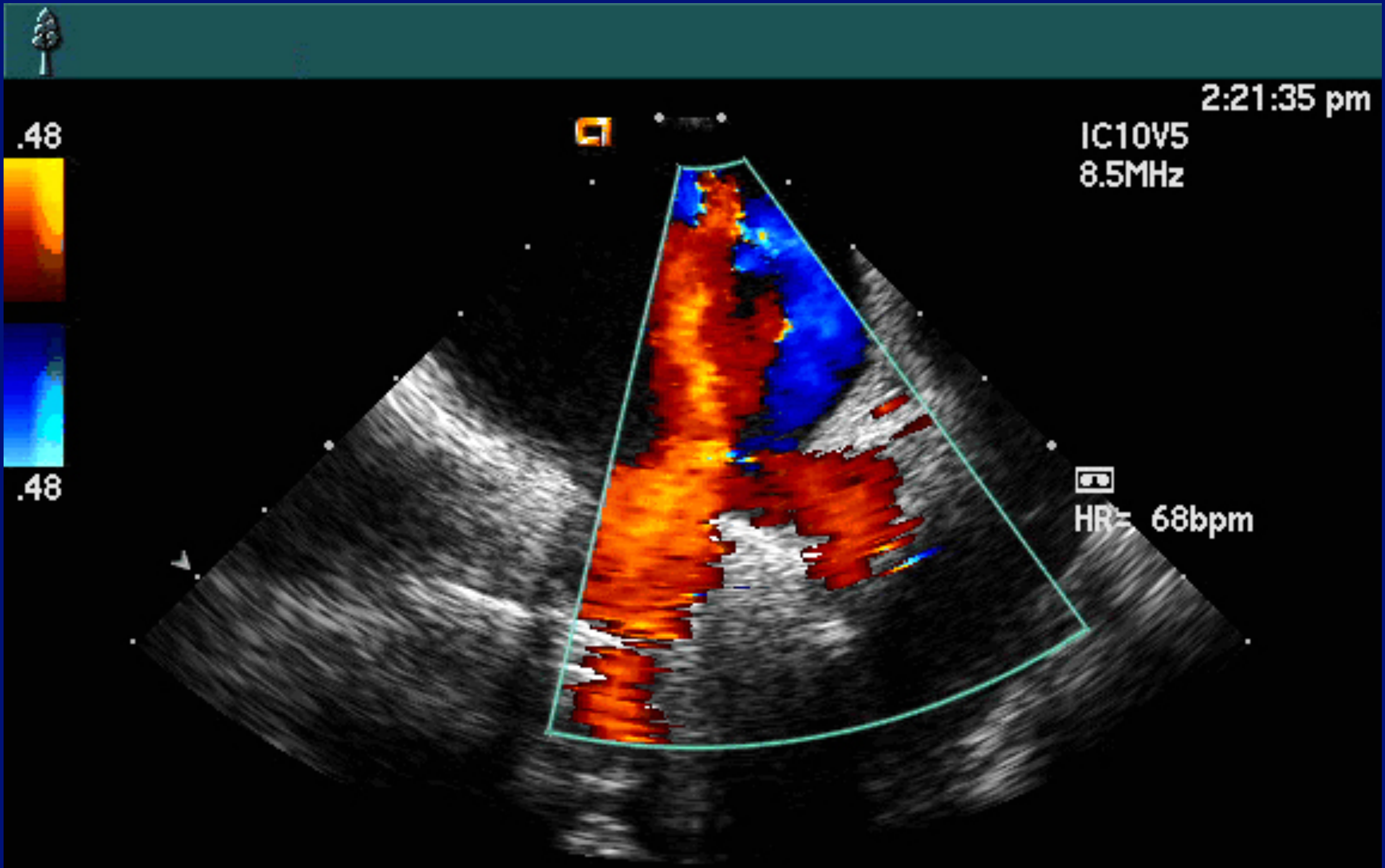
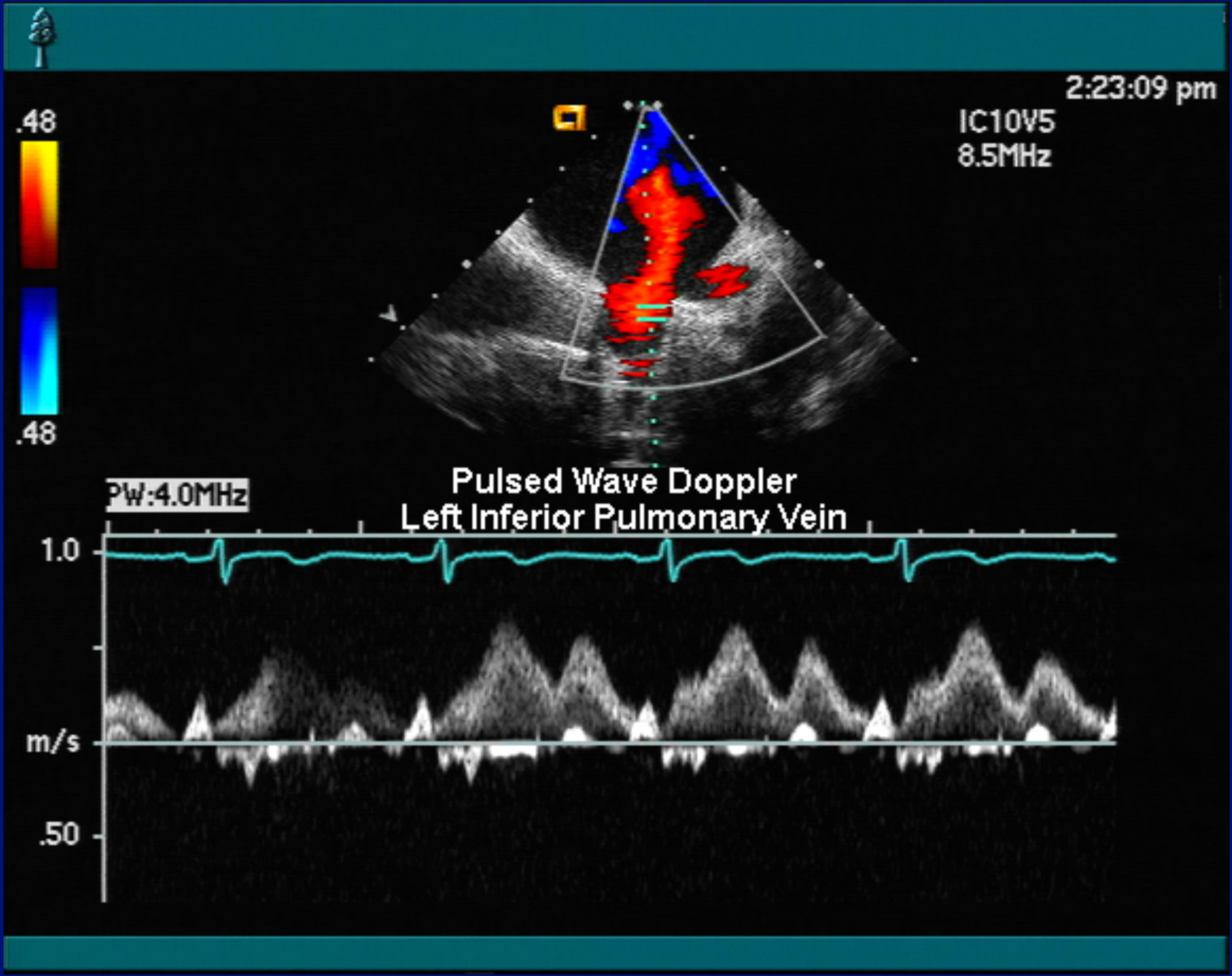
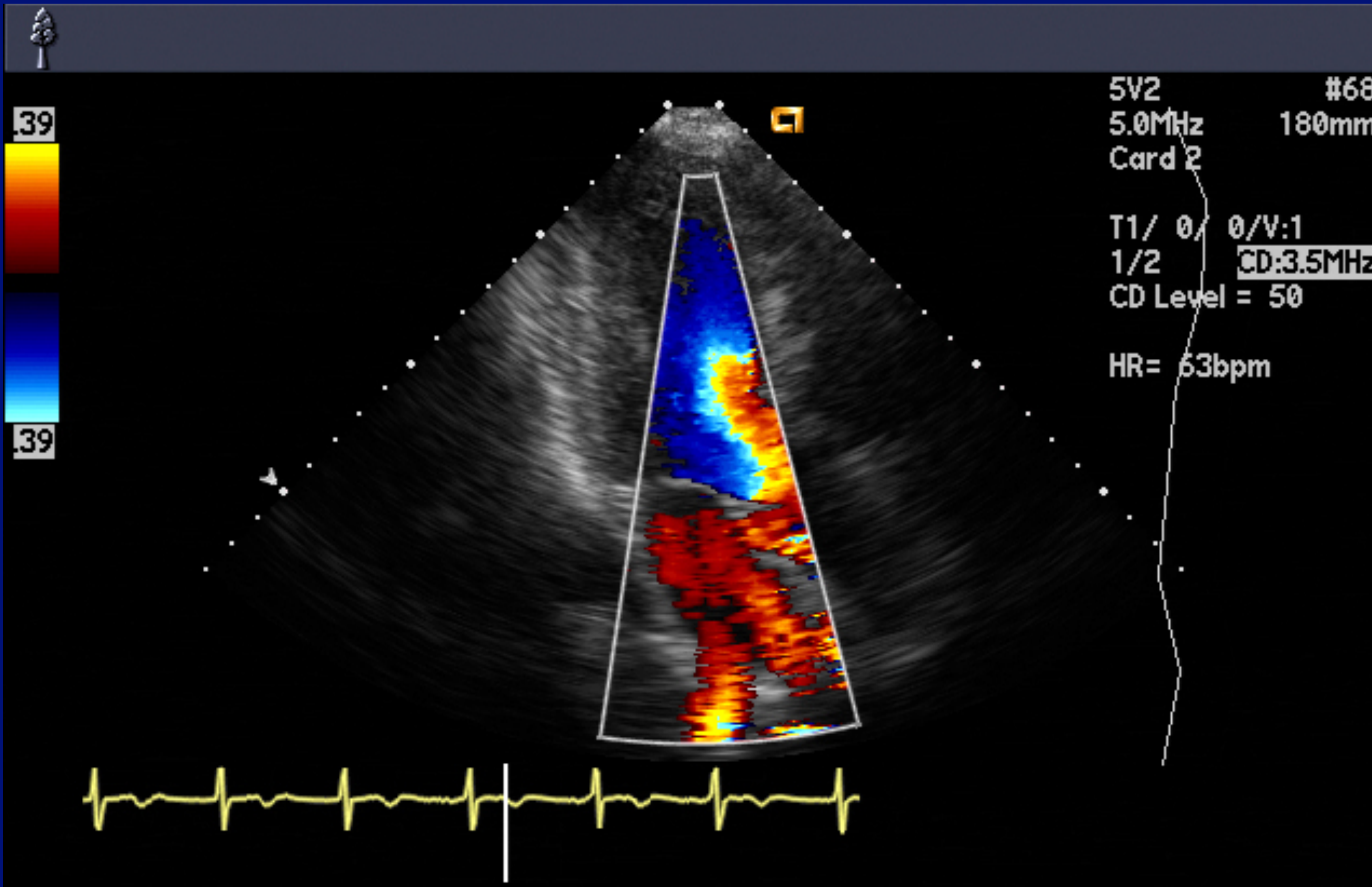
Chapter 8: Color and Spectral Doppler

