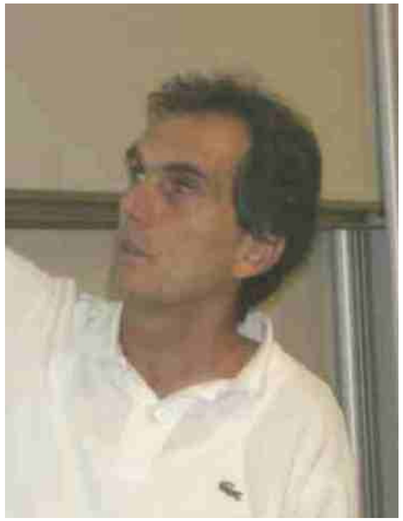
2012 :15th SESSION of ESMP

Lecture presented in Archamps (Salève Building) by :

Piero TORTOLI (Florence)



European School of Medical Physics - Archamps

Università degli Studi di Firenze

Ultrasonic Doppler Modes

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Outline

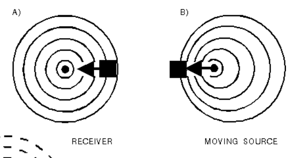
- Doppler effect
- Doppler systems building-blocks:
  - Transducer, TX, RX, Processing
- Continuous Wave (CW) mode
- Pulsed Wave (PW) mode
  - Single-gate (TCD, Duplex)
  - Multi-gate
  - Flow-imaging
  - Power, Harmonic & Tissue Doppler imaging
- Doppler artefacts (aliasing, blooming...)

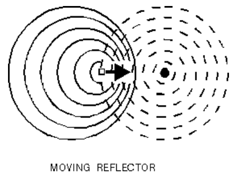
Doppler effect

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

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

Doppler effect

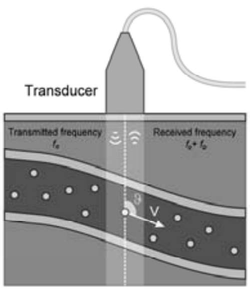




If the transmitter and the receiver are still but a reflector or scatterer is moving, the Doppler effect takes place in the same way as in A) or B)

A moving reflector or scatterer (   ) returns echoes with higher frequency if it is approaching the source/receiver or of lower frequency if it is moving away from the source/receiver

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

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
  - zero, when the Doppler angle is 90°

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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);

Ultrasound Doppler equipment

Handheld systems (fetal monitoring, PAOD…)

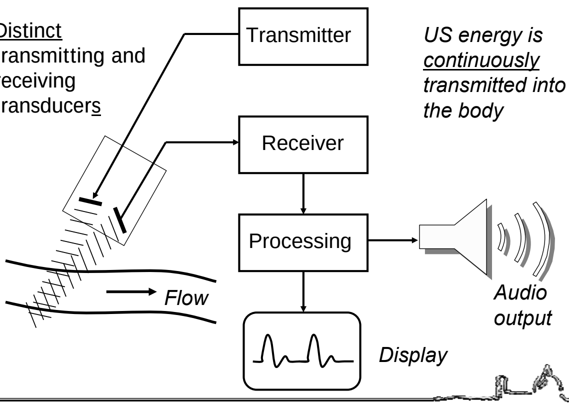
Portable systems (TCD, bedside echo-cardiography…)

Advanced systems (assessment of stenosis, hemodynamics, heart valve function, TDI…)

Doppler systems building blocks: I-Continuous Wave (CW) systems

Distinct transmitting and receiving transducers

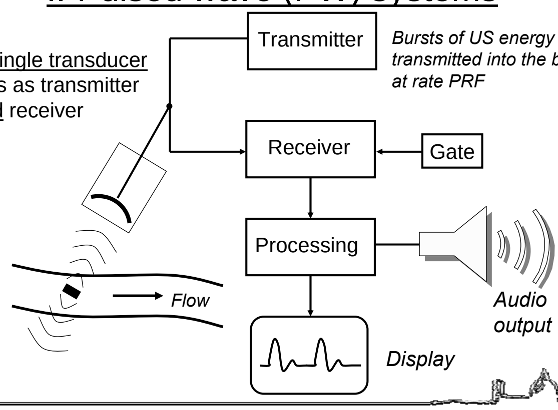
US energy is continuously transmitted into the body



