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Ultrasonic Doppler Modes

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Outline

- Doppler effect
- CW/PW Doppler systems building-blocks
- Pulsed Wave (PW) mode:
  PRF, sample volume, spectral broadening, mean frequency estimation...

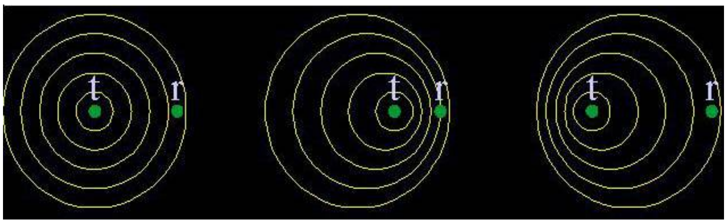
Advanced Doppler systems and methods:

- ➢ Single-gate (TCD, Duplex)
- ➢ Multi-gate
- ➢ Flow-imaging
- ➢ Power, Harmonic & Tissue Doppler imaging

- Doppler artefacts (aliasing, blooming...)

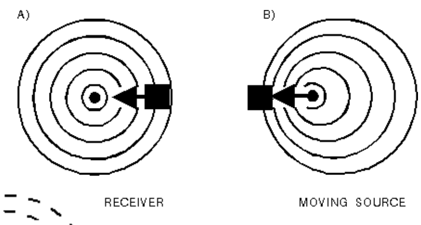
Doppler effect

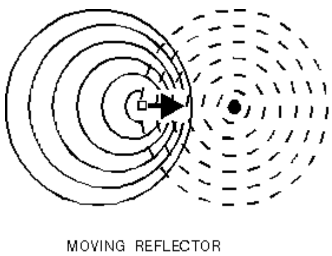
Change in the observed frequency of a wave, due to motion



Fixed Tx and Rx	Rx approaching Tx	Rx receding from Tx
$f_r = f_t$	$f_r > f_t$	$f_r < f_t$

Doppler effect





If the transmitter and the receiver are still but a reflector or scatterer is moving, the Doppler effect takes place in the same way as in A) or B)

A moving reflector / scatterer returns echoes with:

- ***higher frequency if it is approaching the source/receiver or***
- ***lower frequency if it is moving away from the source/receiver***

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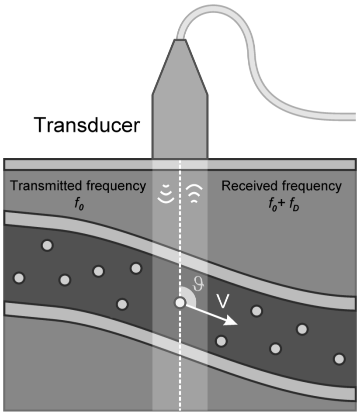
Doppler effect



f_0 = 5 MHz
c = 1500 m/s
ϑ = 60°
v = 30 cm/s

$f_d \cong$ 1 kHz

Difference between Tx and Rx frequencies:

$$f_d = 2\frac{f_0}{c}\cos\vartheta \times v$$

f_0 Tx frequency

ϑ angle between directions of sound propagation and of target path

c sound wave velocity

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Doppler equation

$$f_d = 2\frac{f_0}{c}\cos\vartheta \times v$$

The Doppler frequency shift is proportional to the target velocity, *v*. But it is also:

- proportional to the transmitted frequency, f_0
- proportional to *cos* ϑ *- i.e. it decreases as* $\vartheta \rightarrow 90°$

(and, in particular is 0, when ϑ *= 90°)*

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Blood velocities

Vessel	Speed range (cm/s)
Carotid artery	100 - 150
Ascending aorta	20 - 290
Descending aorta	25 - 250
Abdominal aorta	50 - 60
Femoral artery	100 - 120
Artérioles	0.5 - 1
Capillaries	0.02 - 0.17
Inferior cava vein	15 - 40

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Doppler instrumentation

- 2 - 6 MHz
  Abdominal ultrasound, obstetrical and gynaecological exam, echocardiography, transcranial Doppler;
- 7.5 - 14 MHz
  Small parts, vascular Doppler;
- 10 - 20 MHz
  Ophthalmology, special vascular exam;
- 20 - 50 MHz
  Intra-Vascular UltraSound (IVUS), ultrasound biomicroscopy (ophthalmology, dermatology);