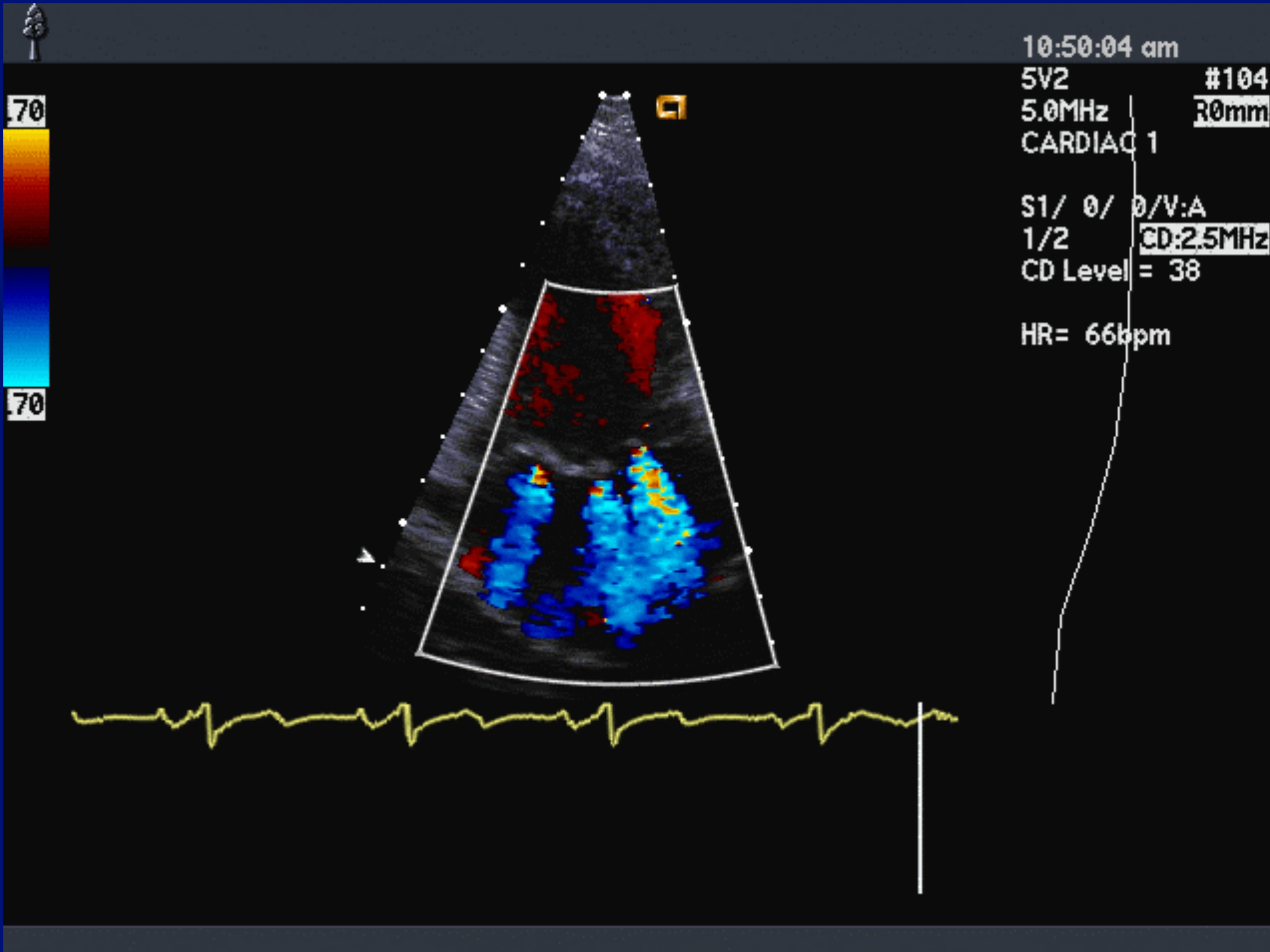


Color Doppler
Left Pulmonary Veins

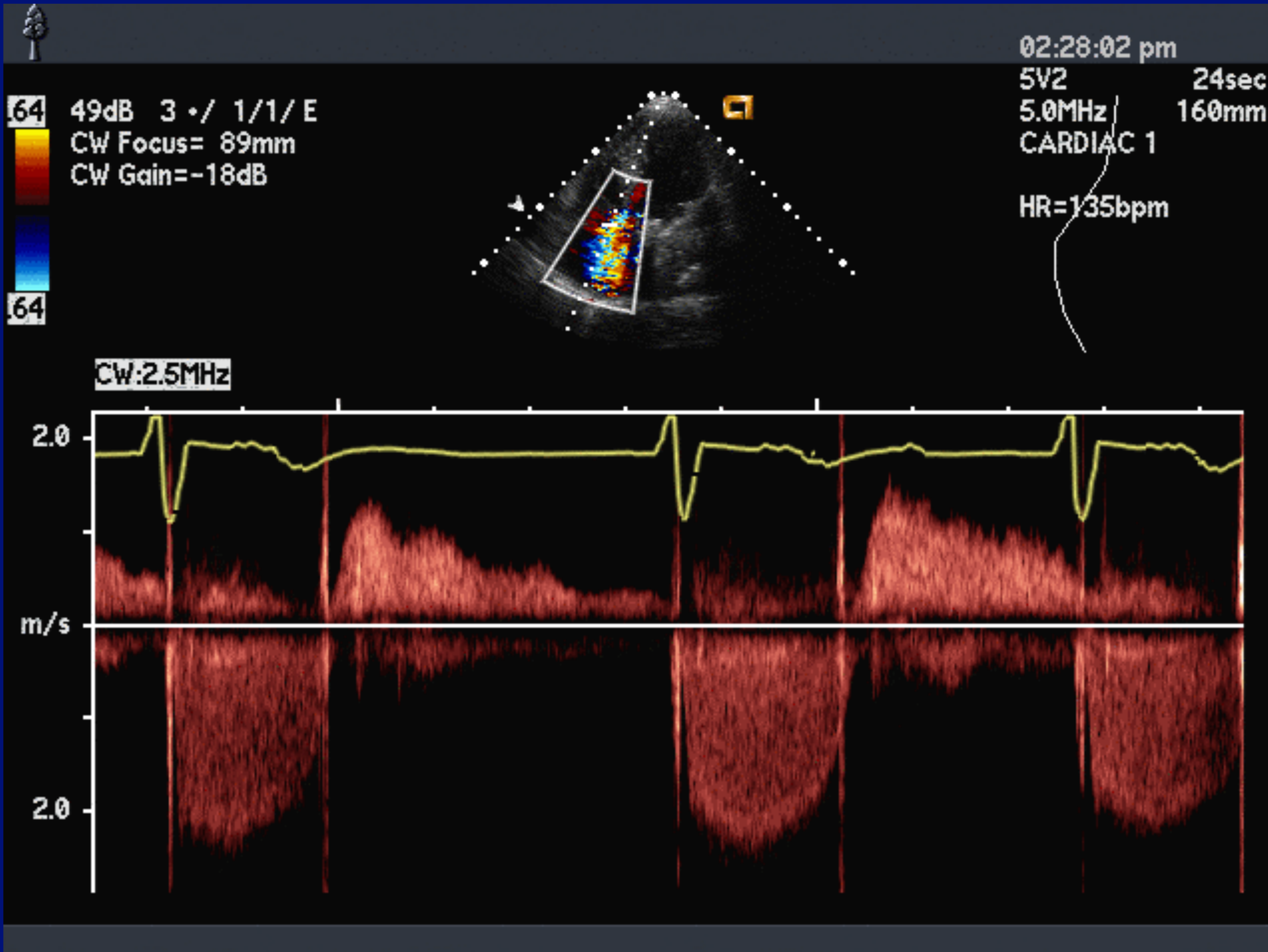

2:23:09 pm
IC10V5
8.5MHz
.48
.48
PW:4.0MHz
Pulsed Wave Doppler
Left Inferior Pulmonary Vein
1.0
m/s
.50



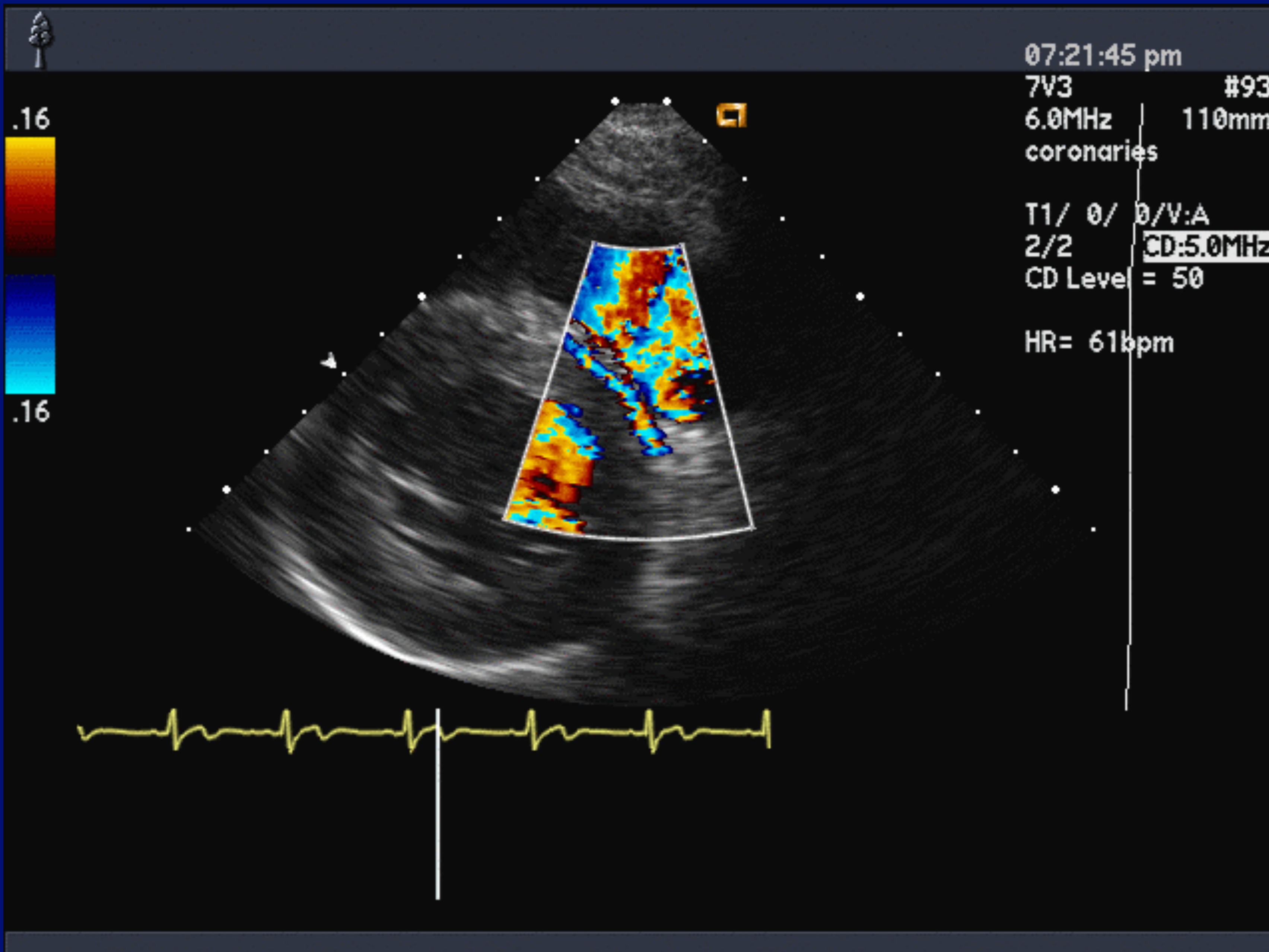
Pulmonary Vein Inflow

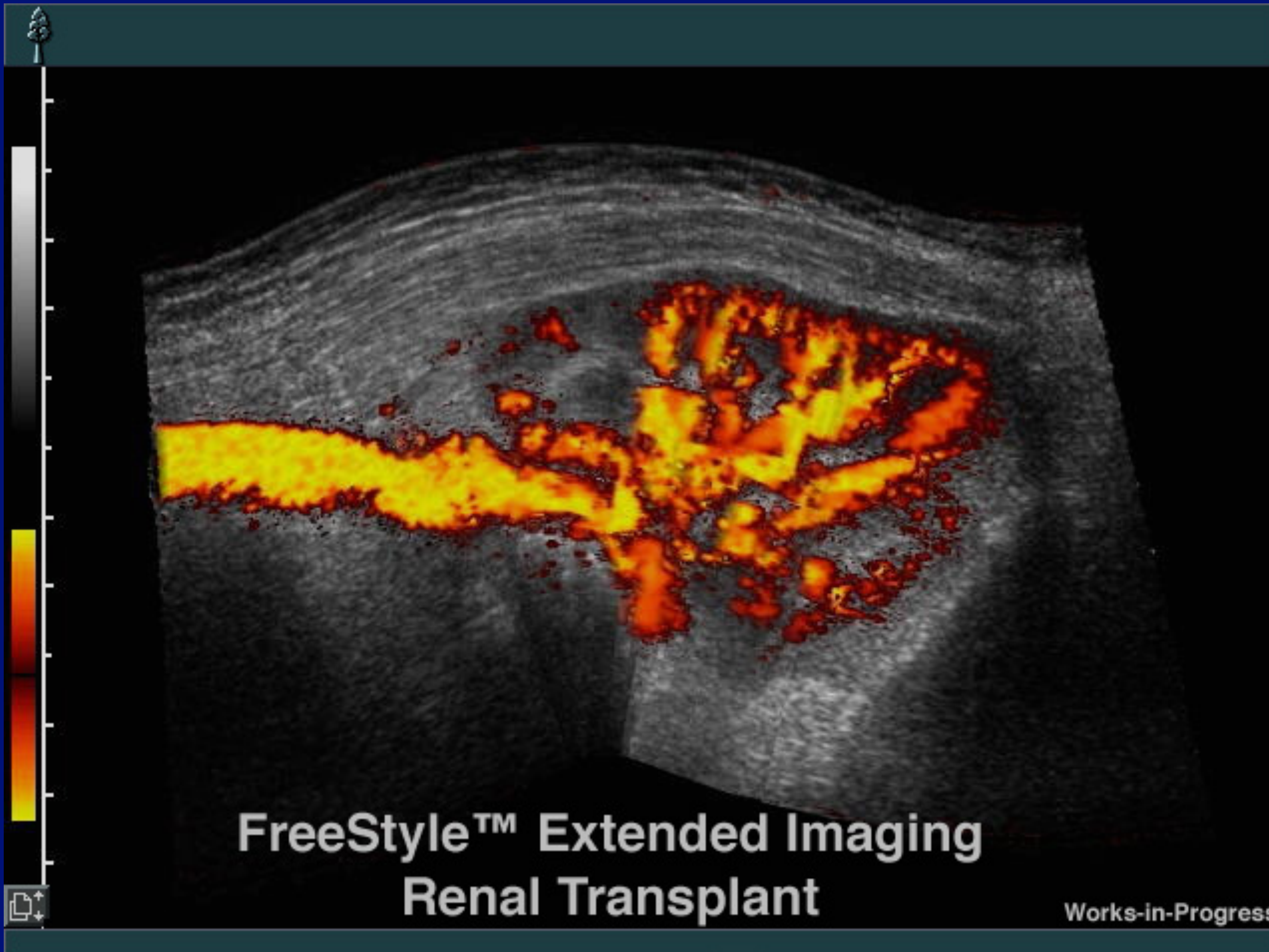


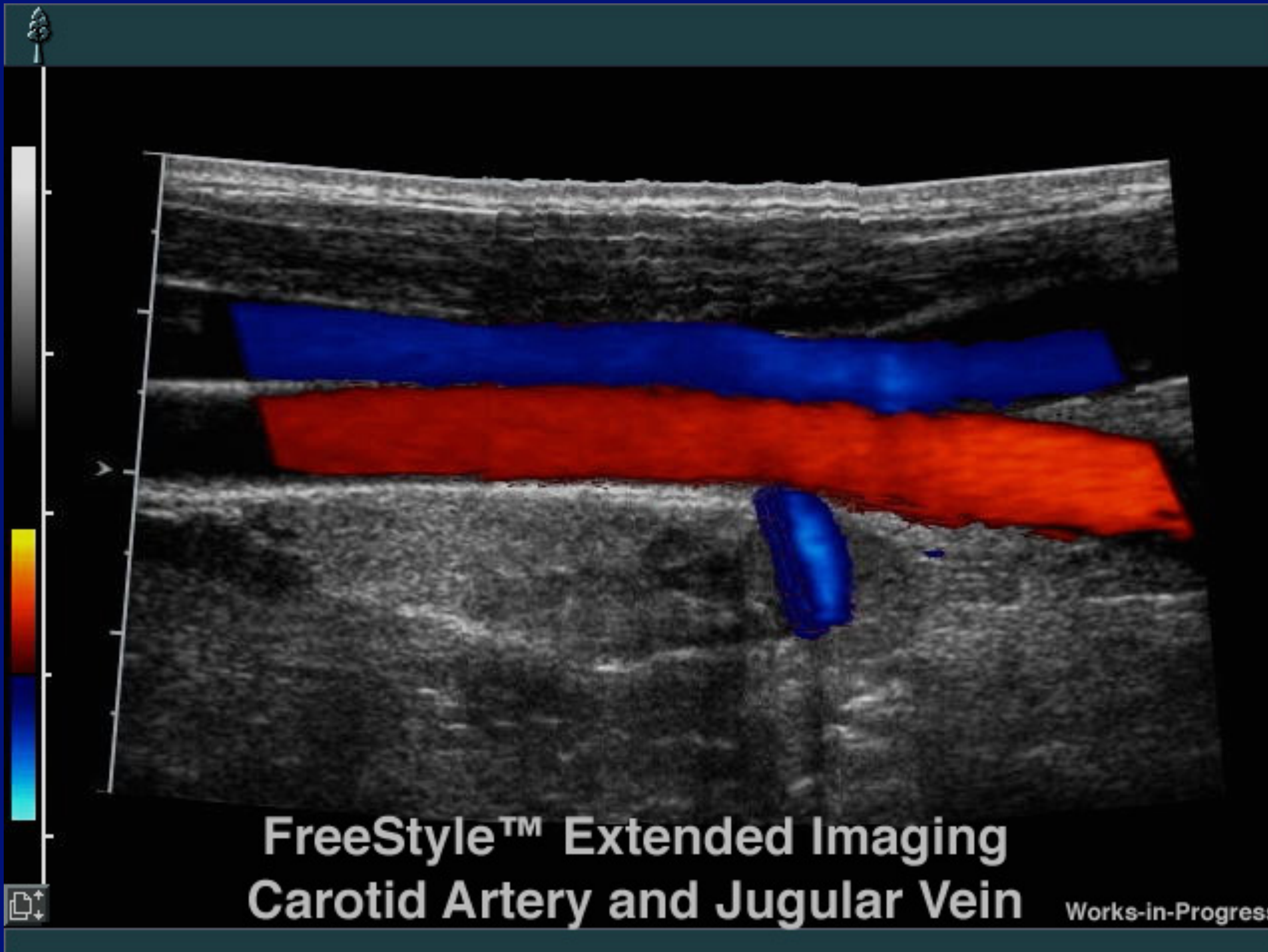
10:50:04 am
5V2
#104
5.0MHz
R0mm
CARDIAC 1
S1/ 0/ 0/V:A
1/2
CD:2.5MHz
CD Level = 38
HR= 66bpm
70
70