Doppler systems building blocks: II-Pulsed wave (PW) systems

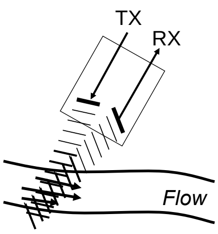
A single transducer acts as transmitter and receiver

Bursts of US energy are transmitted into the body at rate PRF



CW systems: benefits & drawbacks

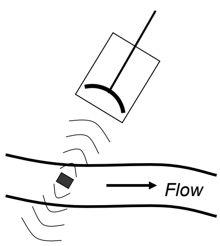
Echoes backscattered from the region where TX and RX beams overlap, are integrated in the receiver



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

PW systems: benefits & 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*

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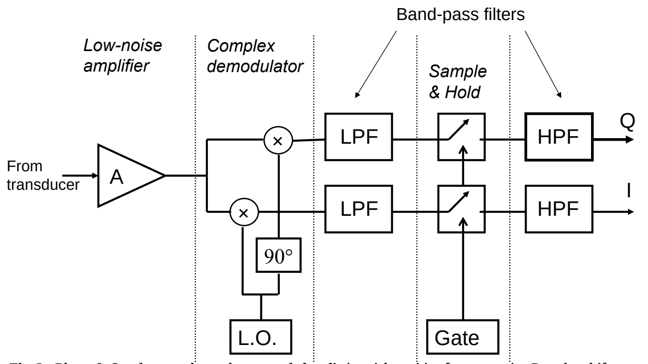
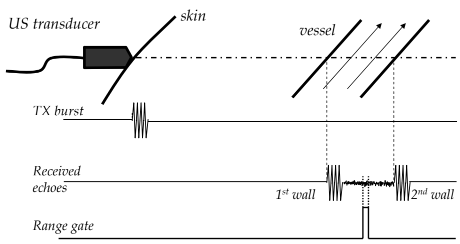
Doppler receiver architecture



•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)

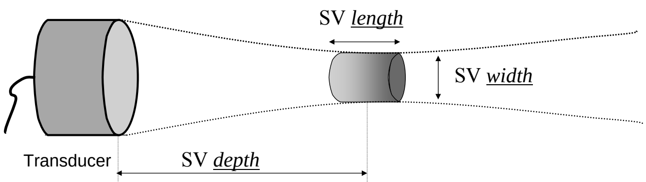
PW receiver: Gate (Sample & Hold)



- In PW systems, an electronic gate selects the information backscattered from the region of interest (*sample volume*).
- For each transmitted burst, *one* sample of the Doppler signal is obtained.

PW systems: Sample Volume (SV)

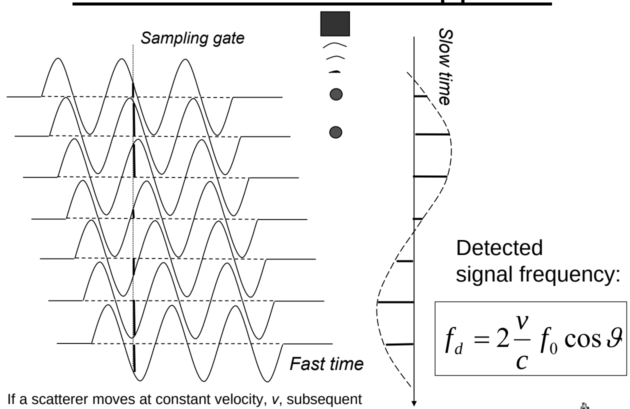
Blood/tissue volume contributing to the Doppler signal



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

Small SV → ✓ Better resolution
➢ Worst S/N

PW mode: is it still "Doppler"?



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

Doppler frequency detection: Audio output

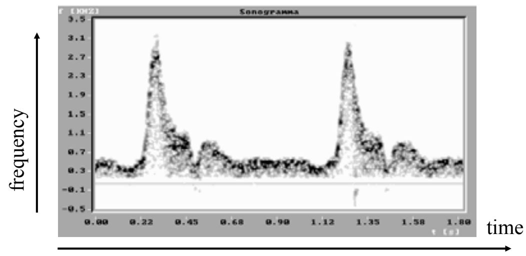
All Doppler frequencies fall in the audio range

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

J.V. C.C.A.

