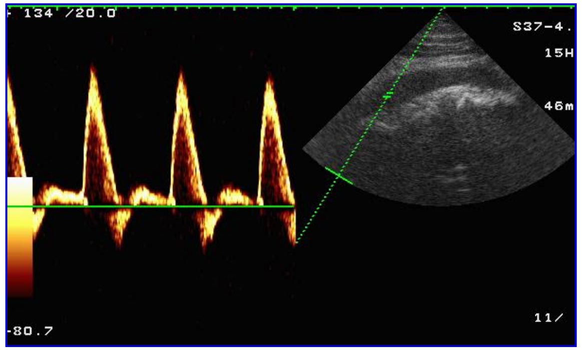
Doppler Waveforms: Arteries

Multiphasic pattern

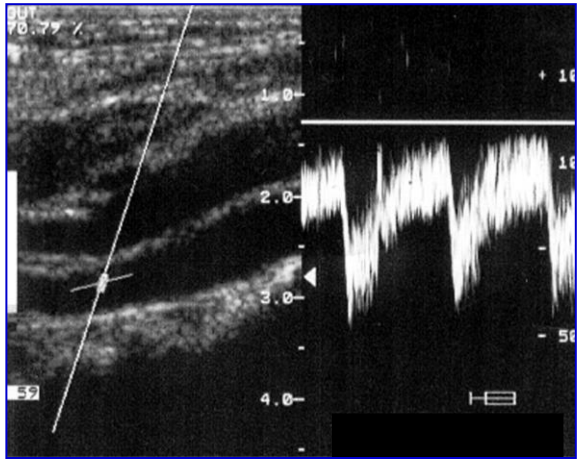
Waveform crosses the zero-flow baseline and contains both forward and reverse velocity components.