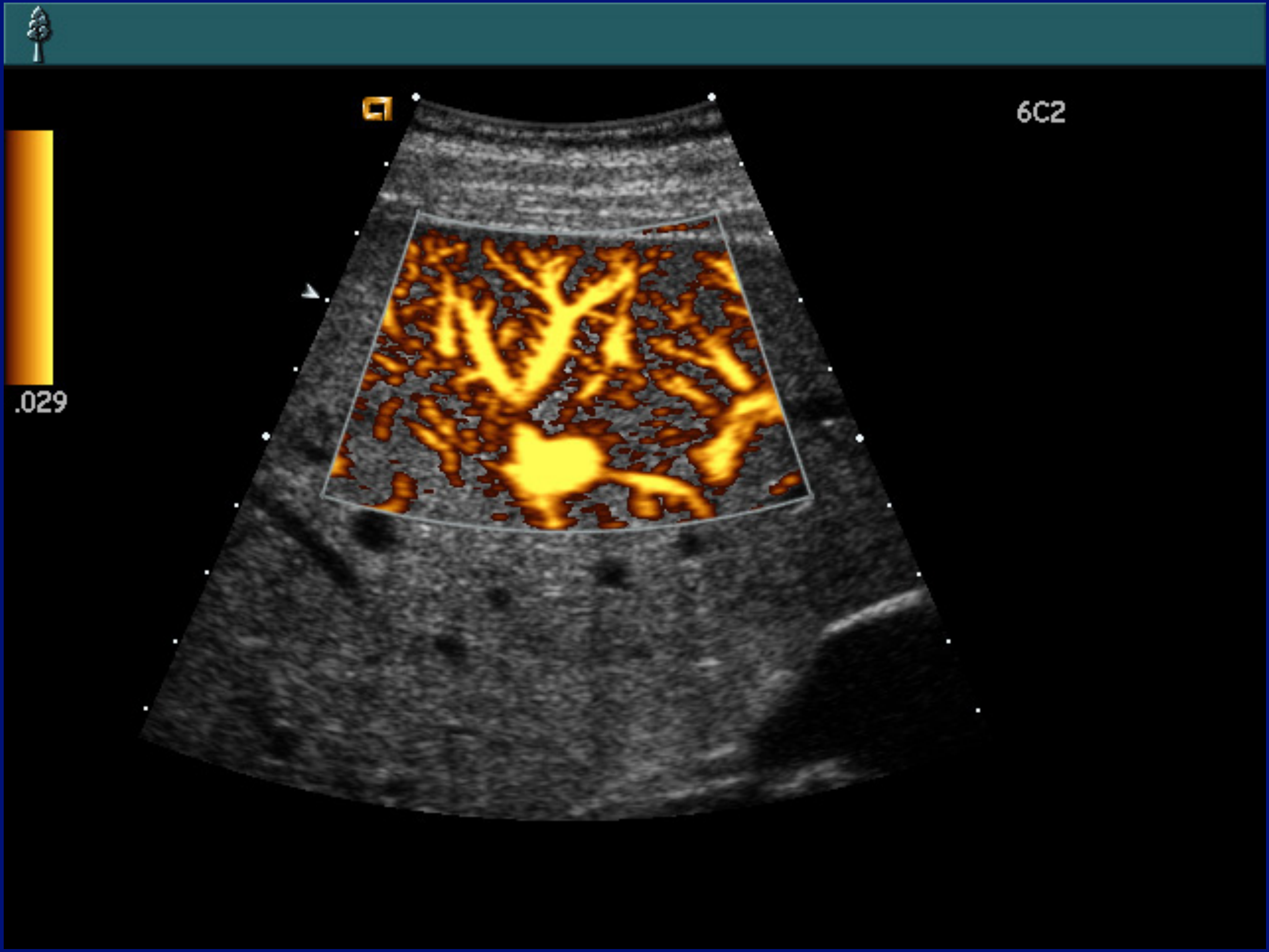


02:28:02 pm
5V2 24sec
5.0MHz 160mm
CARDIAC 1
HR=135bpm
64
49dB 3 •/ 1/1/ E
CW Focus= 89mm
CW Gain=-18dB
64
CW:2.5MHz
2.0
m/s
2.0


.16
.16
07:21:45 pm
7V3
#93
6.0MHz
110mm
coronaries
T1/ 0/ 0/V:A
2/2
CD:5.0MHz
CD Level = 50
HR= 61bpm

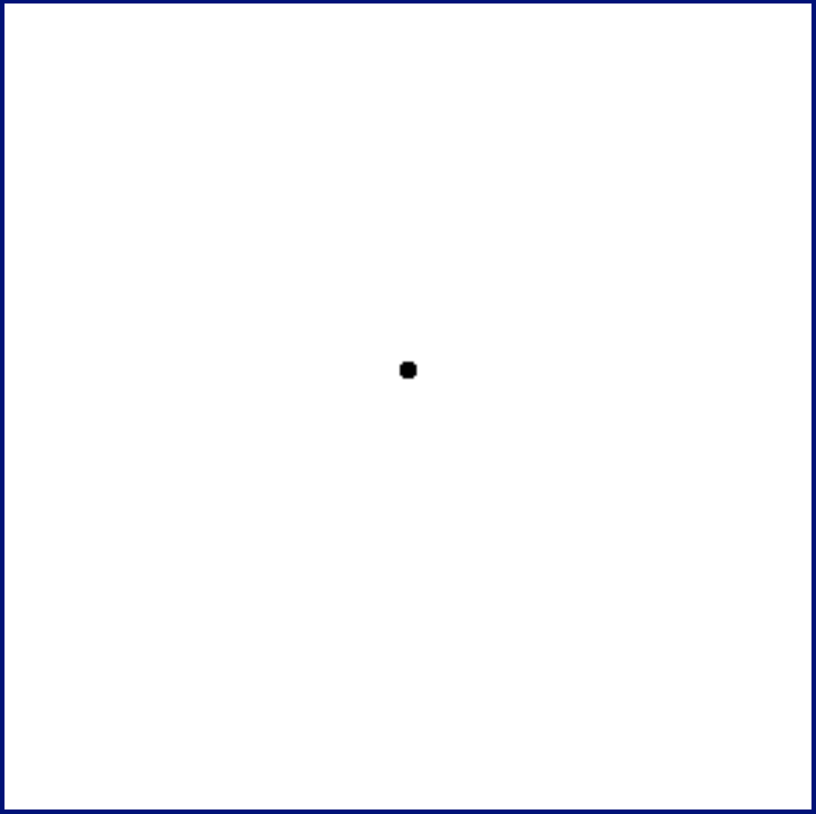

FreeStyle™ Extended Imaging
Renal Transplant
Works-in-Progress

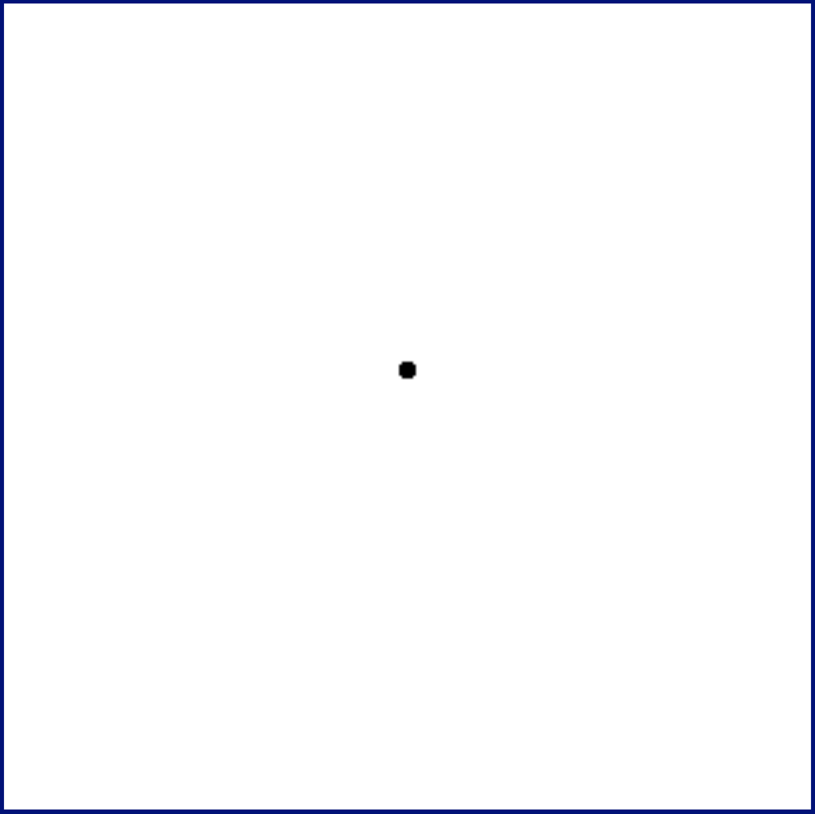

FreeStyle™ Extended Imaging
Carotid Artery and Jugular Vein
Works-in-Progress



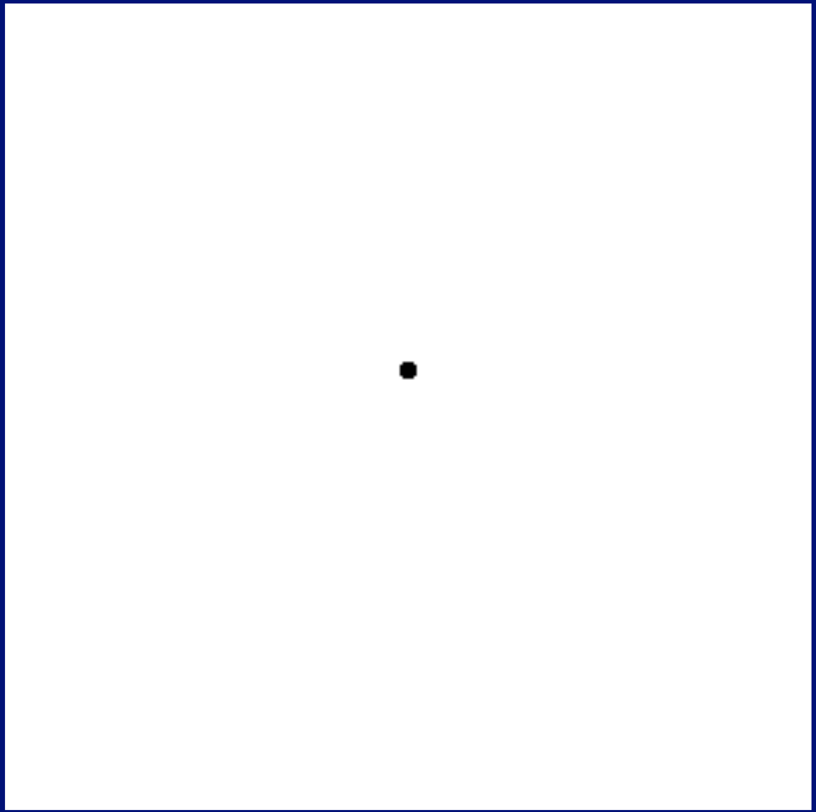
6C2
.029

Doppler Effect

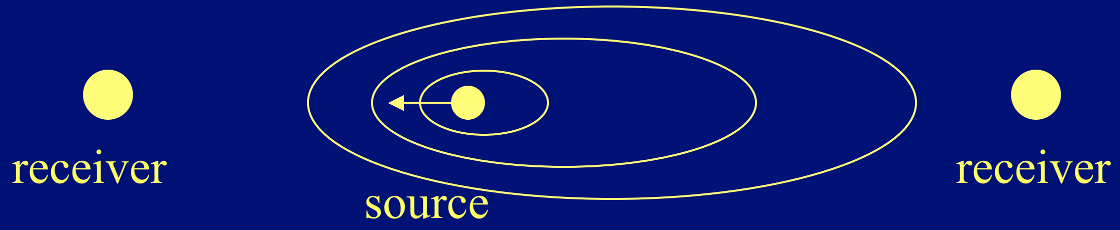




Doppler Effect



Doppler Principles



- Relative motion of the source causes a change in received frequency.
- Blood flow velocity is measured by detecting Doppler frequency shifts.

$f_d = f - f_s = v_r f_s / c$

Doppler Principles

- When both source and receiver are stationary: $f_s = c/\lambda$
- When source is stationary and receiver is moving:

$$(cT/\lambda + v_r T/\lambda)$$

$$\Downarrow$$

$$f = (c + v_r)/\lambda$$

$$\Downarrow$$

$$f_d = f - f_s = v_r f_s / c$$

$f_d = f - f_s = v_r f_s / c$

Doppler Principles

- When receiver is stationary and source is moving:

$$(c - v_s)/f_s$$

$$\Downarrow$$

$$f = f_s c/(c - v_s)$$

$$\Downarrow$$

$$f_d = f - f_s = f_s v_s/(c - v_s)$$

Doppler Equations

$$f_d = f_s \frac{v_r + v_s}{c - v_s}$$

$$f_d \approx f_s \frac{(v_r + v_s)}{c}$$

where f_d is the Doppler frequency shift,

f_s is the carrier frequency,

c is the sound velocity in blood,

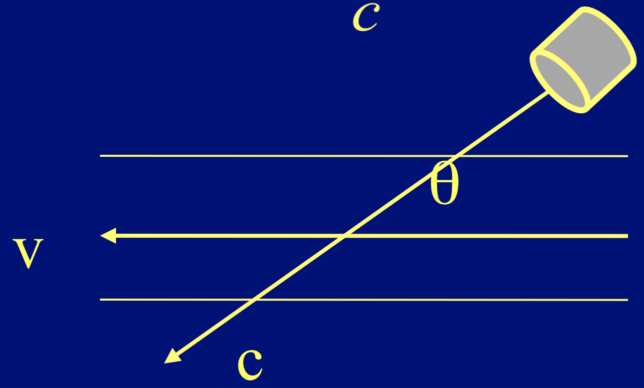
v_s and v_r are source and receiver velocities.