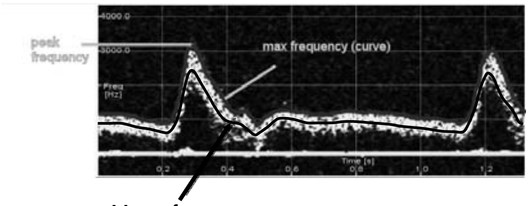
Doppler frequency detection: Spectral Analysis

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

Maximum & mean frequency



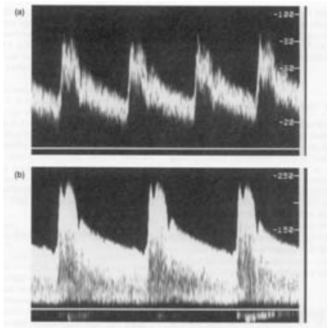
Mean frequency curve

Application of spectral analysis: Stenosis detection in the carotid artery

a. Healthy subject

b. Patient with proximal stenosis

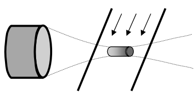
(turbulence)

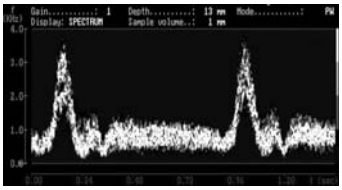


(Courtesy of Johan Thijssen)

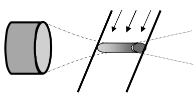
Influence of SV dimensions

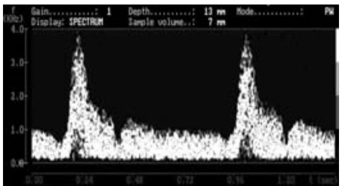
Small Sample Volume





Large Sample Volume

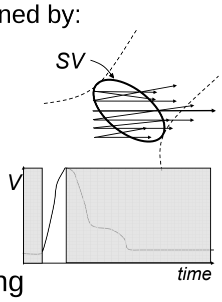




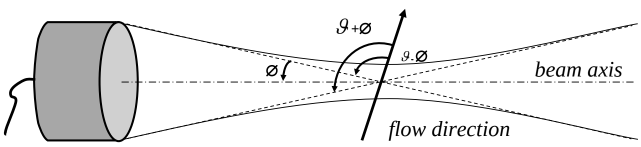
Doppler spectral broadening

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)*



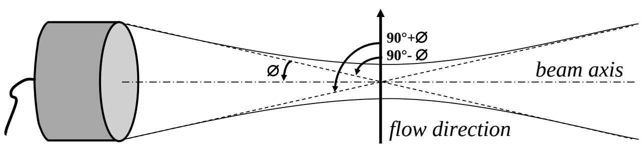
Geometric spectral broadening



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

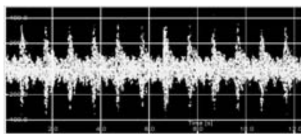
The corresponding Doppler spectrum extends over a range around the nominal Doppler frequency

Transverse Doppler spectrum



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

Corresponding spectrum is symmetrical around zero frequency



Mean frequency estimation

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

P(ω): Doppler signal power spectral density

Doppler signal Autocorrelation: $R(t) = \int P(\omega) \exp(j\omega t) d\omega$

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

→ Mean frequency can be expressed as: $\boxed{\varpi = \frac{1}{J} \frac{R'(0)}{R(0)}}$

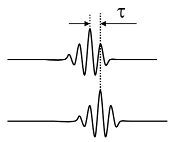
Mean frequency estimation: Autocorrelation

- In PW systems, one sample of the Doppler signal is obtained for each pulse transmitted at PRF.
- In the numerical domain, the mean frequency can be obtained through:

$$\varpi = PRF \frac{1}{(N_C - 1)} \arctan \frac{\sum_{k=0}^{N_c-2} Q(k+1)I(k) - I(k+1)Q(k)}{\sum_{k=0}^{N_c-2} I(k+1)I(k) - Q(k+1)Q(k)}$$

