生醫超音波技術

台大電機系 李百祺

Outline

- Fundamentals of ultrasound
- Focusing in ultrasound
- Ultrasonic blood flow estimation
- Nonlinear ultrasonics

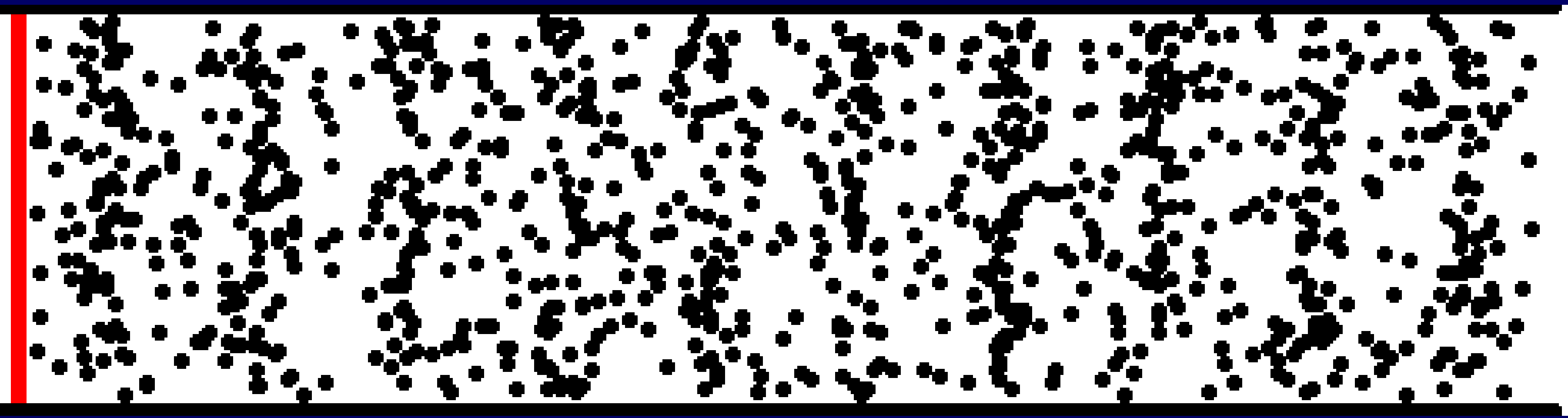
What is ultrasound?

Characteristics of Ultrasound

- A mechanical wave:
  - Characterized by pressure, particle velocity and displacement.
  - Density change of the propagating medium.
  - But it is still a wave, i.e., there is reflection, refraction, scattering, diffraction, attenuation…etc.