Doppler Ultrasound

- Primary scattering site: red blood cell. The platelet is too small and the number of leukocytes is not significant.
- The red blood cell size is around several microns. Thus, scattering and speckle are also present.
- The red blood cells in a sample volume are assumed to move in unison.

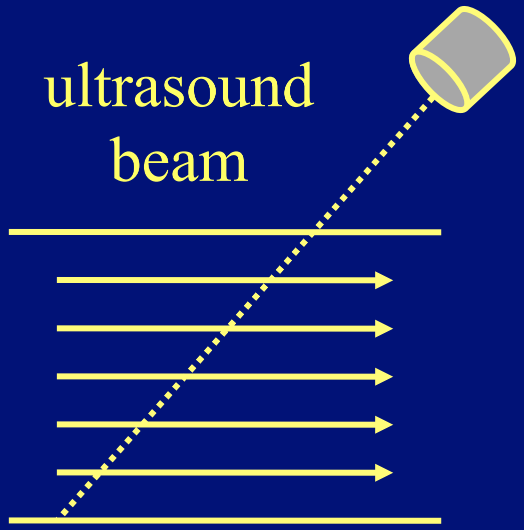
Doppler Equations

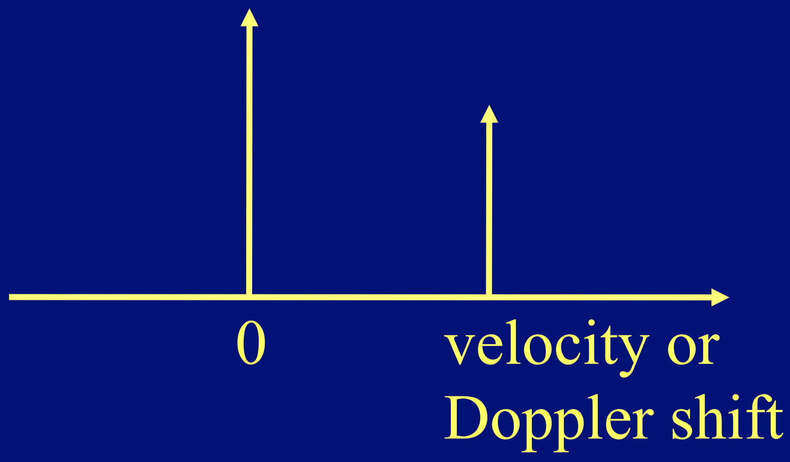
$$f_d = \frac{2vf_s}{c}\cos\theta$$



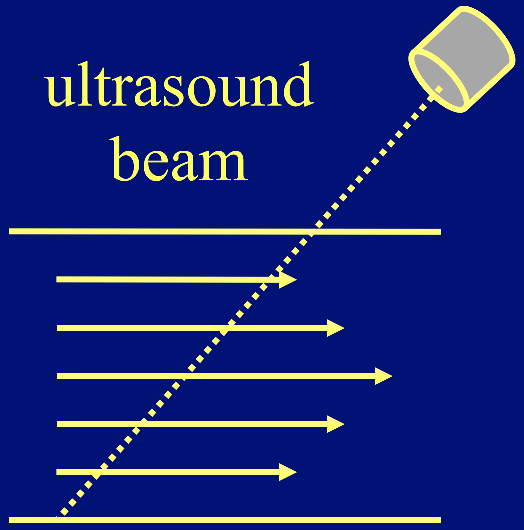
- Typical physiological flows (5-10m/sec at most) are much slower than sound velocity in the body (~1500m/sec).
- Doppler shift is doubled due to round-trip propagation.
- Only parallel flows can be detected.

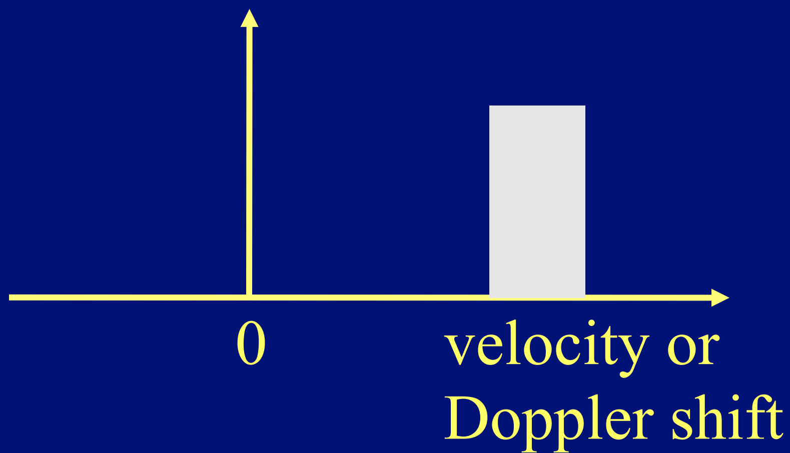
Flow Pattern v. Velocity Profile



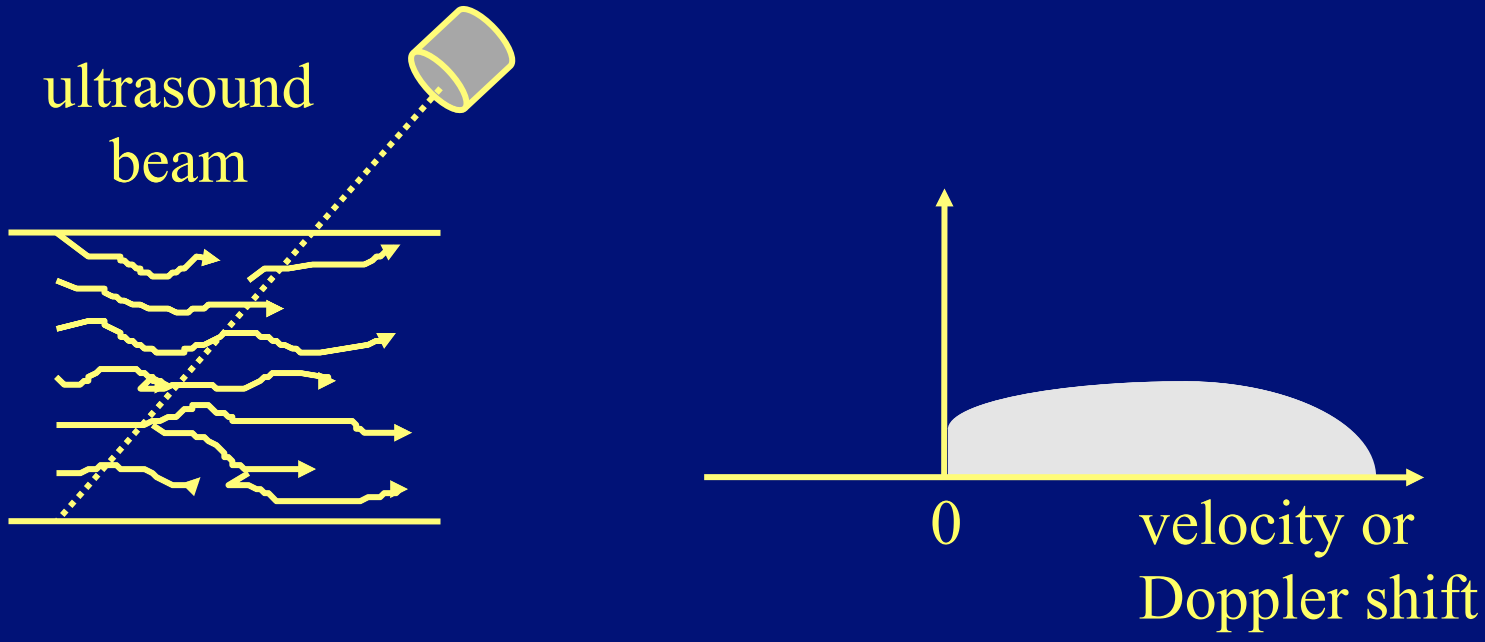


Flow Pattern v. Velocity Profile



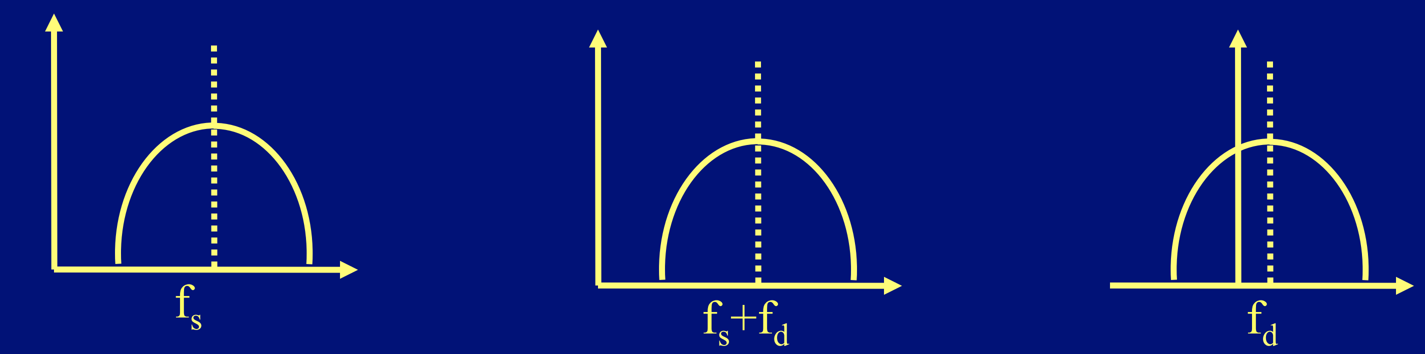


Flow Pattern v. Velocity Profile



Doppler Spectrum Estimation

original Doppler shifted demodulated

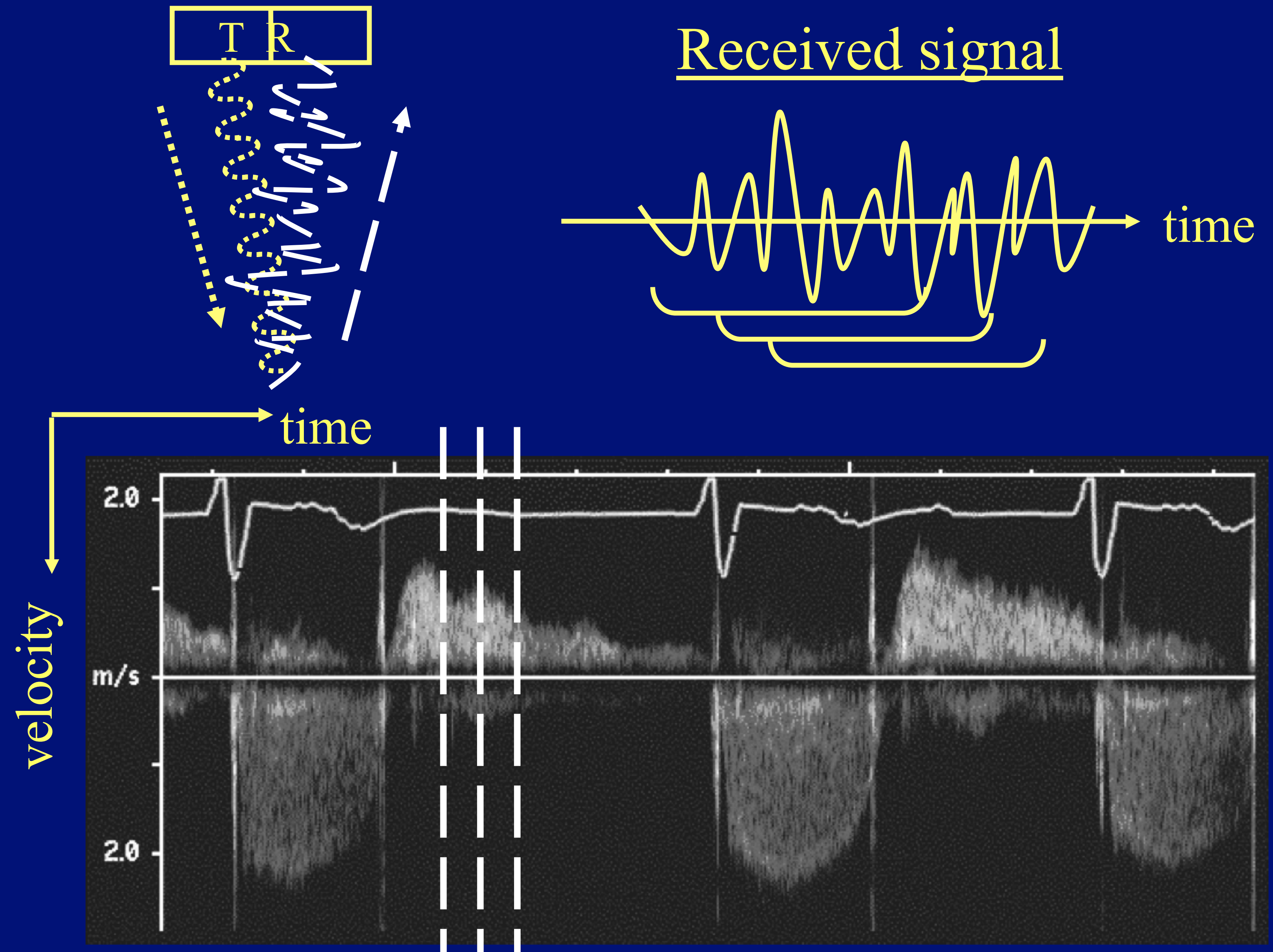


- Short-time Fourier transform (Spectral Doppler).
- Correlation based estimation (Color Doppler).