(I,Q: complex Doppler signal components
N_c: N. of consecutive samples used for estimation)

Mean frequency estimation: Cross-correlation

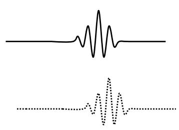


$S_N(t)$: N^{th} Doppler echo

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



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

Quantification of Doppler waveforms

Pulsatility index (1-10):

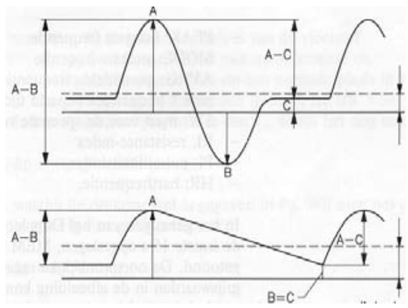
PI = (A-B)/mean

= (peak systole-peak diastole) / mean

Resistance index (0-1):

RI = (A-C)/A

= (peak systole-end diastole) / peak systole

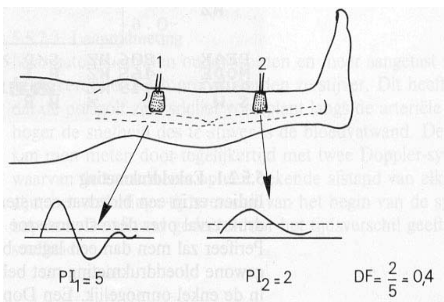


(Courtesy of Johan Thijssen)

Peripheral vascular "damping factor"

Damping factor:

$DF = PI_2 / PI_1$



(Courtesy of Johan Thijssen)

Summary of first part

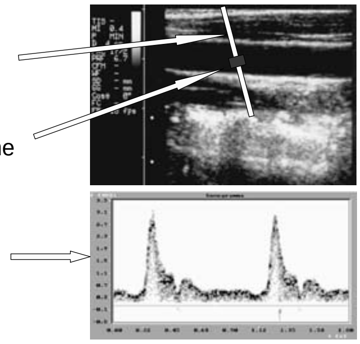
- Doppler equipment basically includes:
  - Transmitter (CW/PW)
  - Receiver
  - Processing
- Full digital signal processing is used
- Choice between different processing methods depends on application

Ultrasonic Doppler Modes: Outline of second part

- Pulsed Wave (PW) mode:
  - Duplex (Single-gate)
  - Multi-gate
  - Flow-imaging
  - Power and Harmonic Doppler
  - Tissue Doppler Imaging
- Doppler artefacts (aliasing, angle ambiguity, blooming…)

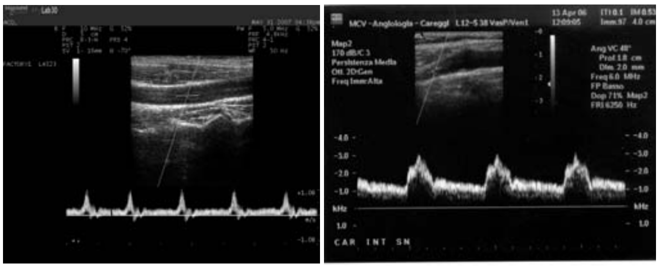
Echo-Doppler (Duplex) PW systems

- A (M-mode) scan line can be superimposed to a B-mode image
- Over the scan line, a specific sample volume can be selected
- The Doppler signal produced from the gated sample volume is analysed