High resistance





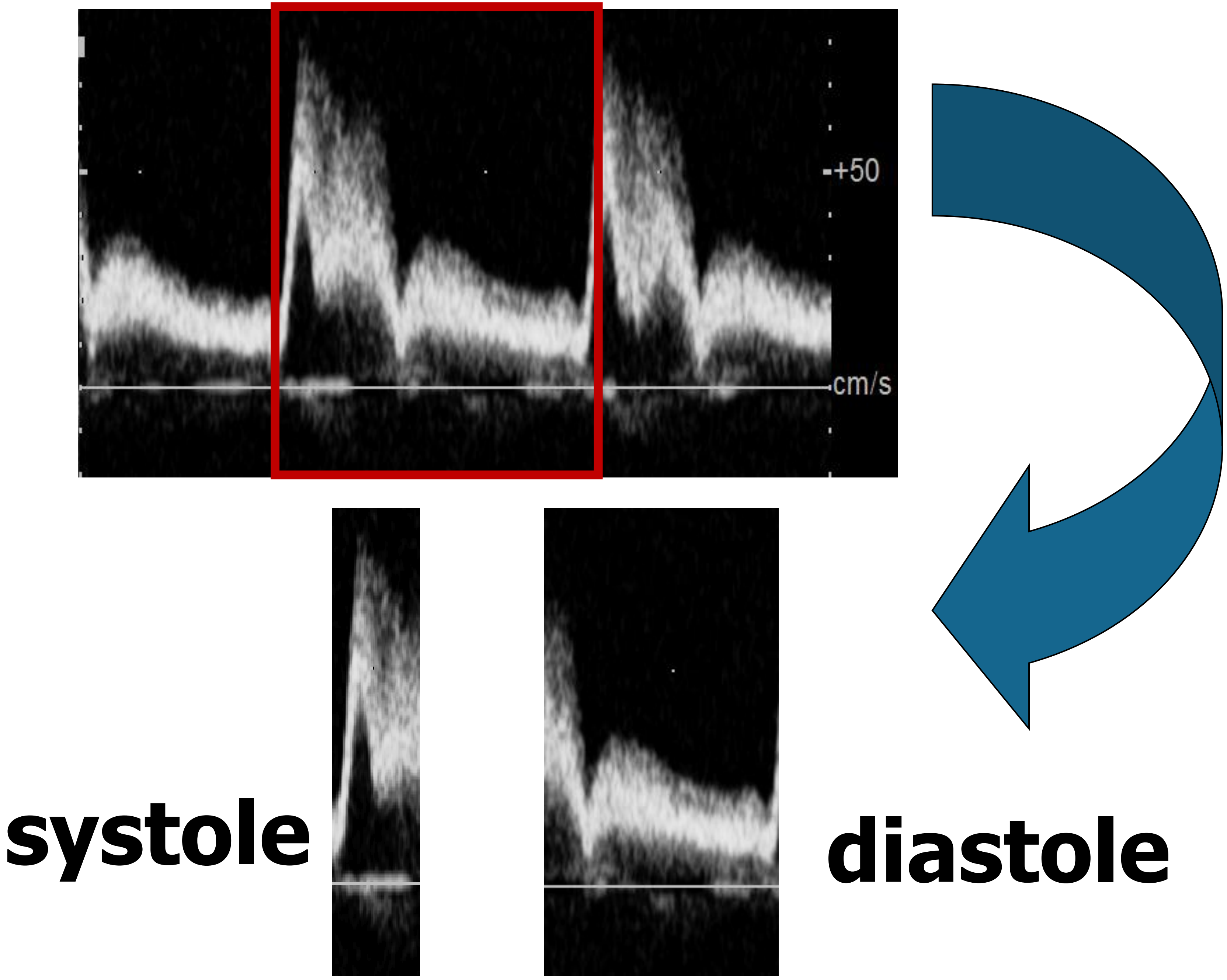
Intermediate resistance

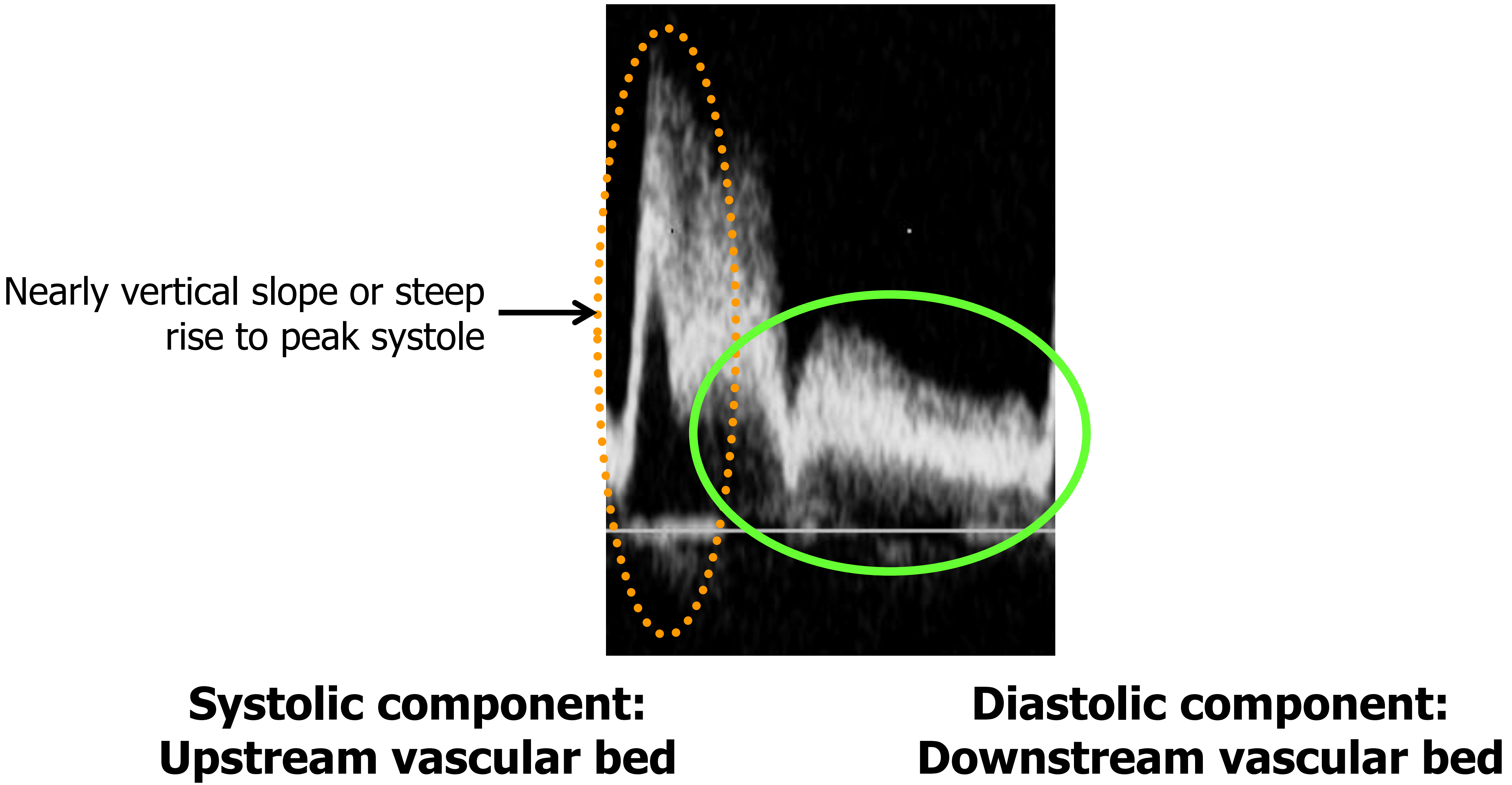


Monophasic and low resistance pattern

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

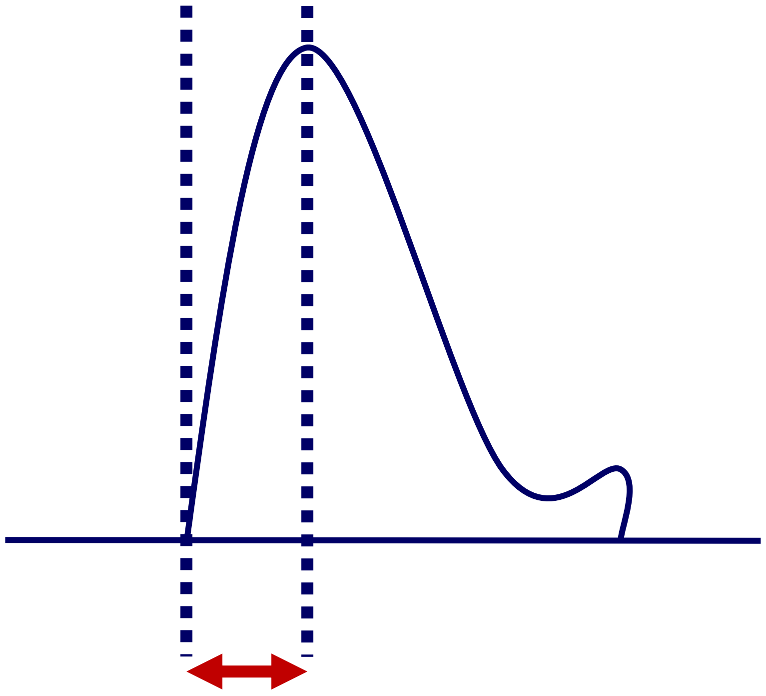

+50
cm/s
systole
diastole


Nearly vertical slope or steep rise to peak systole
Systolic component: Upstream vascular bed