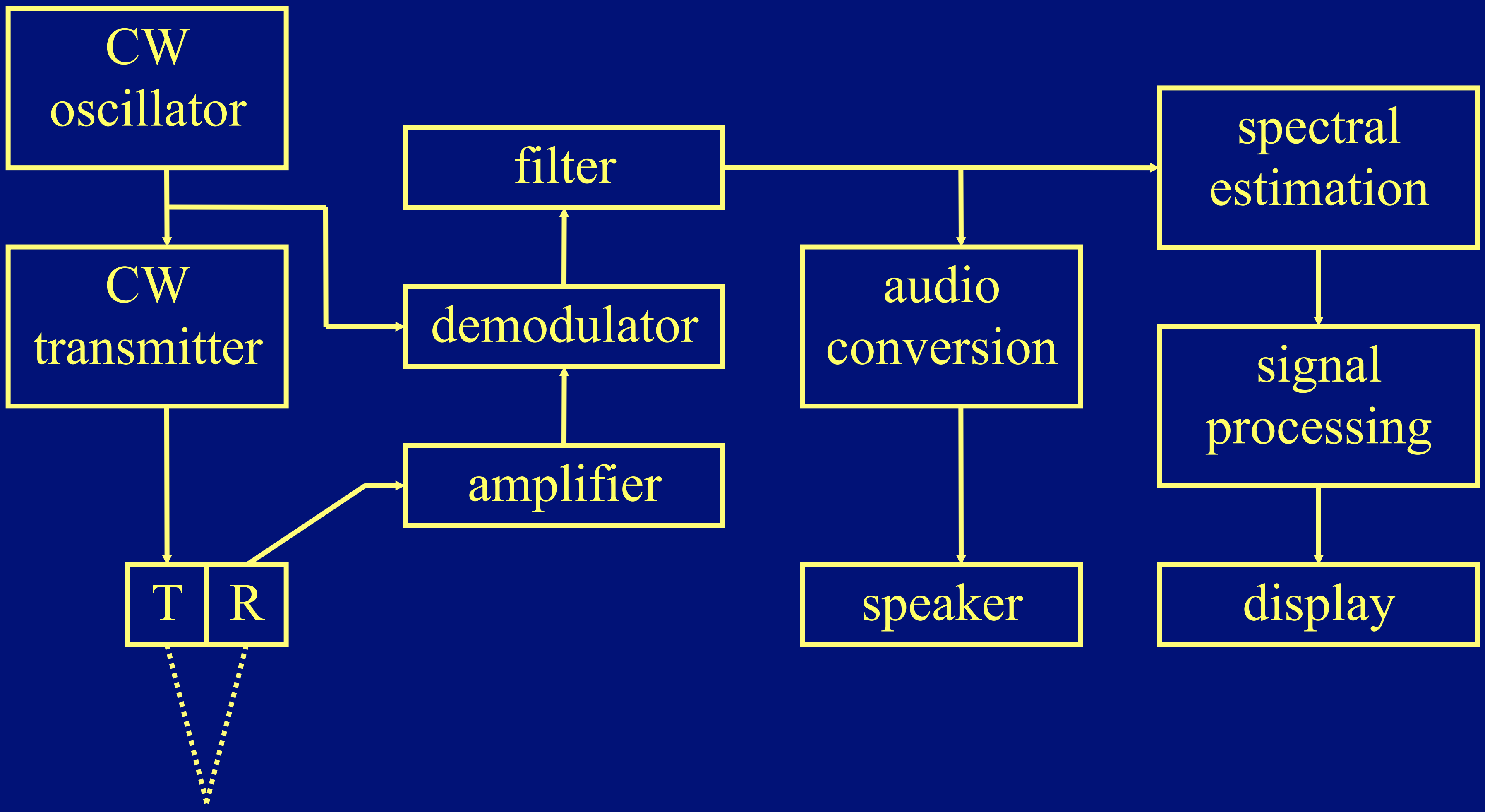
Blood Flow Measurements

- Short Time Fourier Analysis: PW,CW, Audio Doppler.
- Correlation processing: Color Doppler, Doppler Power, Doppler Energy, Convergent Color Doppler.
- Tracking.
- Correlation Analysis.

Continuous Wave (CW) Doppler



CW Doppler


CW oscillator
CW transmitter
T
R
filter
demodulator
amplifier
audio conversion
speaker
spectral estimation
signal processing
display

CW Doppler

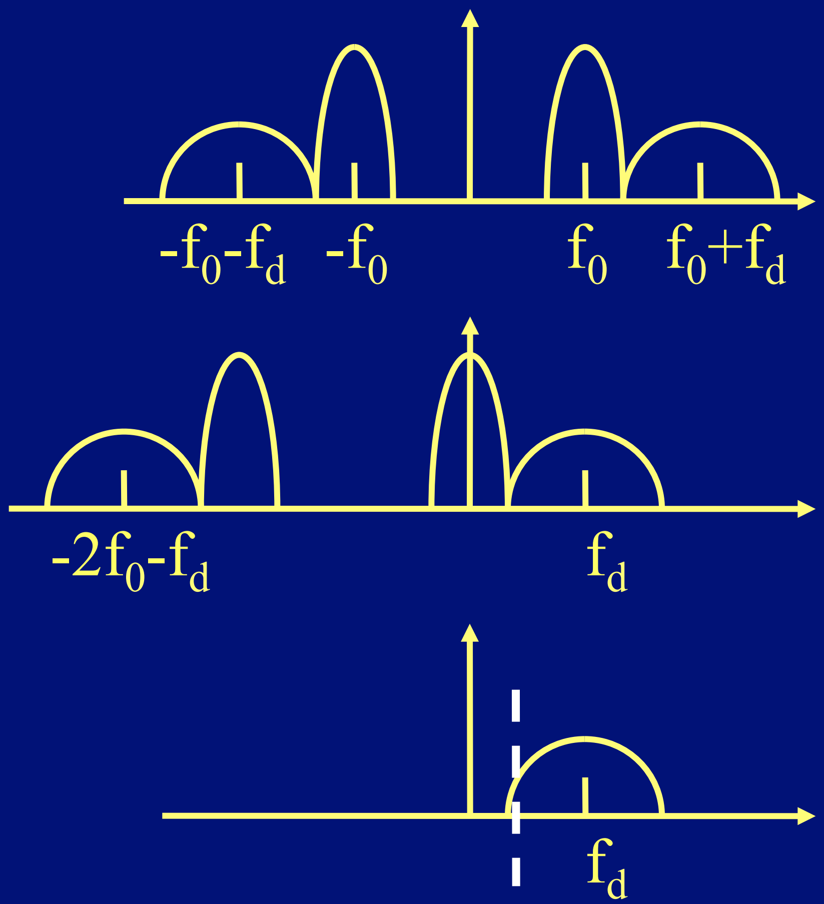
- Array CW and AUX CW (half transmit, half receive).
- Mainly for Cardiology.
- Good velocity (frequency) resolution.
- No range resolution. Flows along the same direction are all detected.
- Frequency downshift due to attenuation can be ignored.

CW Doppler Processing

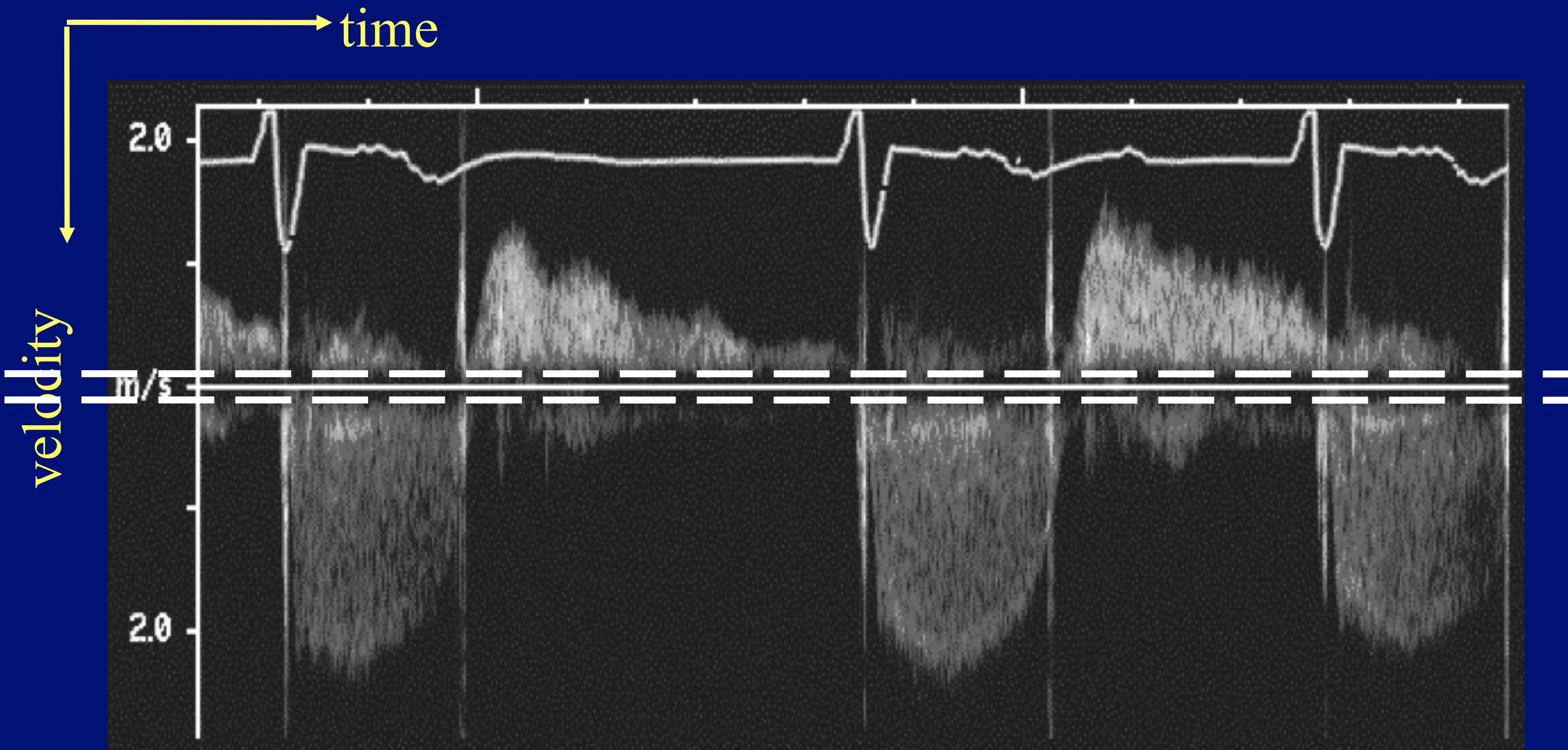
original spectrum

demodulated

demodulated and filtered



Wall Filter (Clutter Filter)



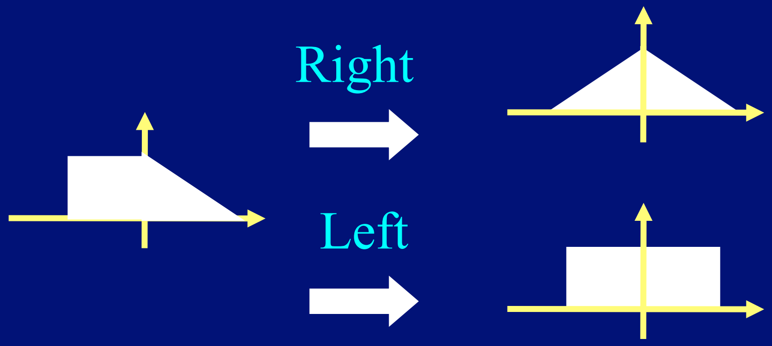
CW Doppler Processing

- Time-interval histogram.
- 32-128 pt FFT.
- Model-based spectrum estimation (AR), time-frequency analysis.
- Magnitudes are converted in dB and displayed.
- Post-processing similar to B-mode.

Audio Doppler

$$f_d = \frac{2vf_s}{c}\cos\theta$$

- For typical blood velocities and carrier frequencies, the Doppler shifts from blood happen to be in the human audible range (near DC to 20KHz).
- Positive shifts in one channel and negative ones in the other.
- Hilbert transform.
- Clinically useful.

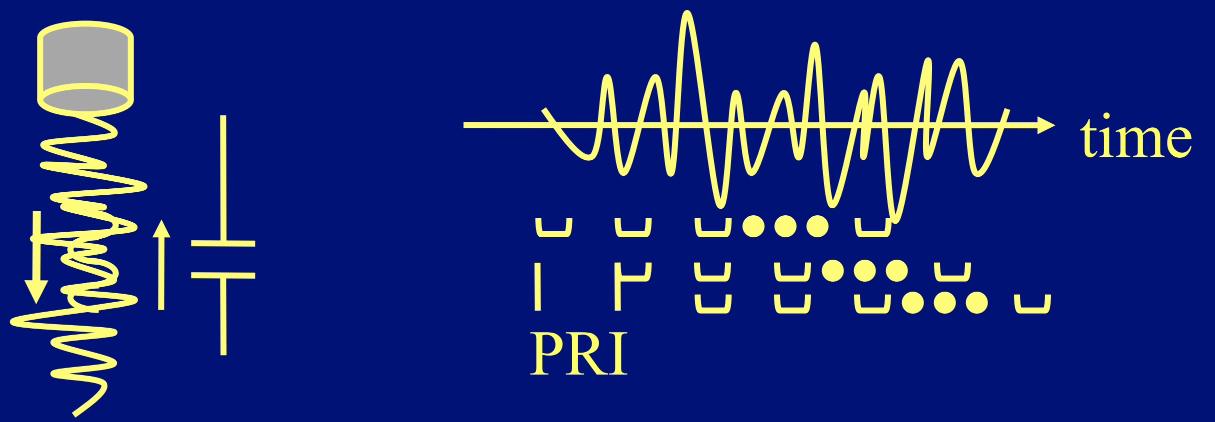


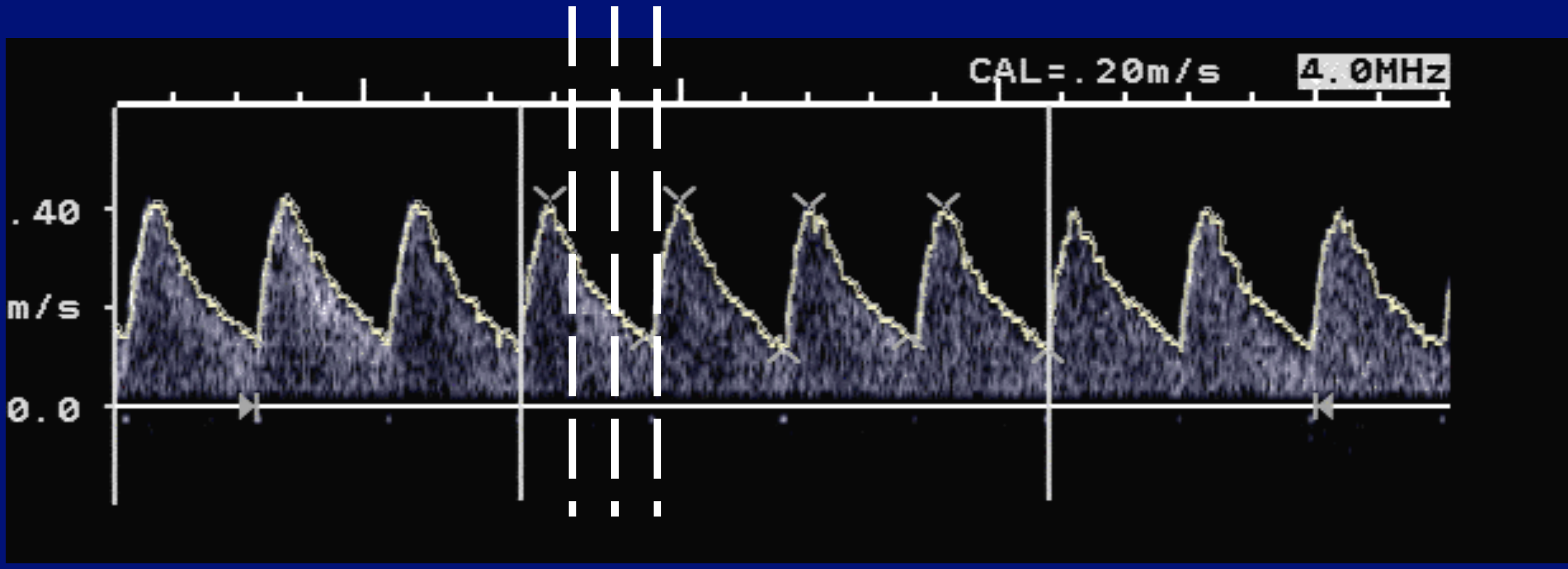
CW → PW

- CW: No range resolution.
- Sampling in time = sampling in range.