Ideal for stenosis assessment

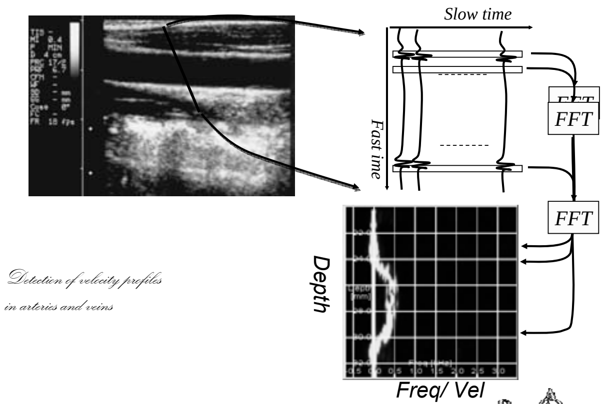
Echo-Doppler (Duplex) examples

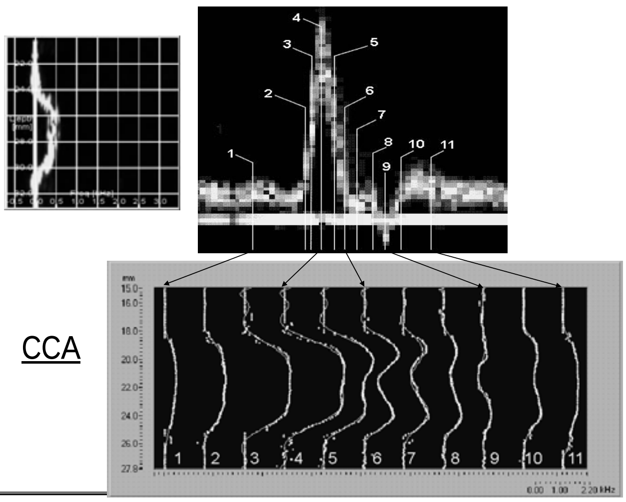


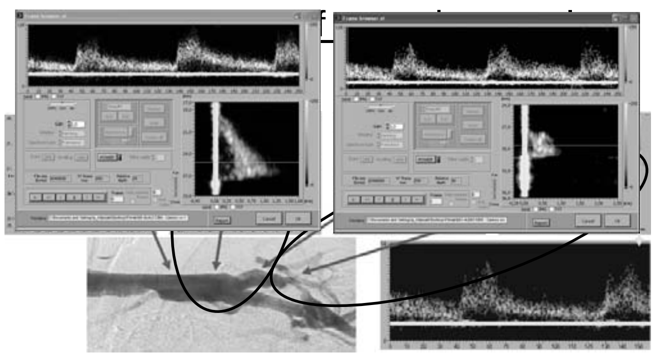
Healthy CCA

Stenotic Internal CA

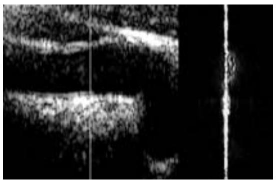
Multigate Spectral Doppler systems





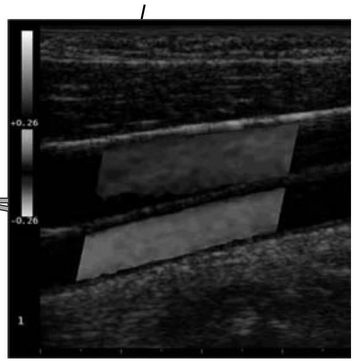


Dual (B+MSD) Mode



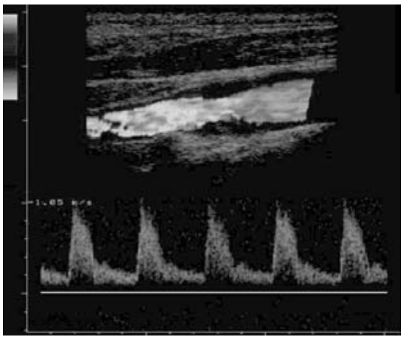
Flow imaging mode

- Real-time 2D velocity maps are obtained
  - By firing several pulses for each scan line
  - By estimating the mean frequency (velocity) detected at each depth
  - By color-coding consecutive pixels according to the detected mean frequencies
  - By scanning a 2-D region
- *Frame rate limitations*
- *Unsuitable for low velocities*