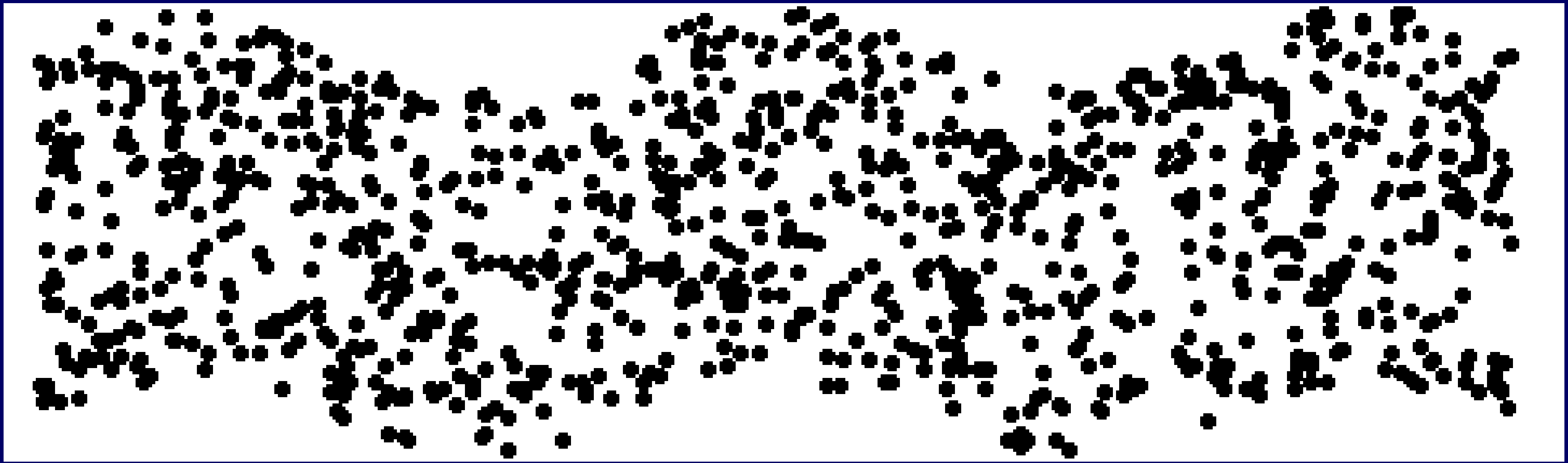
Basics of Acoustic Waves

- Longitudinal Wave:



Basics of Acoustic Waves

- Shear Wave:



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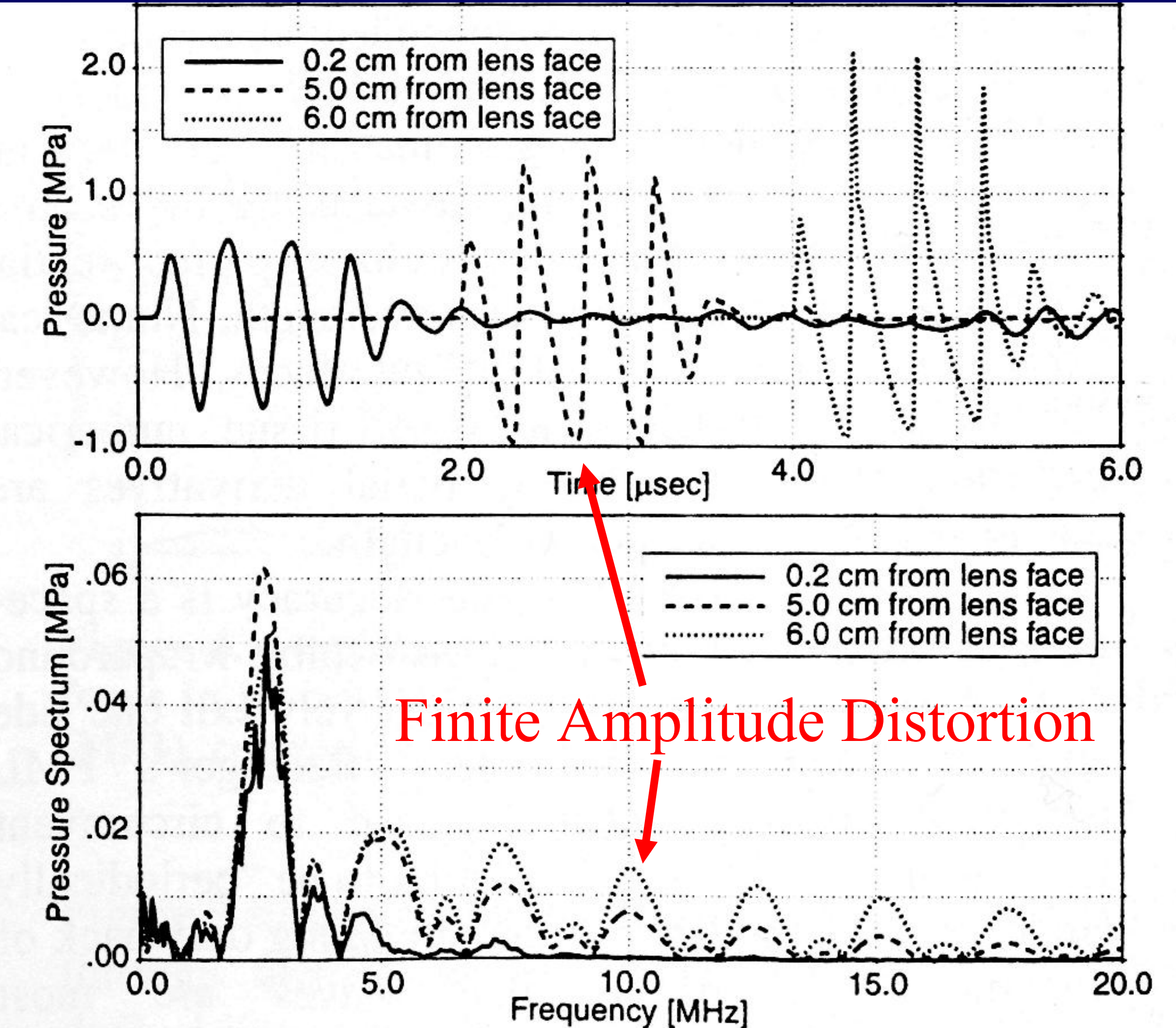
Sound Velocity and Density Change