Diastolic component: Downstream vascular bed

Upstream Vascular Bed

Acceleration time (AT)

It measures the slope of the ascending branch of the ultrasound Doppler curve allowing to suspect the existence of an upstream stenosis.



Normal values ≤ 70-140 msec

Downstream Vascular Bed

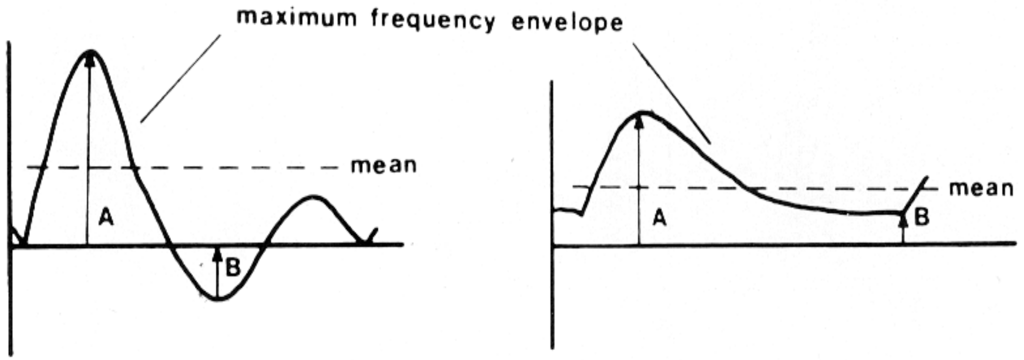
Resistive Index (RI)