→ CW Doppler to PW Doppler.

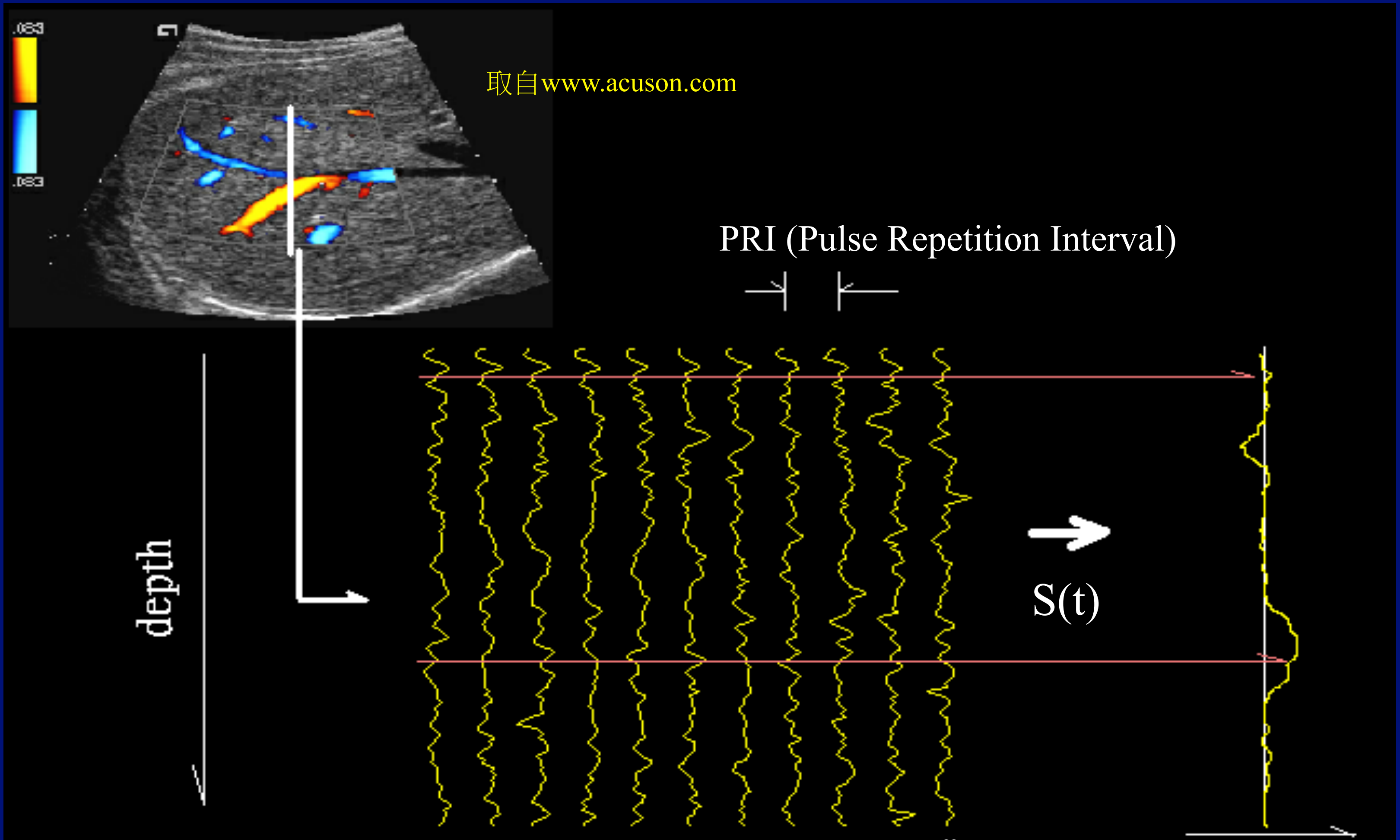
Pulsed Wave (PW) Doppler





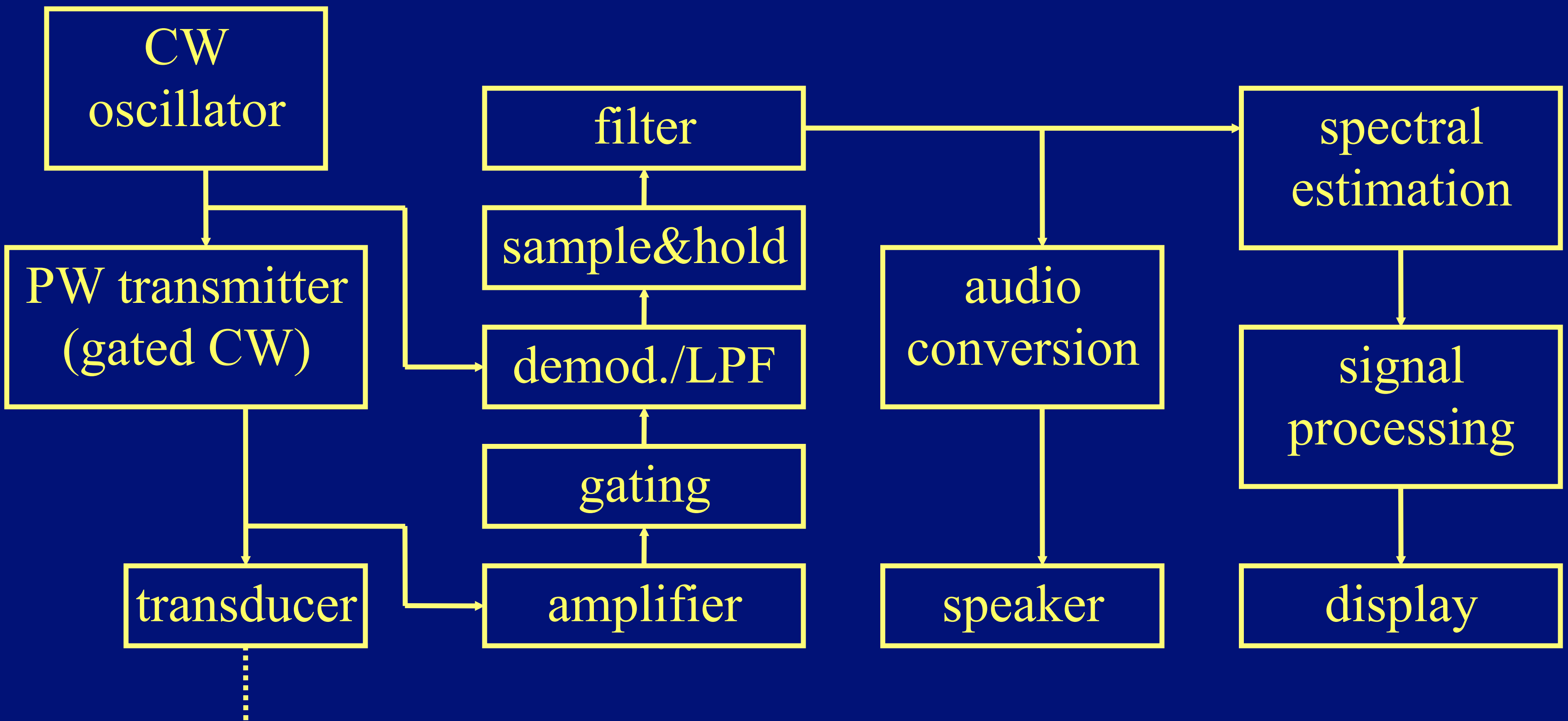
Another View for PW Doppler,…

Autocorrelation Processing

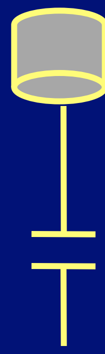


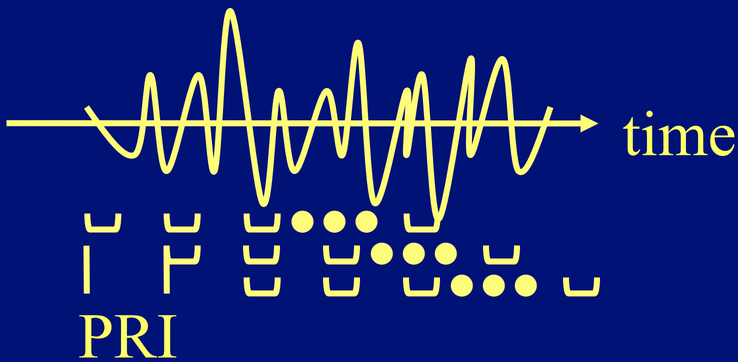
Autocorrelation function: $R(t) \equiv \int_{-\infty}^{\infty} S(t+\tau)\, S^{*}(\tau)\, d\tau$

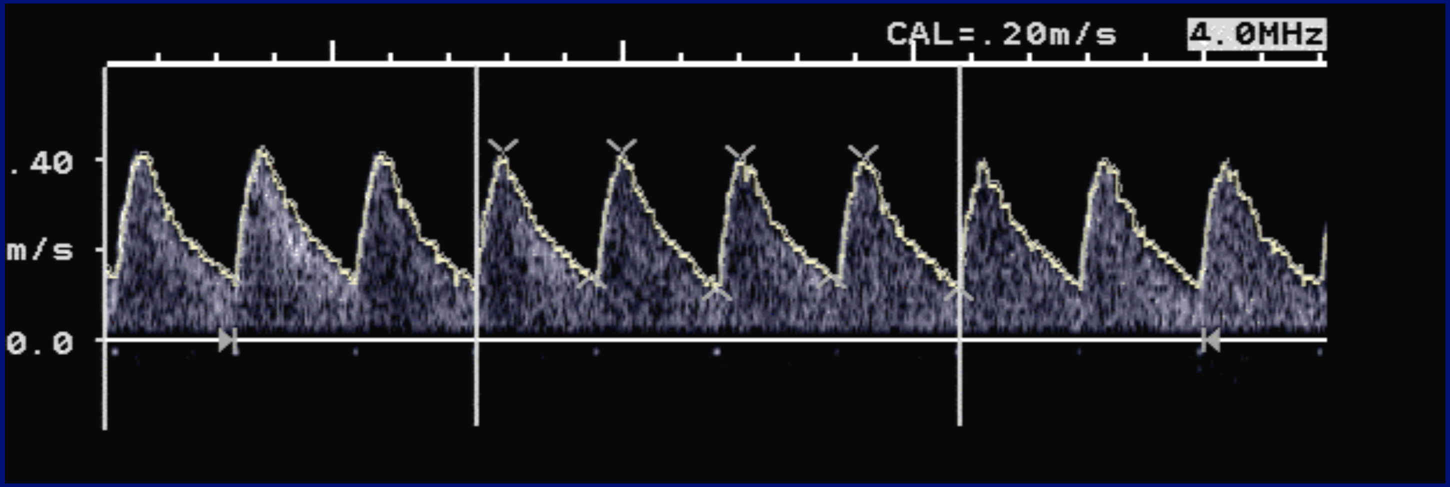
PW System Diagram



Pulsed Wave (PW) Doppler







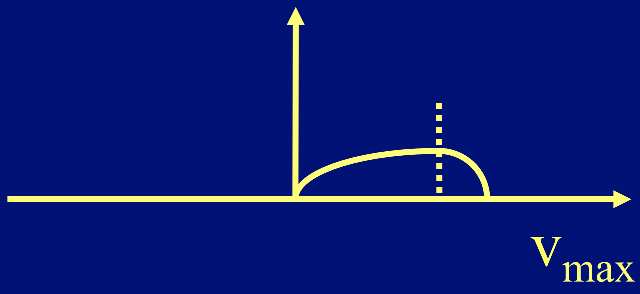
Velocity Ambiguity

$$2f_{max} \leq \frac{1}{PRI}$$

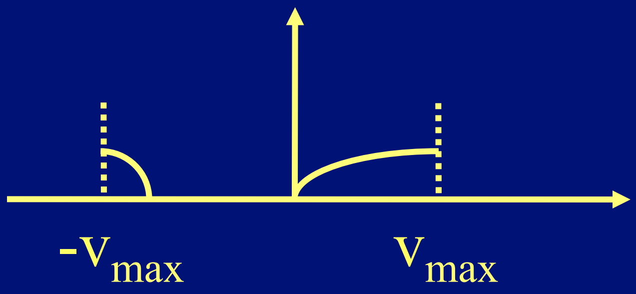
$$2f_{max} = \frac{4v_{max} f_s}{c} \leq \frac{1}{PRI}$$