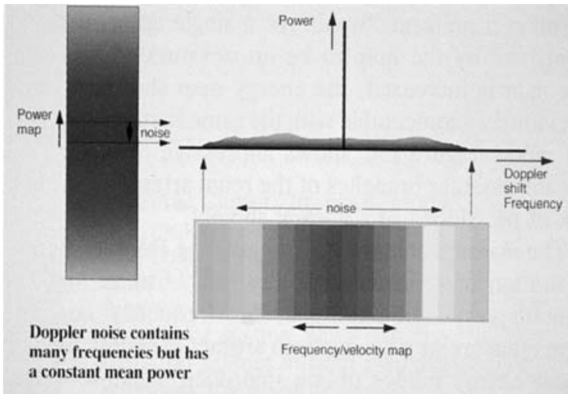


Multigate processing applied to multiple scan lines

Example of Doppler imaging: non-hemodinamic internal carotid stenosis



Power Doppler



Power Doppler mode

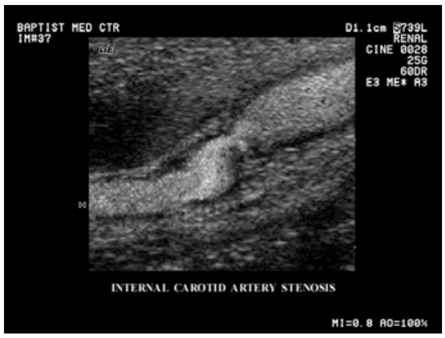
- For each scan line, the power of Doppler echoes is detected and integrated (persistance)

  ☺ High S/N
  ☺ Ideal for small vessels

  ➢ All movements (including "slow" blood and tissue movements) are detected
  ➢ Qualitative (velocity magnitude is ignored)

Same hardware as for Doppler imaging: software differences

B-Flow Mode

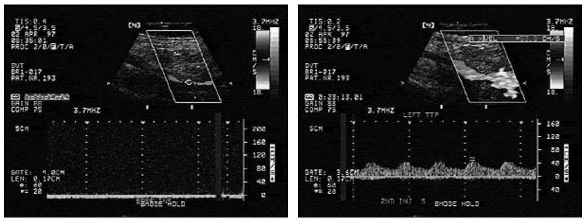


High resolution; High blood/tissue ratio

Doppler modes with Contrast agents

Echo enhancement with contrast agents

Injection of US contrast agents (microbubbles in a shell) generates strong backscattering (*echo enhancement*)



Useful for small, deep, hardly accessible vessels (eg:TCD analysis)

Harmonic Doppler mode

- Non-linear behaviour of US contrast agents yields 2nd harmonic ($2{\times}f_t$) components much stronger than those generated by tissue

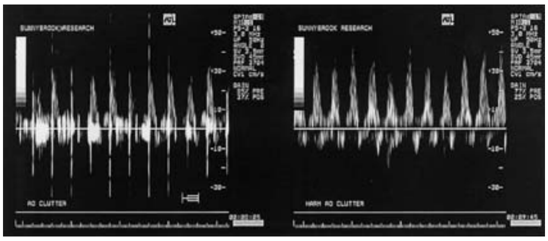
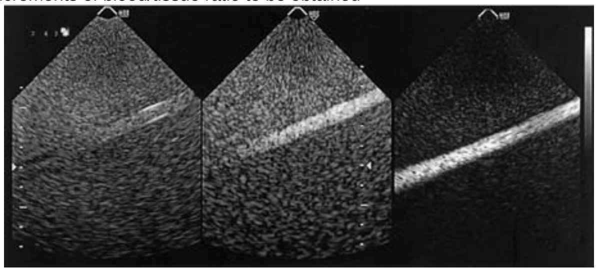


Figure 6. *Clutter rejection with harmonic spectral Doppler.* **A.** *The abdominal aorta of an animal is examined with harmonic spectral Doppler. In conventional mode, clutter from the moving wall causes the familiar artifact, which also obscures diastolic flow.* **B.** *In harmonic mode, the clutter is almost completely suppressed so that flow can be resolved. The*

Need for wideband transducers – Suitable for perfusion assessment

Harmonic Doppler modes

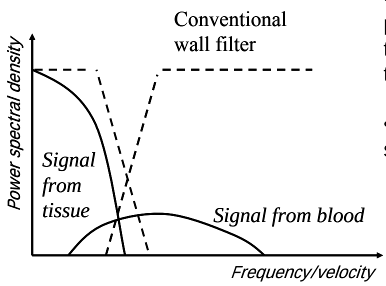
- Detection of 2nd harmonic echoes allows to reverse the roles of blood & tissue in US images
- More sophisticated TX-RX strategies (eg: *pulse inversion*) allow further increments of blood/tissue ratio to be obtained



Conventional US imaging | Harmonic Doppler imaging | Pulse inversion Doppler imaging