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

Low resistance arteries: upper limit 0.70

Pulsatility Index (PI)

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



Ratios between velocities, so they are not affected by the Doppler angle

Blood Flow

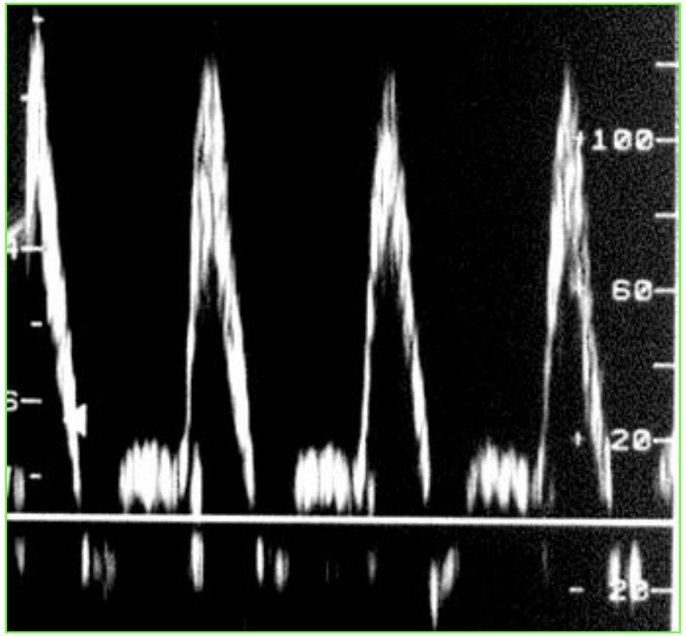
$$F = V_m \cdot A$$

F = Blood flow

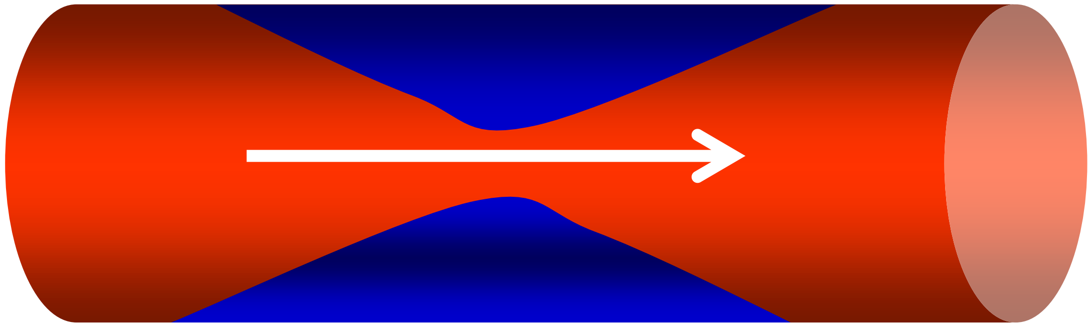
Vm = Mean velocity

A = Area of the vessel

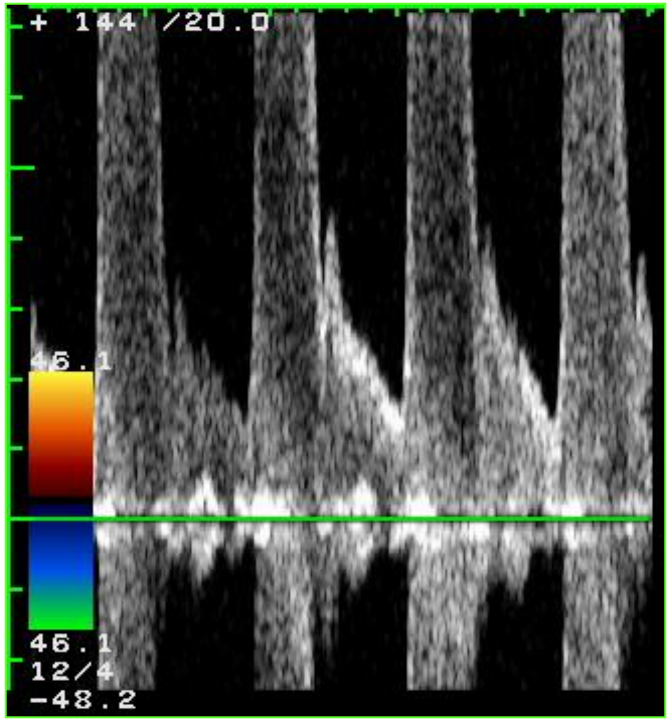
Normal



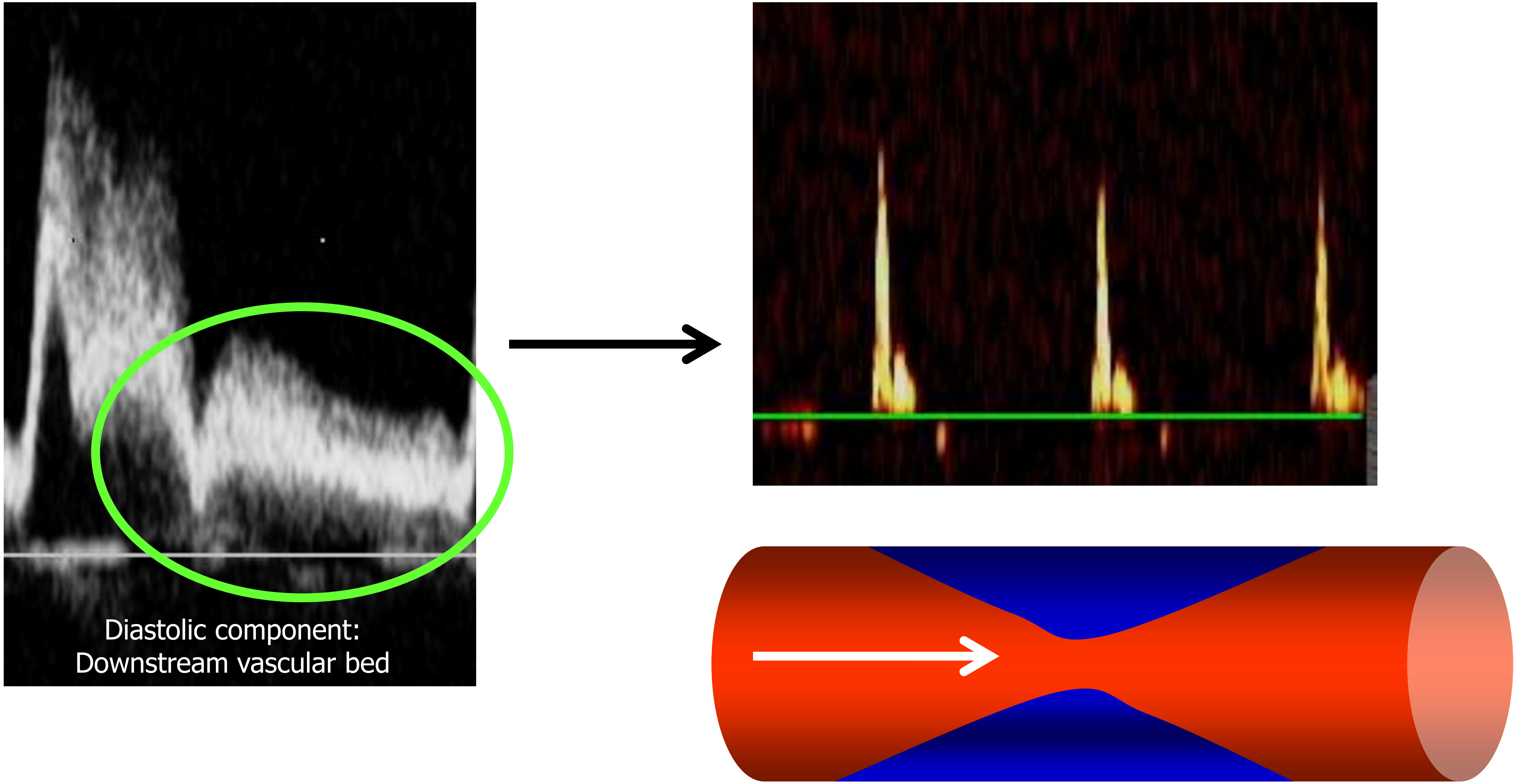
(F = Vm . A)