$$v_{max} \leq \frac{\lambda}{4 \times PRI}$$

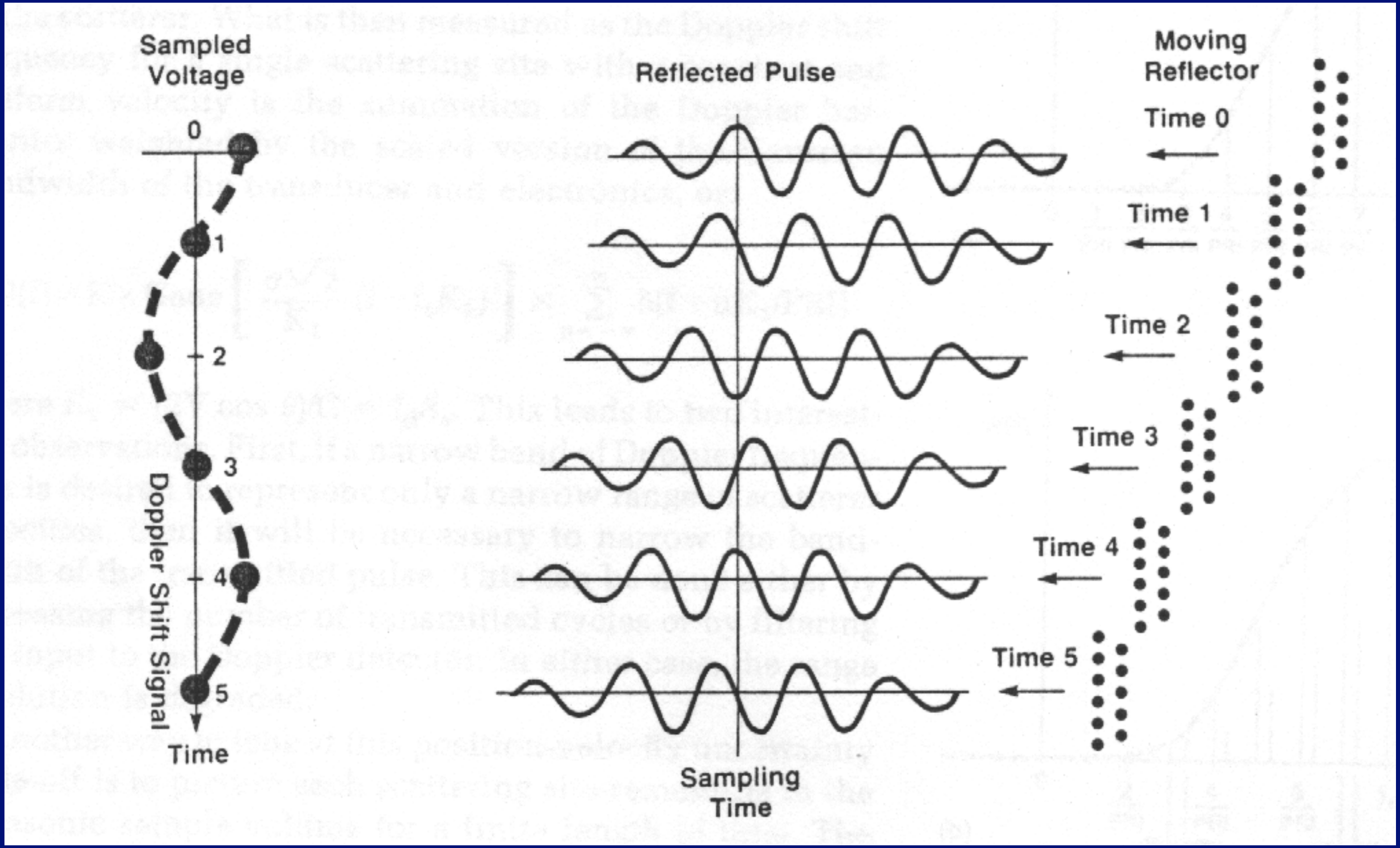
no aliasing



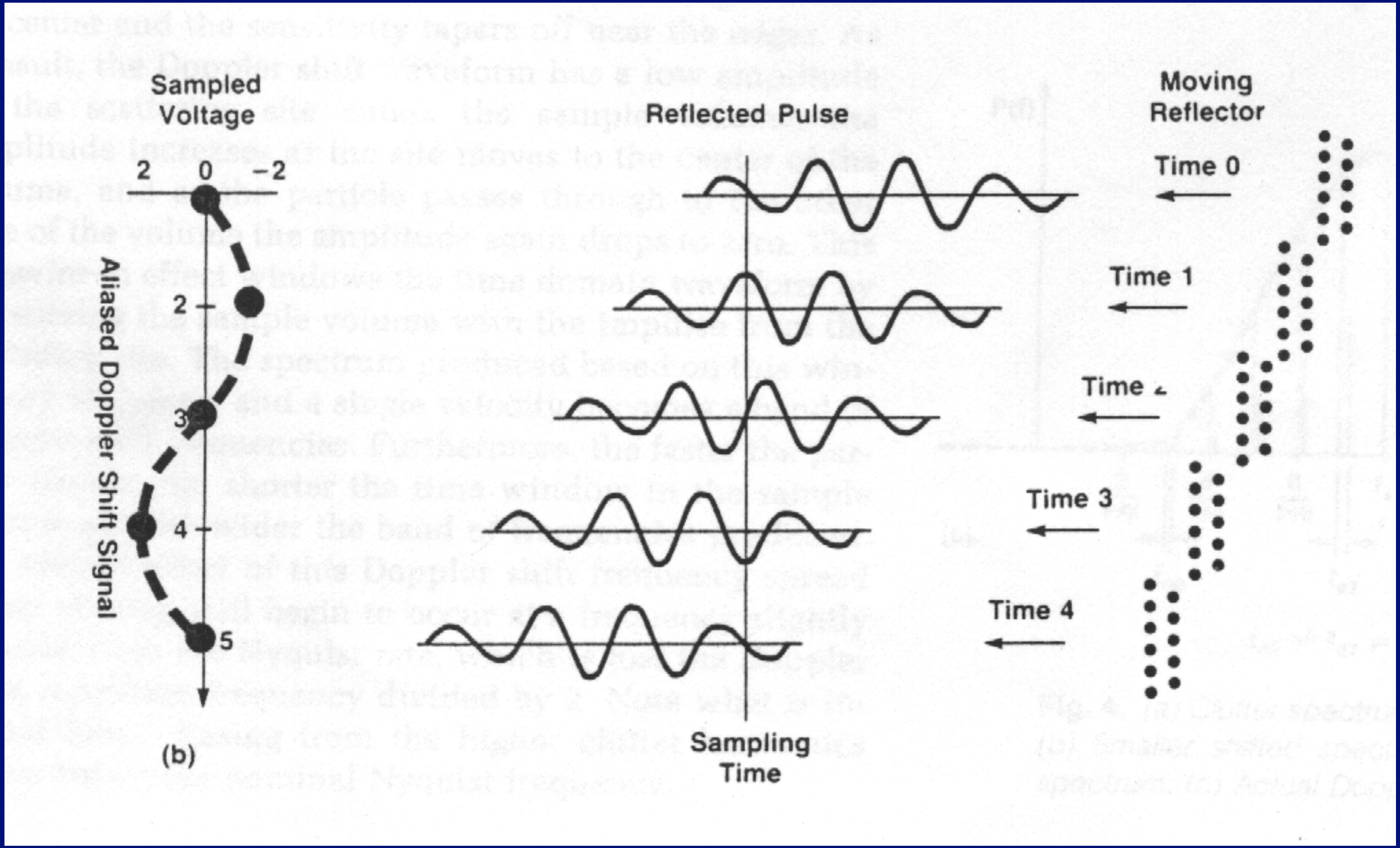
aliasing



Velocity Ambiguity (no aliasing)

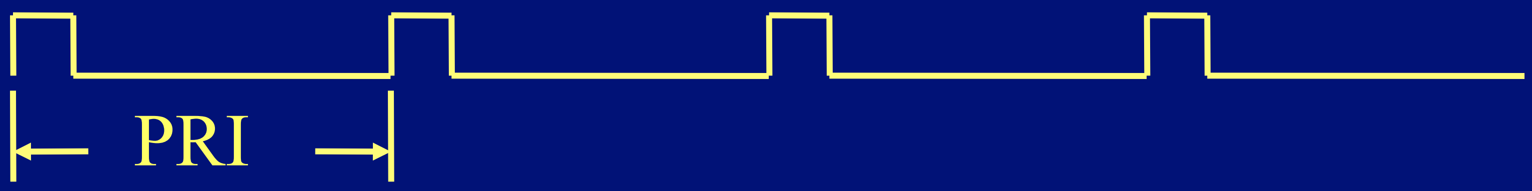


Velocity Ambiguity (with aliasing)



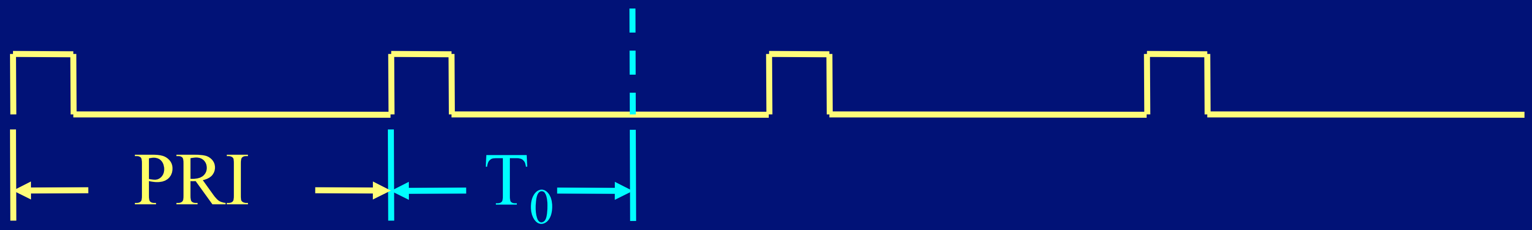
Range Ambiguity

$$c \times PRI / 2$$



Range Ambiguity

$c \times PRI / 2$

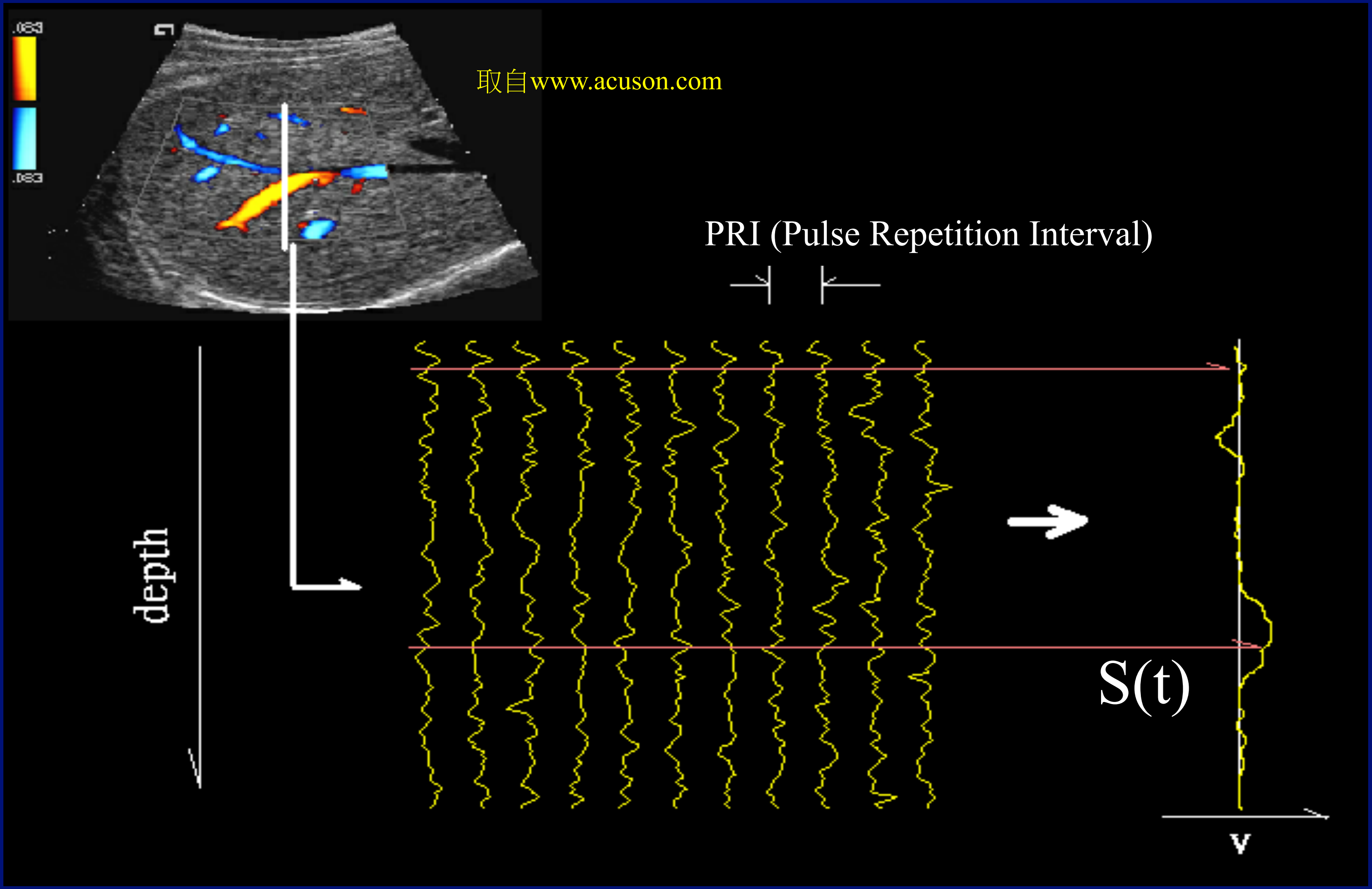


$c \times T_0 / 2$ OR $c \times (PRI + T_0) / 2$?

Pulse Wave (PW) Doppler

- Pulse-echo method, similar to B-mode.
- Post-processing similar to CW.
- Adjustable range resolution (gate).
- Maximum detectable velocity is $\lambda/(4*PRI)$.
- Maximum depth is $(c*PRI)/2$.
- 32-128 point FFT.

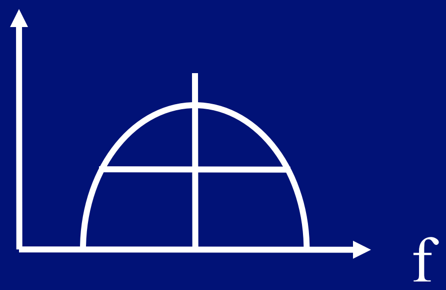
PW Blood Flow Measurements



PW → Color Doppler

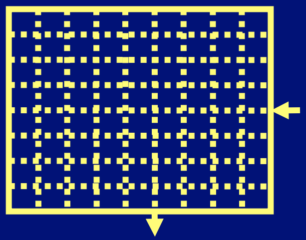
- Single gate → multiple gates.
- Local flow information → 2D flow information.
- Less time for velocity estimation: quantitative → qualitative.