$$v(x) = c_0 + (1+\frac{B}{2A})u(x)$$

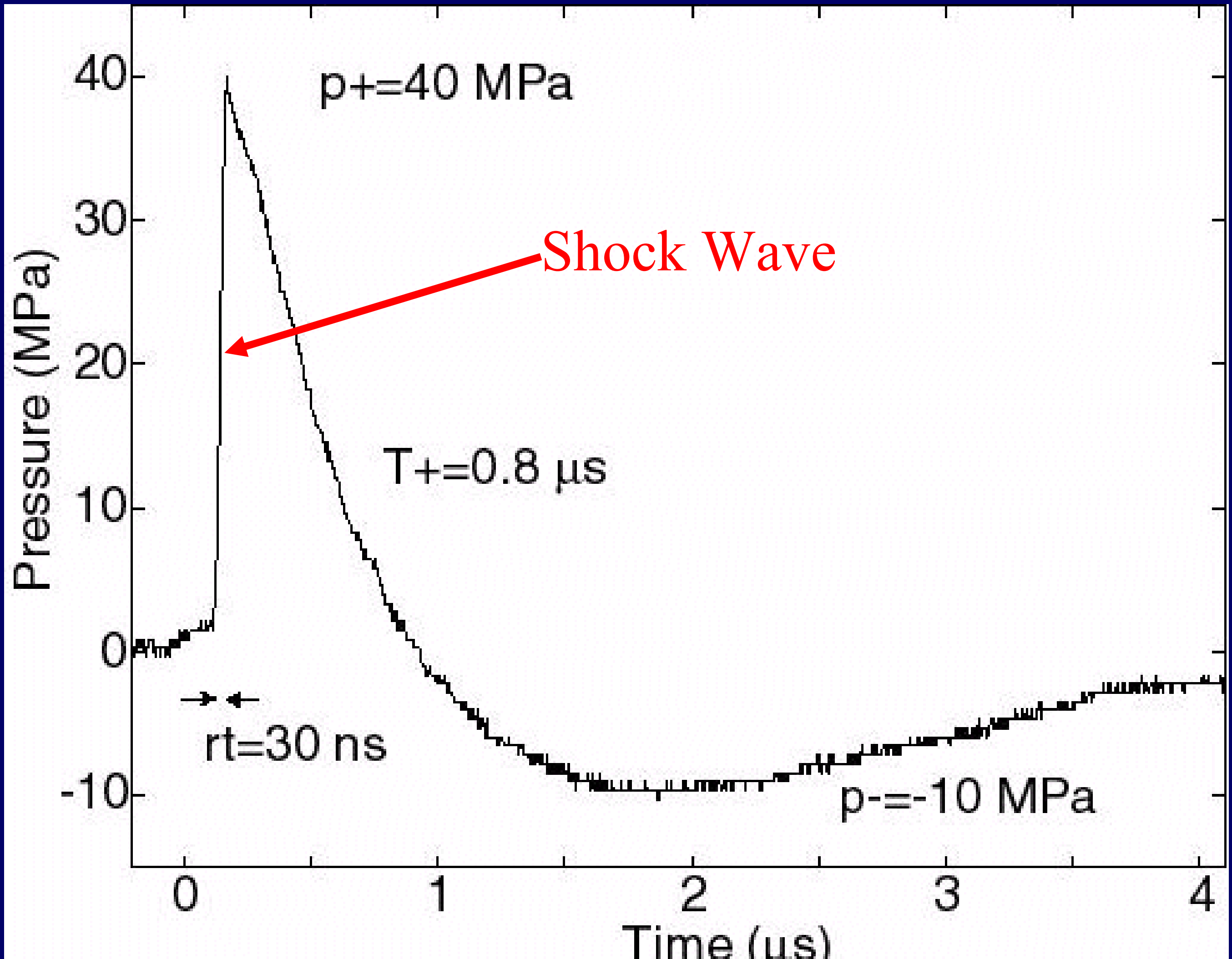
Phase velocity

Nonlinearity

Particle velocity



When Peak Pressure Is Very High