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US Doppler equipment

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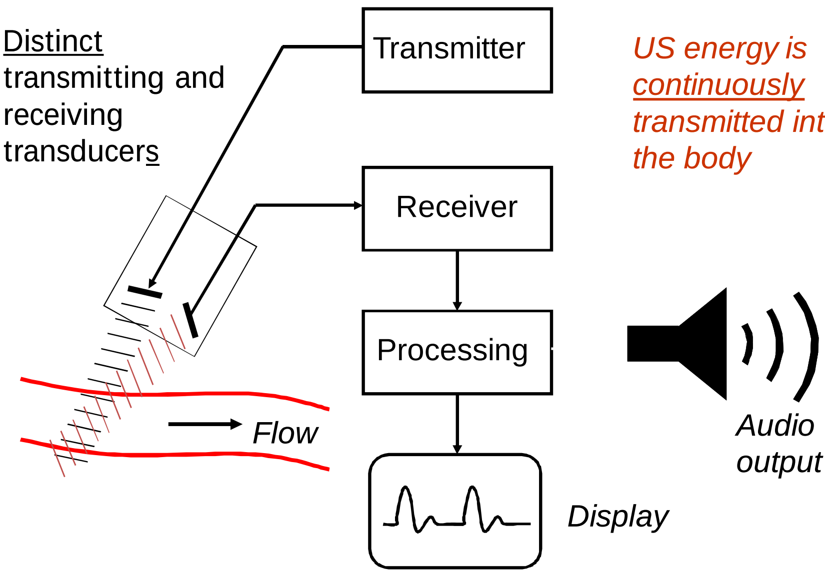
Integrated US equipment

Continuous Wave (CW) systems

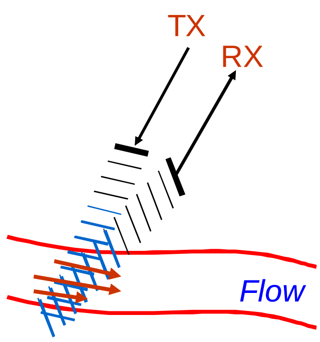
Distinct transmitting and receiving transducers

US energy is *continuously* transmitted into the body



CW: benefits and drawbacks

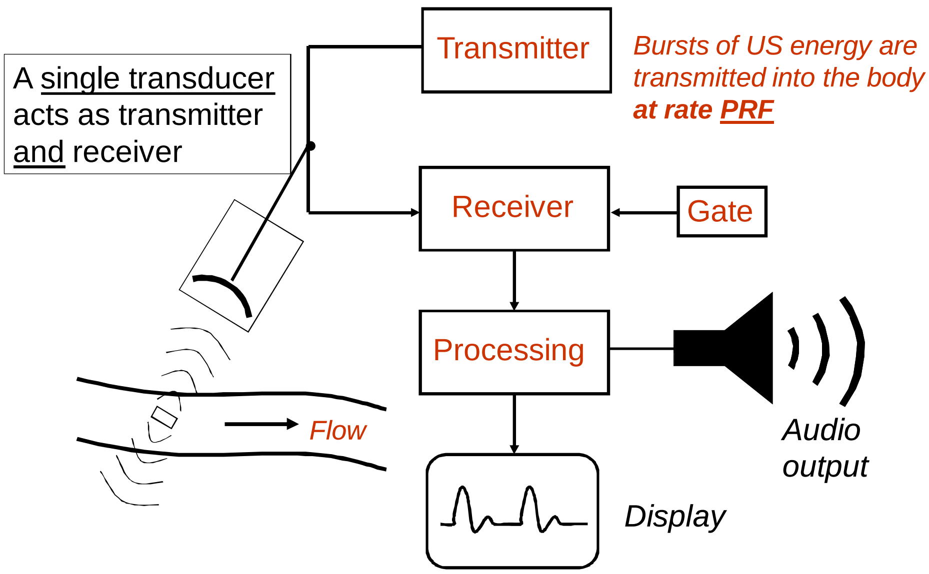
Echoes backscattered from the region where TX and RX beams overlap, are integrated in the receiver



- *Large investigated volume* →
  - ✓ easy transducer positioning
  - ➢ *strong "clutter"*
  - ➢ *no possibility of selecting the region for investigation*
  - ➢ *no discrimination between different flow contributions*
  - ✓ No *aliasing*