Stenosis

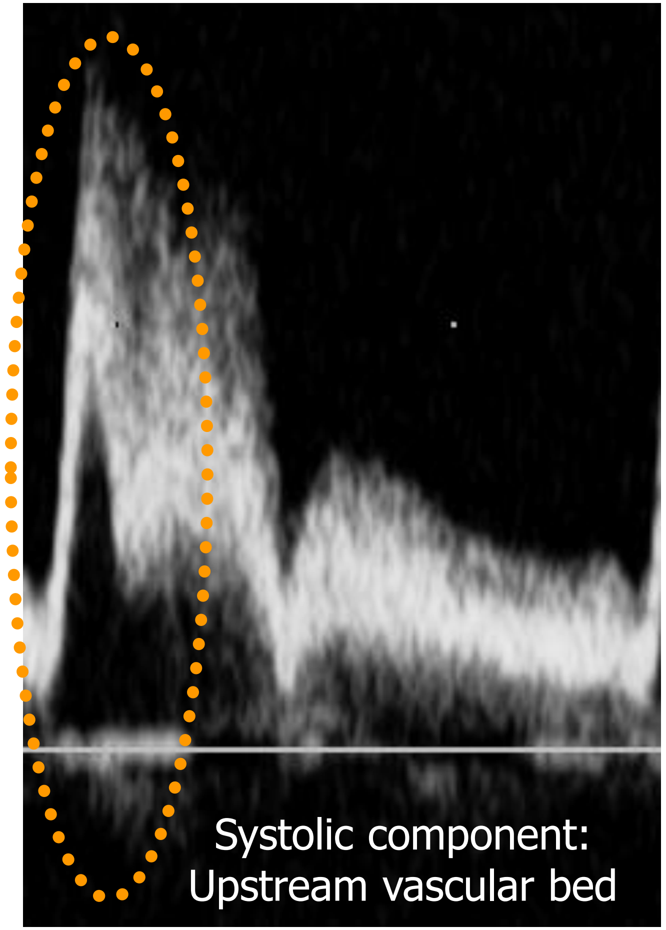


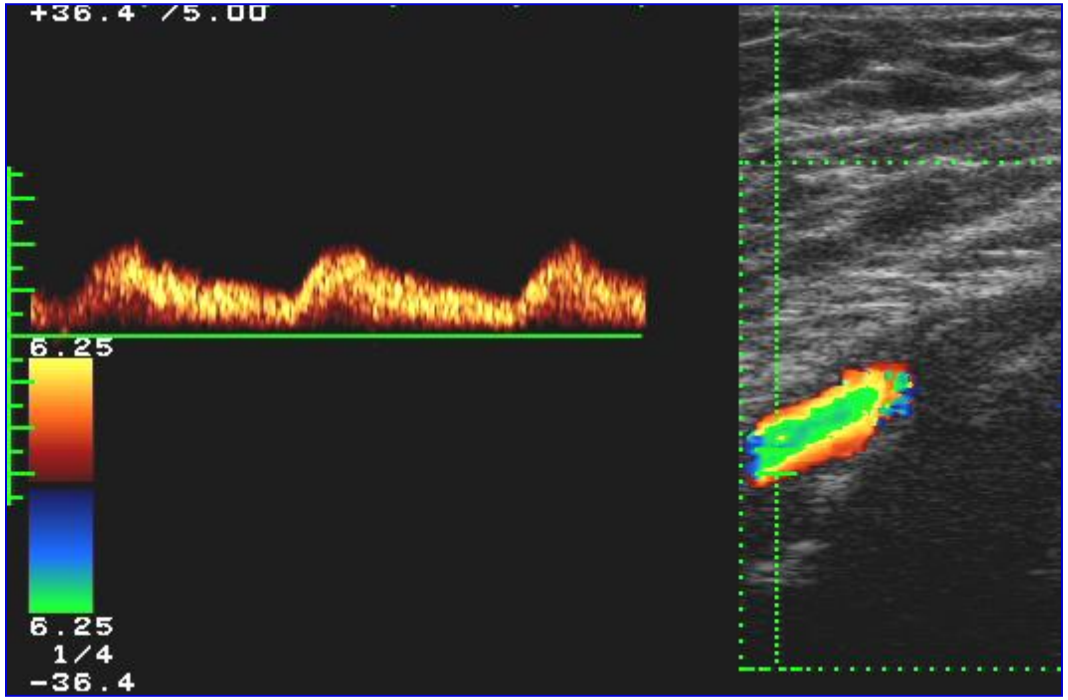
Indirect Criterion for Downstream Stenosis: Increased Resistance