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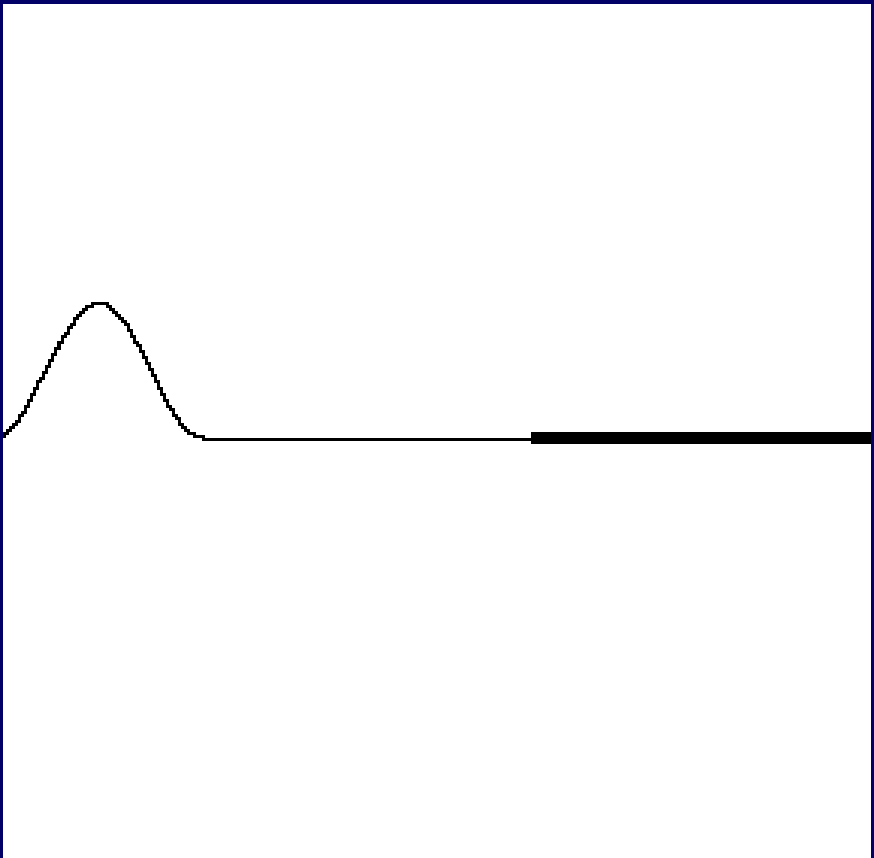
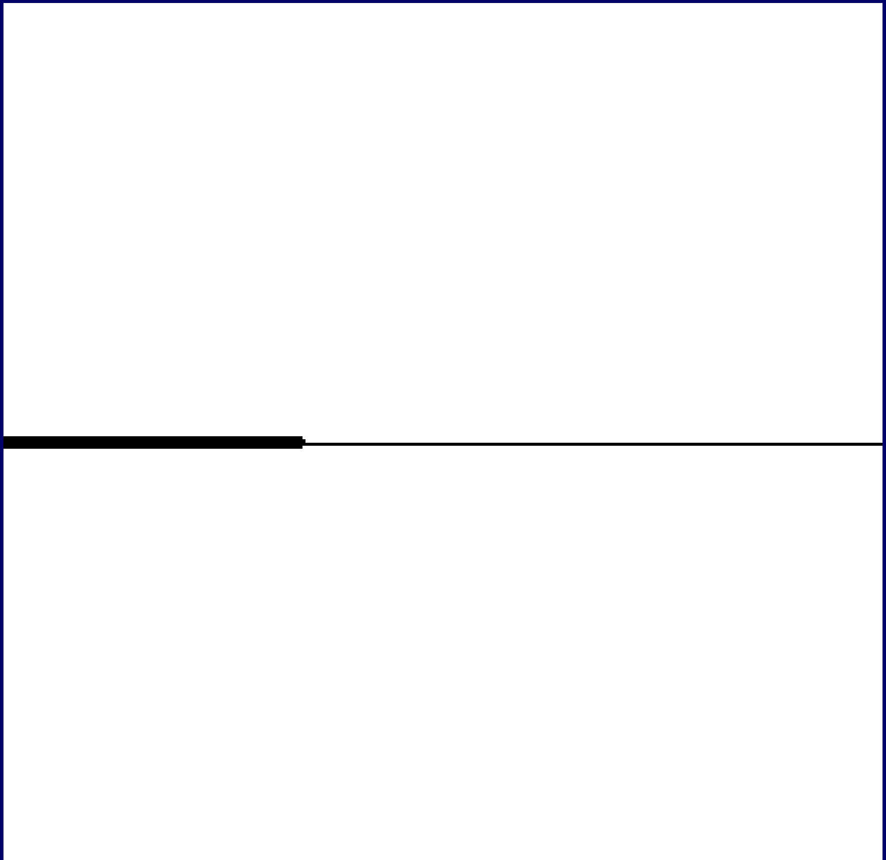
Reflection