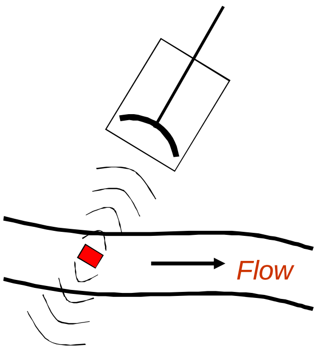
Used only in cardiology

PW systems



PW: benefits and drawbacks

Only the echoes backscattered from the selected *sample volume* are *gated* in the receiver



- Selection of the R.O.I. →
  - ✓ possible discrimination between different flow contributions
  - ➢ possible difficulties in transducer positioning
- ➢ Risk of *aliasing*

Used in most advanced instruments

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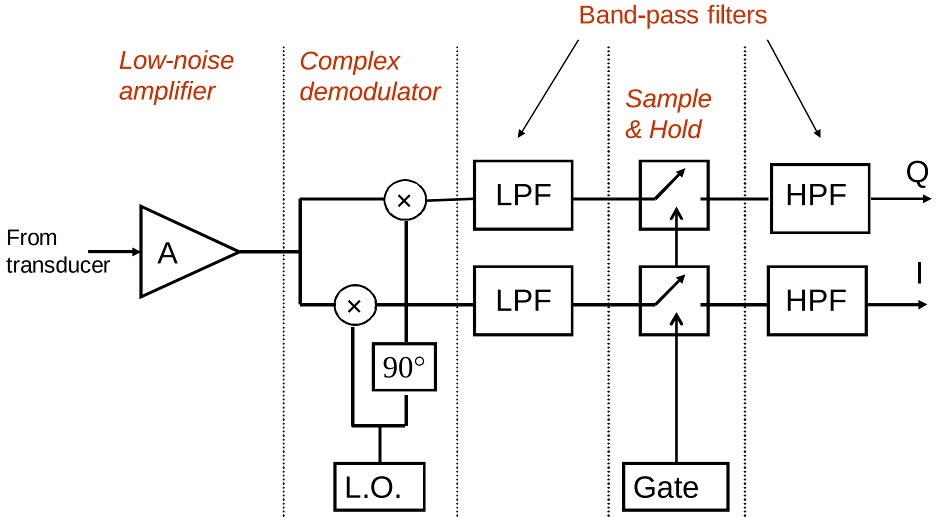
Doppler RX architecture



•The In-Phase & Quadrature channels are needed to distinguish positive from negative Doppler shifts
•In recent systems, the echo-signal is sampled at rf (digital processing)

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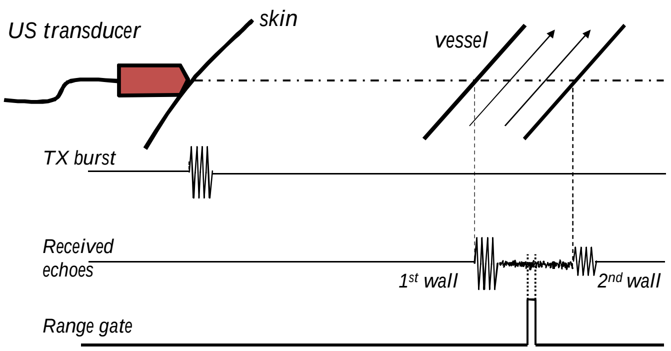
PW RX: Gate (Sample/Hold)



•Bursts are transmitted at *PRF* rate: for each TX burst, *one* sample of the Doppler signal is obtained (*time sampling*).
• The electronic gate selects the information backscattered only from the region of interest (*sample volume*).

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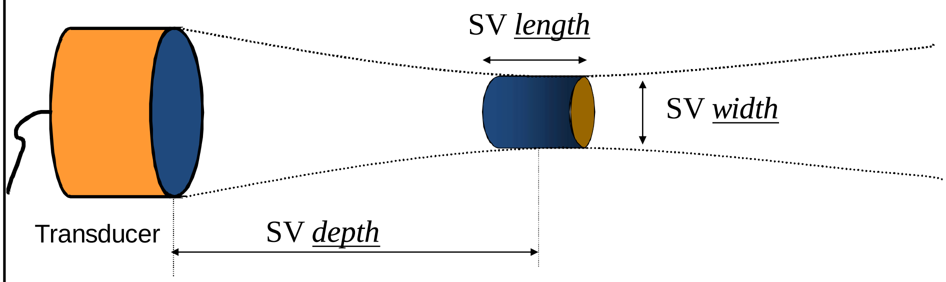
PW sample volume

Blood/tissue volume contributing to the Doppler signal



- The *depth* and the *length* can be set by the operator
- The *width* depends on the transducer features/settings

Small SV → ✓ Better resolution
➢ Worst S/N

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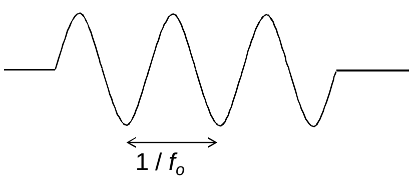
Pulse Repetition Frequency (PRF)

For each Pulse Repetition Interval (PRI), one burst of few cycles at frequency f_o is transmitted.