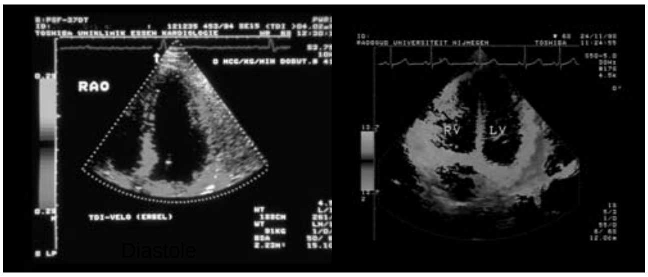
Tissue Doppler Imaging (TDI)

Tissue Doppler imaging (TDI)



- The wall filter partially suppresses the echo-signal from tissue
- In TDI, the blood signal is suppressed!

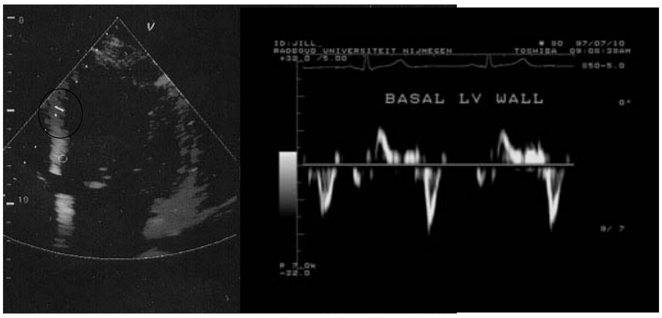
Tissue Doppler images of left ventricle



(Courtesy of Johan Thijssen)

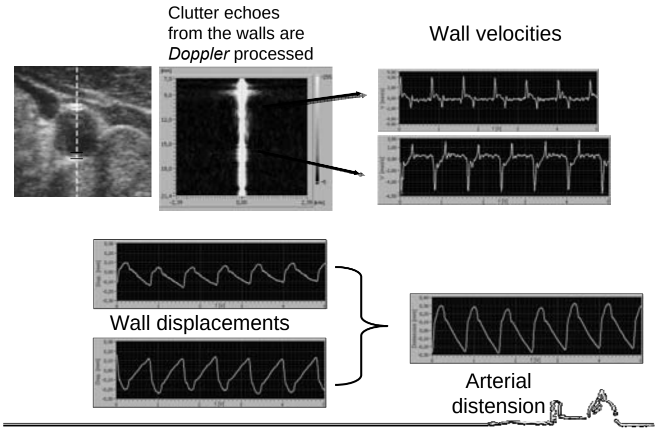
High signal, low velocity image

TDI: single gated Doppler waveforms



(Courtesy of Johan Thijssen)

Arterial wall movement detection



Doppler artefacts

PW system artefacts: aliasing

Aliasing is due to an insufficient sampling rate

- For each transmitted pulse, one sample of the Doppler signal at a given depth is obtained
- Doppler samples are produced at PRF rate
- If the sampling frequency, PRF, is too low with respect to the Doppler frequency, f_d (i.e. if f_d > PRF/2) → ***aliasing***

PW systems artefacts: aliasing

PW systems artefacts: aliasing

If subsequent pictures of the chronograph are taken too rarely, the hand seems to rotate into the wrong direction

PW systems artefacts: aliasing

Aliasing occurs for sampling frequency $f_s > 2B$, with B being the signal bandwidth (*Nyquist limit*).

For PW systems:

f_s = PRF

$B = f_{dmax}$ (maximum Doppler frequency)

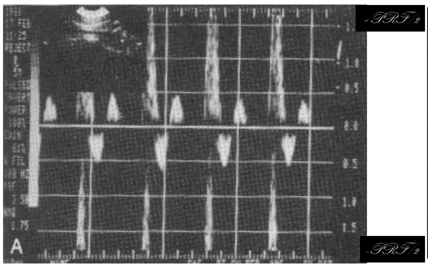
→Nyquist limit: $\mathrm{PRF} > 2B = 2 f_{d\max} = 4 \frac{v_{\max}}{c} f_0 \cos\vartheta$

$$\mathrm{PRF}_{\max} = \frac{c}{2d}$$ ⟵ 2 x depth

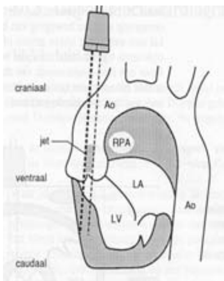
$$v_{\max} < \mathrm{PRF}_{\max} \frac{c}{4 f_0 \cos\vartheta} = \frac{c^2}{8 f_0 d \cos\vartheta}$$