Color Doppler Parameters



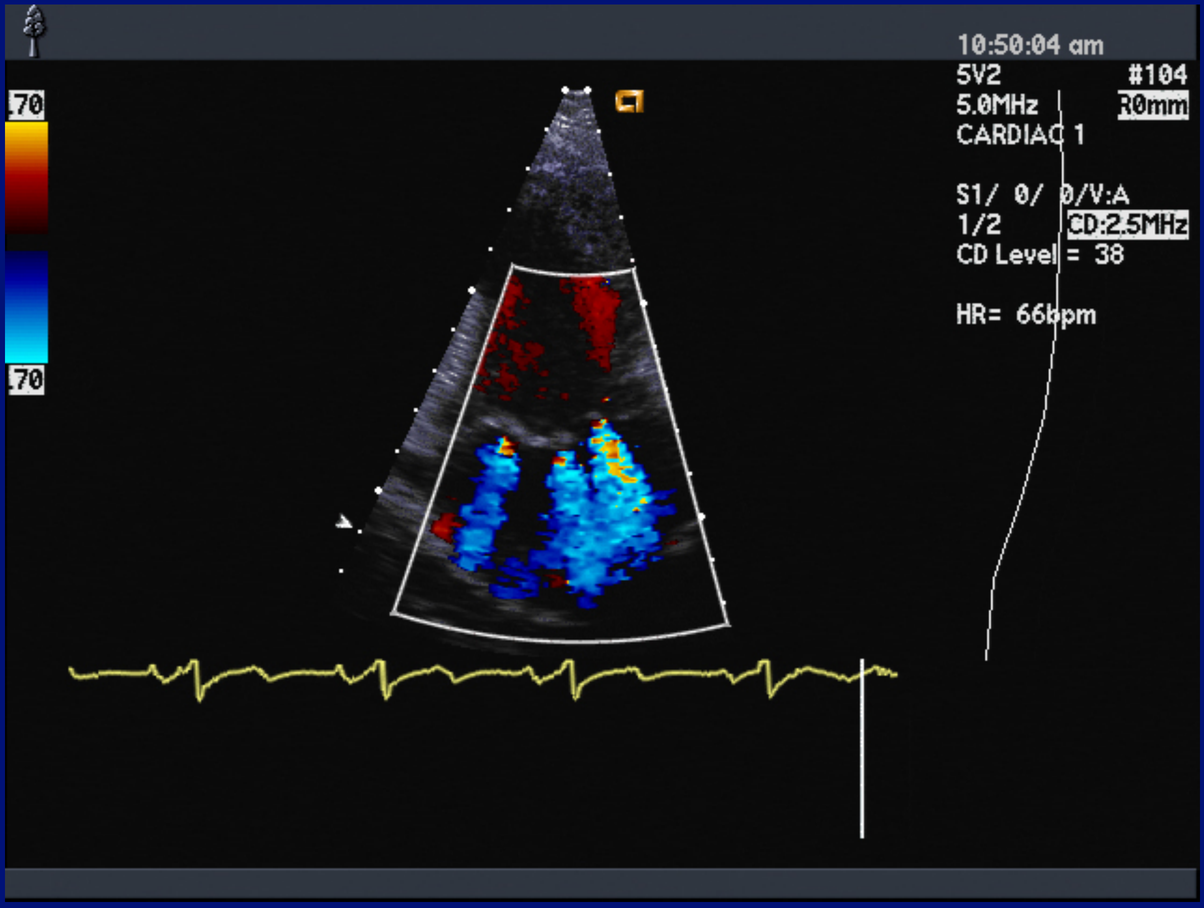
- Use efficient time domain correlation techniques to calculate flow characteristics.
- Auto-correlation of the Doppler signal.
- Commonly derived parameters are <u>mean velocity (including directionality), variance and energy (power).</u>

Color Doppler

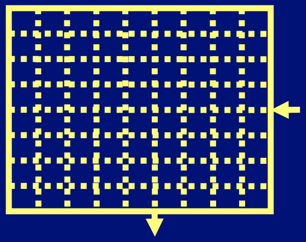


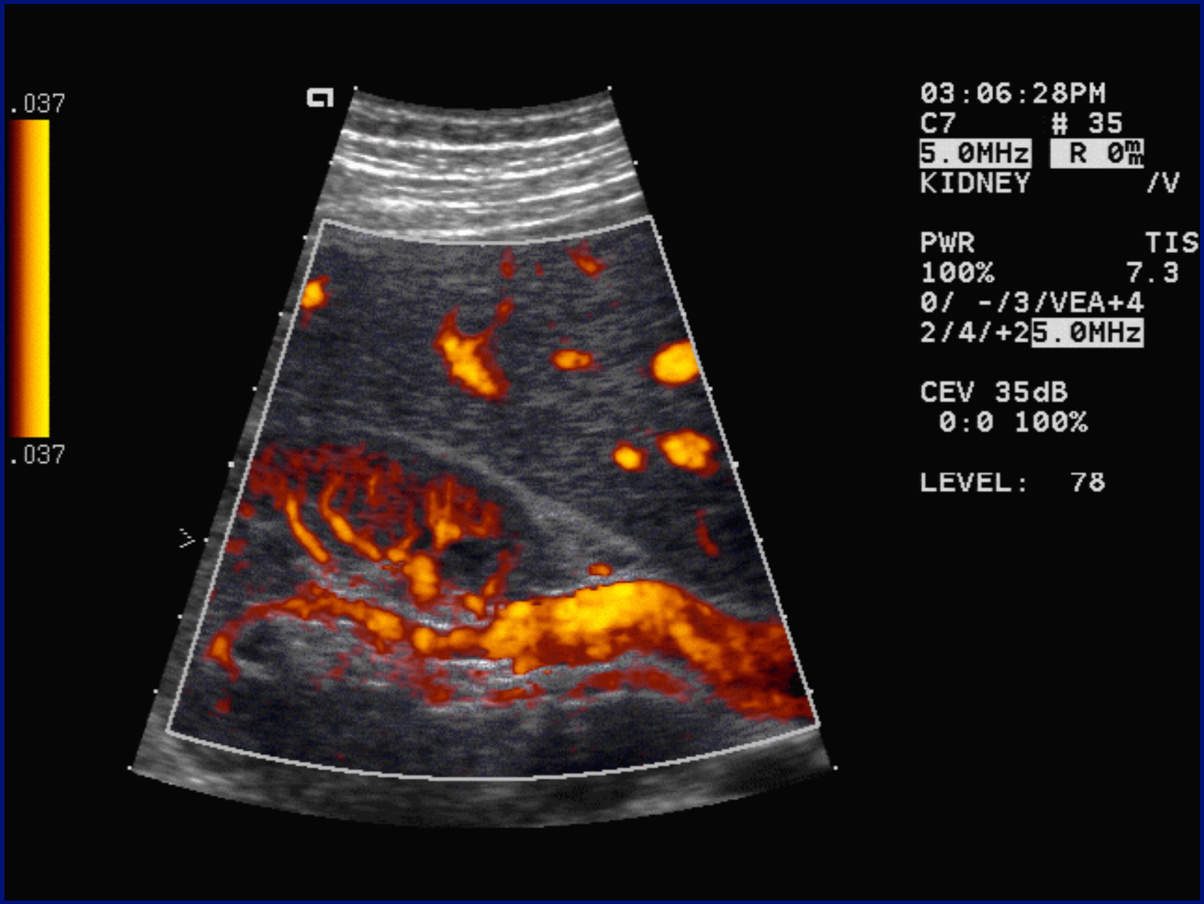
multiple gates

multiple firings



Color Doppler





Color Doppler

- Similar to B-mode, except that each line is fired multiple times (5-15).
- Correlation processing.
- Multiple range gates along each line.
- Real-time two-dimensional flow imaging.
- Poor velocity (frequency) resolution.

Color Doppler Derivation: Mean Velocity

$$R(t) \equiv \int_{-\infty}^{\infty} S(t+\tau)\, S^*(\tau)\, d\tau$$

$$R(t) = \int_{-\infty}^{\infty} P(\omega)\, e^{j\omega t}\, d\omega$$

$$R(0) = \int_{-\infty}^{\infty} P(\omega)\, d\omega$$

$$-j \left.\frac{dR(t)}{dt}\right|_{t=0} = \int_{-\infty}^{\infty} \omega P(\omega)\, d\omega$$

$$\overline{\omega} = \frac{\int_{-\infty}^{\infty} \omega P(\omega)\, d\omega}{\int_{-\infty}^{\infty} P(\omega)\, d\omega}$$

$$\overline{\omega} = -j\,\frac{R'(0)}{R(0)}$$

Color Doppler Derivation: Mean Velocity

$R(t) = |R(t)|e^{j\theta(t)}$ $\quad |R(t)|$: even $\quad \theta(t)$: odd

$$A(t) \equiv |R(t)|$$

$$R(0) = A(0)$$

$$R'(t) = A'(t)e^{j\theta(t)} + j\theta'(t)A(t)e^{j\theta(t)}$$

$$R'(0) = jA(0)\theta'(0)$$

$$\overline{\omega} = \theta'(0) \approx \frac{\theta(T) - \theta(0)}{T} = \frac{\theta(T)}{T}$$

In practice, R(t) is by definition a discrete signal,…

$$\hat{R}(n \times T) = \frac{1}{N-n}\sum_{i=1}^{N-n} S((i+n) \times T) S^*(i \times T)$$

Color Doppler Derivation: Mean Velocity

- For a single scatterer:

$$R(T) = S(T)S^{*}(0)$$
$$\theta(T) = \angle S(T) - \angle S(0)$$

- The flow direction is determined by the sign of the mean frequency.

Color Doppler Derivation: Variance

$$\sigma^2 = \frac{\int_{-\infty}^{\infty} (\omega - \overline{\omega})^2 P(\omega)\, d\omega}{\int_{-\infty}^{\infty} P(\omega)\, d\omega} = \overline{\omega^2} - \overline{\omega}^2$$

$$-\frac{d^2 R(t)}{dt^2}\bigg|_{t=0} \equiv -R''(0) = \int_{-\infty}^{\infty} \omega^2 P(\omega)\, d\omega$$

$$\sigma^2 = -\frac{R''(0)}{R(0)} + \left(\frac{R'(0)}{R(0)}\right)^2$$

Color Doppler Derivation: Variance

$$R''(0) = A''(0) - A(0)(\theta'(0))^2$$

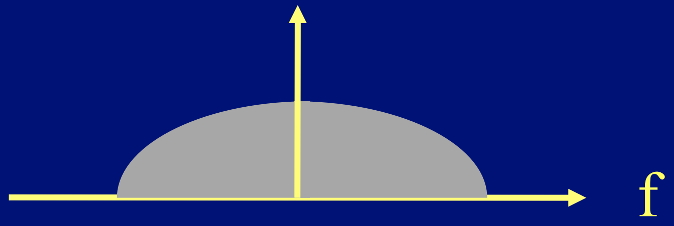
$$\sigma^2 = (\theta'(0))^2 - \frac{A''(0)}{A(0)} - (\theta'(0))^2 = -\frac{A''(0)}{A(0)}$$

$$A(t) = A(0) + \frac{t^2}{2} A''(0) + R$$

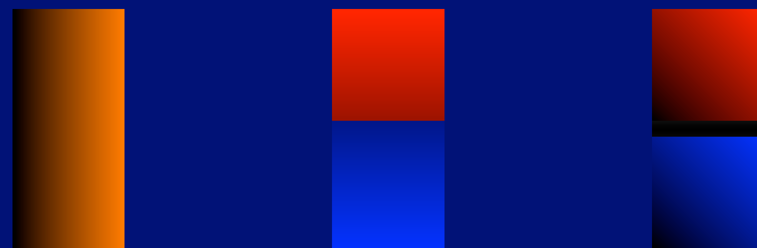
$$\sigma^2 \approx \frac{2}{T^2}\left(1 - \frac{A(T)}{A(0)}\right) = \frac{2}{T^2}\left(1 - \frac{|R(T)|}{R(0)}\right)$$

Color Doppler Derivation: Energy

$$E = \int_{-\infty}^{\infty} P(\omega)\,d\omega = R(0)$$

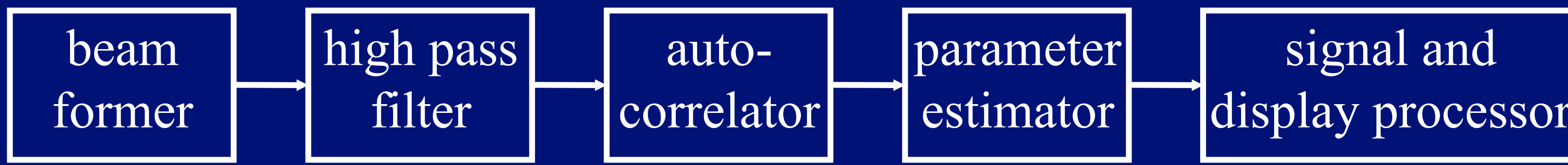


Color Doppler



- Flow parameters are mapped into colors for display (1D or 2D).
- Choice of map affects the presentation of Color Doppler images.

Color Doppler: Signal Processing



- Significant frame rate reduction.
- Small color boxes are often used to increase frame rate.
- Sophisticated systems utilize multiple beam formation to further increase frame rate.

Doppler: Complications

- Non-trivial wall filters are required to remove interference from slow-moving objects.
- Adequate signal processing capabilities and sufficient dynamic range are necessary to detect weak flows.
- Conflicts with frame rate requirements.
- Only parallel flow is detectable.

Homework #3

Due 12:00pm 6/13/2012 by emailing to

paichi@ntu.edu.tw

r99945010@ntu.edu.tw

- Load hw3_dat.mat. In this data file, DopplerData represents a PW Doppler data set. The size of the data is 128 X 400, representing gated received data with 128 firings and 400 data samples for each firing. In the same data file, the following parameters are also included:
  - PRI: pulse repetition interval in usec.
  - fs: sampling frequency in MHz.
  - f0: center frequency of the transmitted pulse in MHz.

- For each firing, perform the following processing. The total number of samples will reduce from 400 to a single complex sample after the processing. Repeat the processing for all firings in order to obtain 128 complex samples.

1. Based on the 128 complex samples, calculate the velocity profile using FFT. The profile should be plotted on a logarithmic scale with a 40dB range. The horizontal axis should also be labeled with proper velocity scale. (30%)

2. Re-do Problem 1 by using only the even samples. Also re-do Problem 1, by using only the first 200 RF data points during the summation. Explain your results. (30%)

3. Based on the original complex samples, calculate and plot the mean velocity, variance and energy as the number of samples increases from 2 to 128. Also compare with the results when only using the center 100 (151:250) points for the summing. Note that the discrete correlation function is defined as the following (40%).

$$\hat{R}(n \times T) = \frac{1}{N-n} \sum_{i=1}^{N-n} S((i+n) \times T) S^*(i \times T)$$

4. (bonus) Explore any related Doppler issues based on the dataset.