The rate (1/PRI) at which the bursts are transmitted is called PRF

- The delay of each echo is proportional to the depth of the target
- The PRF should be low enough that a new burst is not transmitted before the last echo from the max depth (D_{max}) has not come back (**$PRF_{max} = c / (2xD_{max})$**)

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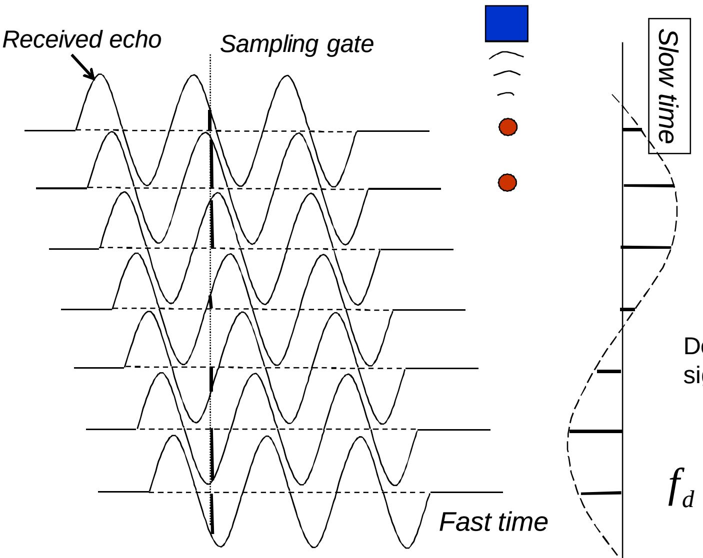
PW: still Doppler?



Detected signal frequency:

$$f_d = 2\frac{v}{c} f_0 \cos\vartheta$$

If a scatterer moves at constant velocity, *v*, subsequent echoes are delayed by a fixed amount: $2 \times v \times \cos\vartheta \times T_{PRF} / c$

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Audio output

All Doppler frequencies fall in the audio range

→ The sound produced by loudspeakers provides immediate (but *qualitative* and *operator-dependent*) information on blood movement

J.V.

C.C.A.

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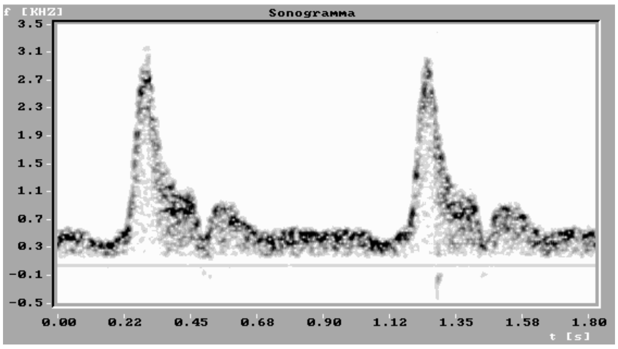
Spectral analysis

Spectral analysis of the Doppler signal allows
distinct velocity contributions to be discriminated



In Doppler spectrograms, subsequent spectra are grey-scale coded and displayed in adjacent vertical lines

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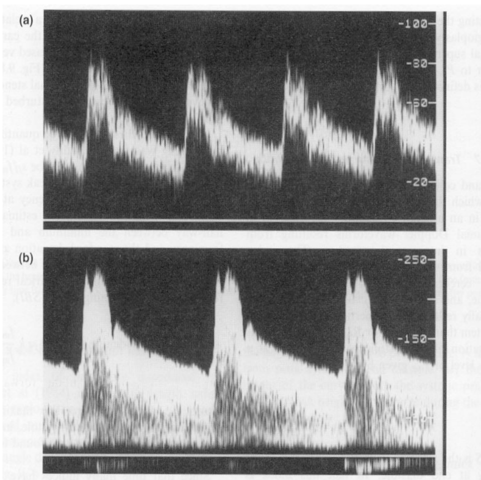
Spectral analysis applications