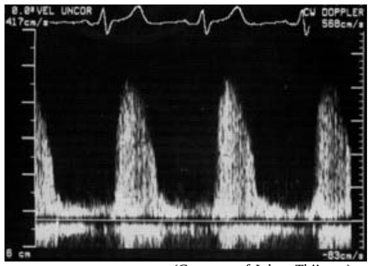
Aliasing effects

In PW Doppler systems, *aliasing* yields Doppler components in wrong positions, or wrong colors in 2-D flow maps



Methods for aliasing limitation
CW Doppler measurement



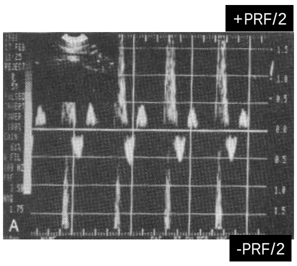


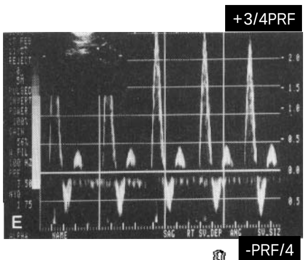
(Courtesy of Johan Thijssen)

Jet stream through aortic valve stenosis

Methods for aliasing limitation

- ✓ Increasing the PRF (D_{max} *decreases*)
- ✓ Increasing the Doppler angle (f_D decreases)
- ✓ Using lower frequency transducers (*worst res*)
- ✓ *Baseline shifting:*

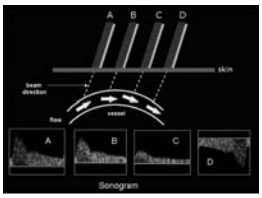




Doppler angle ambiguities

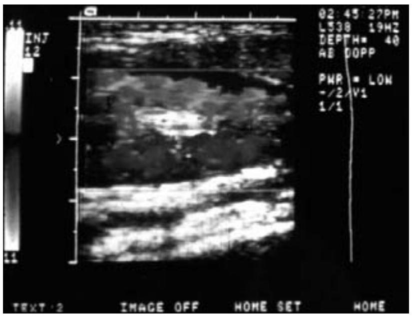
The detected frequency depends on the Doppler angle

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



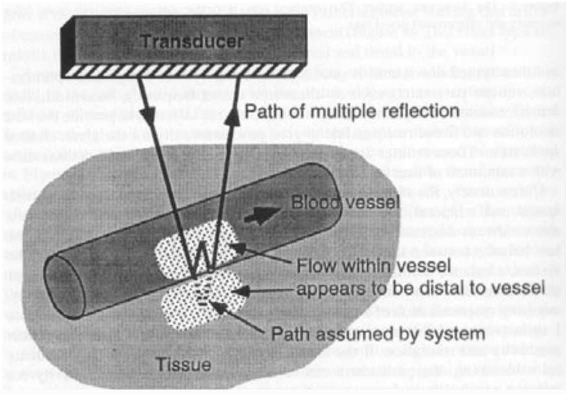
- Frequency/color changes due to a change in the angle of insonation
- If the angle is not known, the frequency cannot be converted to velocity

Doppler artefacts: blooming



Blooming corresponds to the presence of “color” in regions with no movement. It is due to *eccessive* echogenicity of contrast agents

Doppler artefacts: blooming



Blooming risk is minimised by maintaining the Gain as low as possible

Summary

- CW mode is used only in cases where *aliasing* plays a major role (*eg: jets in cardiac valves*)
- All advanced Doppler systems work in PW mode
- PW mode allows range discrimination (flow mapping)
- In advanced Doppler modes, the key element is the transducer (wide bandwidth)
- Further enhancements in velocity detection and reduction of artefacts have to be expected through technological (better transducers!) and software advances