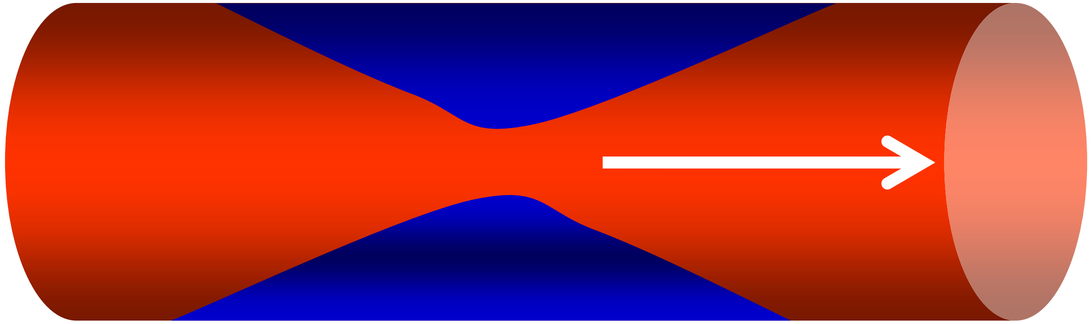


Indirect Criterion for Upstream Stenosis:

Prolonged Upstroke



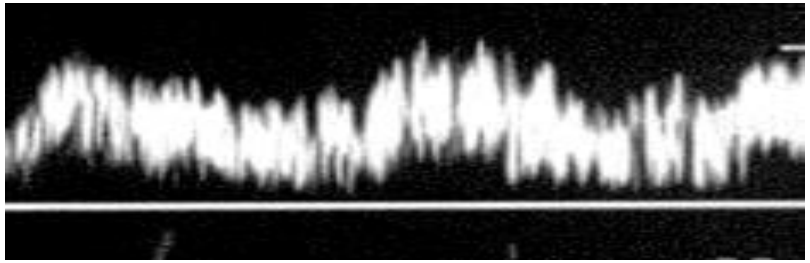


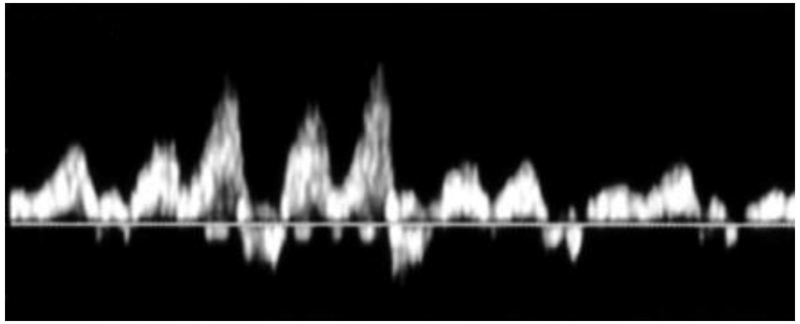


Abnormally slow slope to peak systole

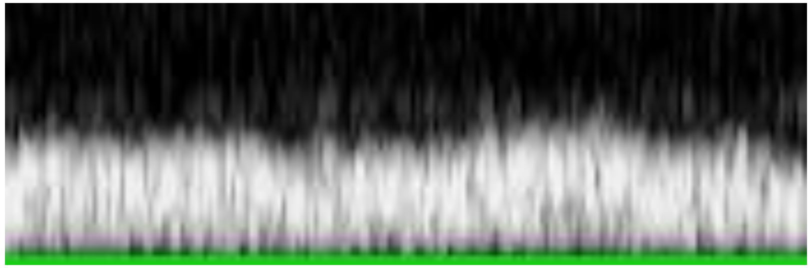
Doppler Waveforms: Veins

Phasic flow (respiratory or cardiac influence on flow velocity)





Continuous flow



Summary

- Frequency Shift = $\dfrac{2\,F_i \,.\, V \,.\, \mathrm{Cos}\,\phi}{C}$

- Pulse Repetition Frequency and Nyquist limit