Detection of stenosis



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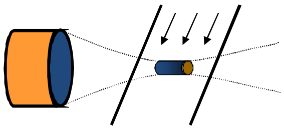
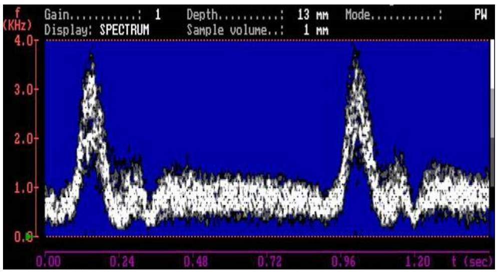
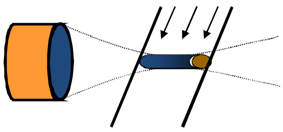
Influence of SV dimensions

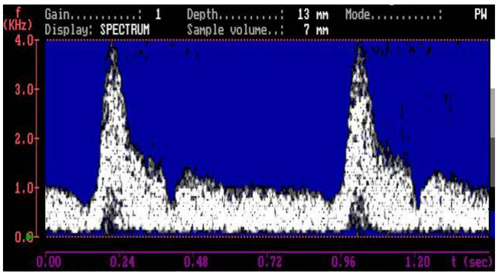
Small Sample Volume





Large Sample Volume





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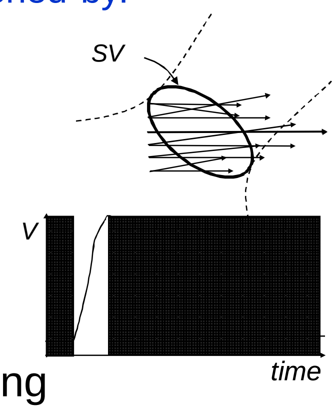
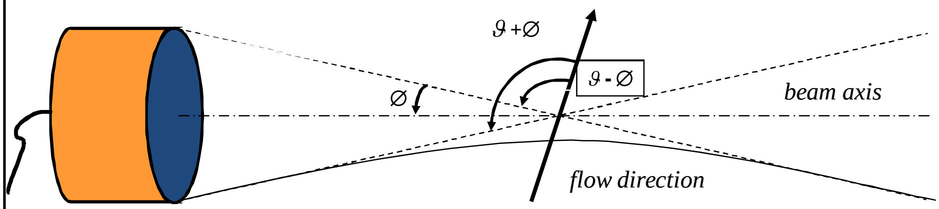
Spectral broadening

The Doppler spectrum is never given by a single line, because is broadened by:

- Velocity gradients *(Flow+SV)*
- Direction variations *(Flow+SV)*
- Accelerations *(Flow+FFT length)*
- Geometric spectral broadening *(Transducer)*



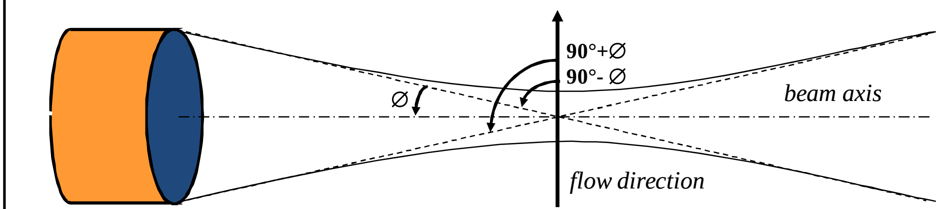
Geometric spectral broadening



The flow is interrogated by a range of angles around the nominal Doppler angle, ϑ

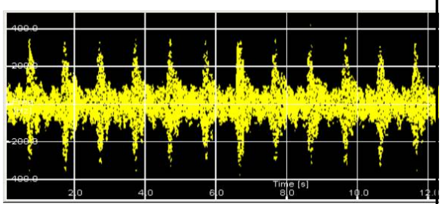
The corresponding Doppler spectrum extends over a range around the nominal Doppler frequency

Transverse Doppler spectrum



The flow is interrogated by a range of angles around the nominal 90° Doppler angle

The corresponding spectrum is symmetrical around zero frequency



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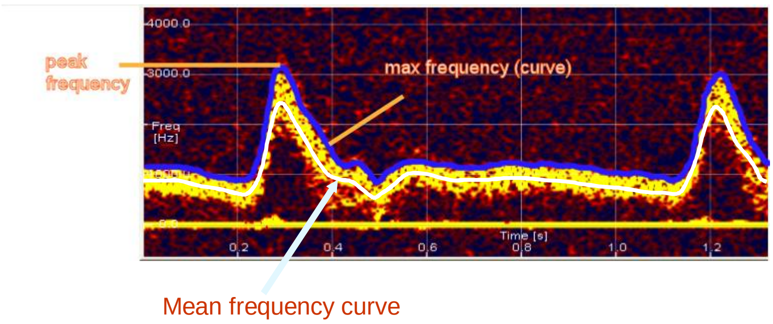
Max and Mean frequency



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Mean freq. Detection: Autocorrelation

$$\varpi = \frac{\int \omega P(\omega) d\omega}{P(\omega) d\omega}$$

P(ω): Doppler signal power spectral density

Doppler signal Autocorrelation:

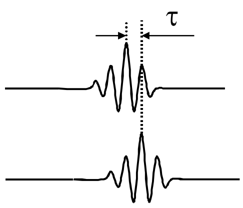
$$R(t) = \int P(\omega) \exp(j\omega t) d\omega$$

$$R'(t) = \frac{dR(t)}{dt} = \int P(\omega) \frac{d \exp(j\omega t)}{dt} d\omega = \int j\omega P(\omega) \exp(j\omega t) d\omega$$

→ The mean frequency can be expressed as: $\varpi = \frac{1}{j} \frac{R'(0)}{R(0)}$

(this equation is widely used in Flow Imaging systems)

Mean freq. detection: Cross-correlation

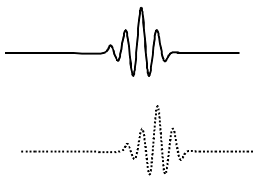


$S_N(t)$: N^{th} Doppler echo

$S_{N+1}(t)$: $[N+1]^{th}$ Doppler echo

When such echoes are stored in a digital memory, τ corresponds to the shift needed to make them overlap

τ can be estimated as the value maximizing:



$$\int S_N(t)\, S_{N+1}(t+\tau)\, dt$$

Quantification of Doppler waveforms

Pulsatility index (1-10):

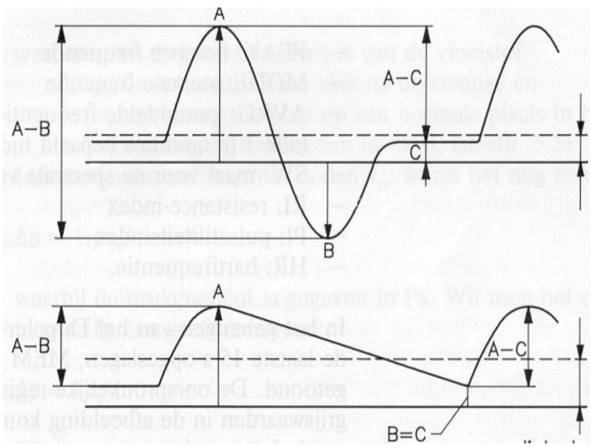
PI = (A-B)/mean

= (peak systole-peak diastole) / mean

Resistance index (0-1):

RI = (A-C)/A

= (peak systole-end diastole) / peak systole

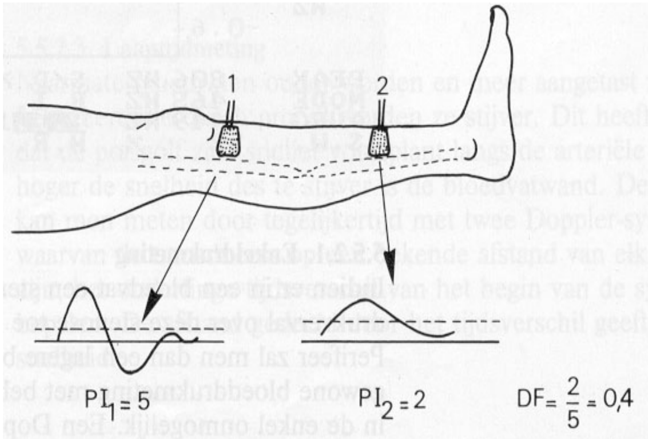


(Courtesy of Johan Thijssen)

Peripheral vascular damping factor

Damping factor:

$DF = PI_2 / PI_1$



(Courtesy of Johan Thijssen)

Summary of the 1st part

- Doppler equipment basically includes:
  - Transmitter (CW/PW)
  - Receiver
  - Processing
- Full digital signal processing is used
- Choice between different processing methods depends on the application