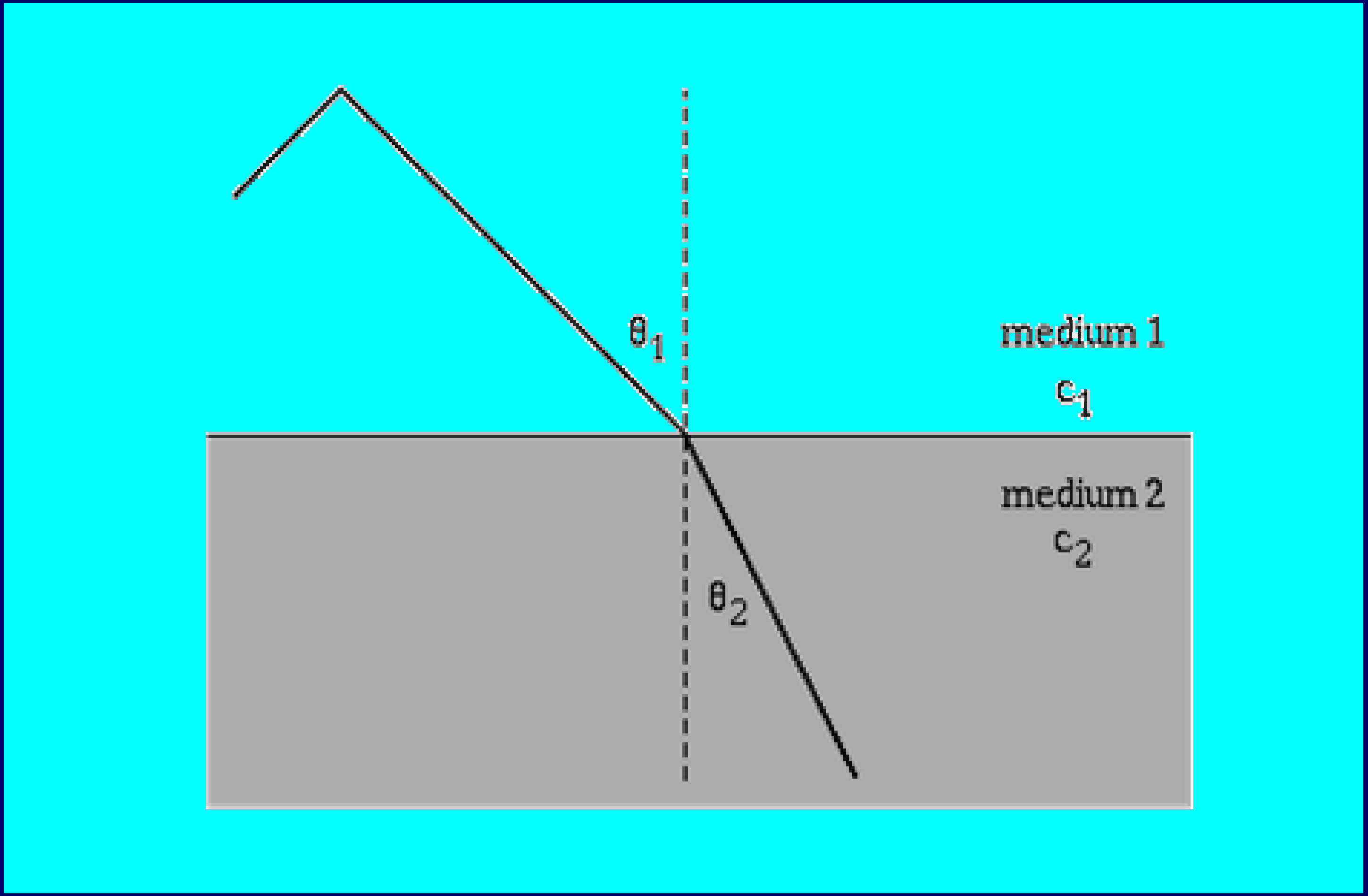
Low Density to High Density



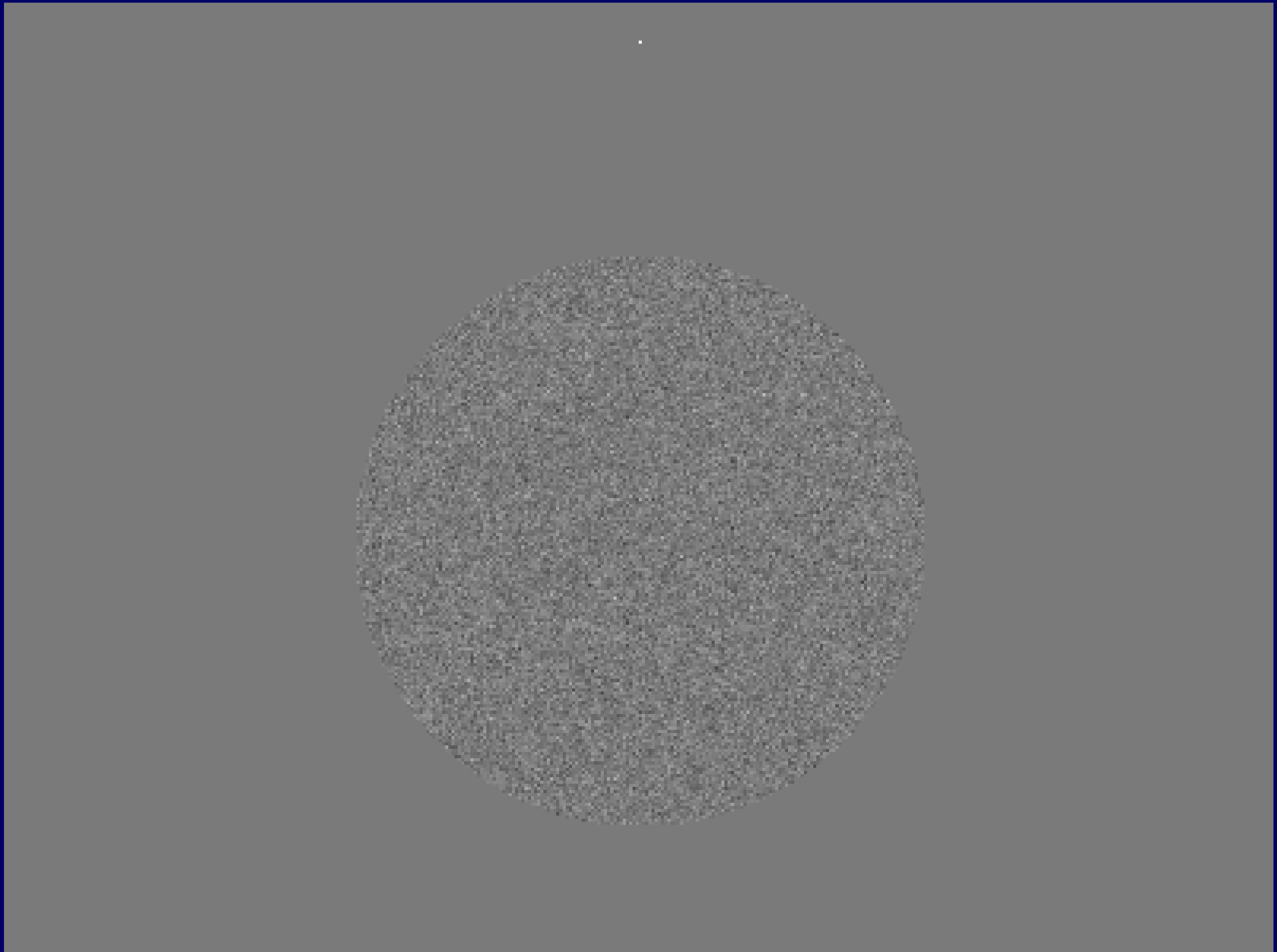
High Density to Low Density



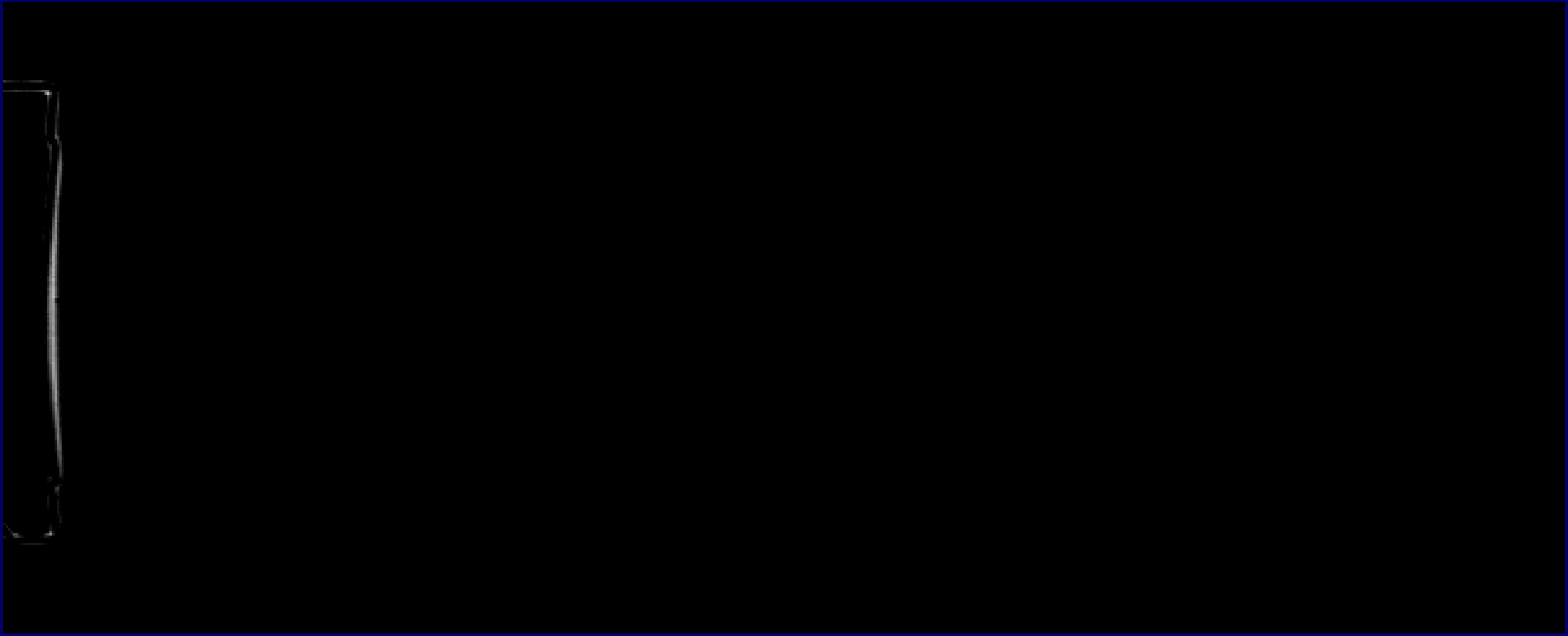
Refraction



Acoustic Scattering



Diffraction



Characteristics of Ultrasound

- Sound wave with frequencies higher than the audible range (>20-25kHz):
  - Typical frequency range for biomedical applications: 0.1-50MHz.
  - $c = f \cdot \lambda$.
  - Sound (propagation) speed in soft tissues are around 1500m/sec. It becomes higher in hard tissues (e.g., bone).

Table IV
Velocity and acoustic impedance of pertinent materials and biological tissues at room temperature (20–25°C)

	Velocity (m/sec)	Impedance $\times 10^{-6}$ (kg/m^2-sec)[a]
Water	1484	1.48
Aluminum	6420	17.00
Air	343	0.0004
Plexiglas	2670	3.20
Blood	1550	1.61
Myocardium (perpendicular to fibers)	1550	1.62
Fat	1450	1.38
Liver	1570	1.65
Kidney	1560	1.62
Skull bone	3360 (longitudinal)	6.00

[a] Rayl is a unit commonly used for acoustic impedance. One rayl = 1 kg/m^2-sec.

Characteristics of Ultrasound

- Affected by the elastic properties of the propagating medium:
  - Various modes of propagation.
  - Hooke's law: $T=eS$ (tensor form in 3D).

$$c = \sqrt{B / \rho}$$

$$\text{Characteri stic impedance } : Z_0 = \rho c$$

TABLE 9.3

REFLECTIVITY OF NORMALLY INCIDENT WAVES

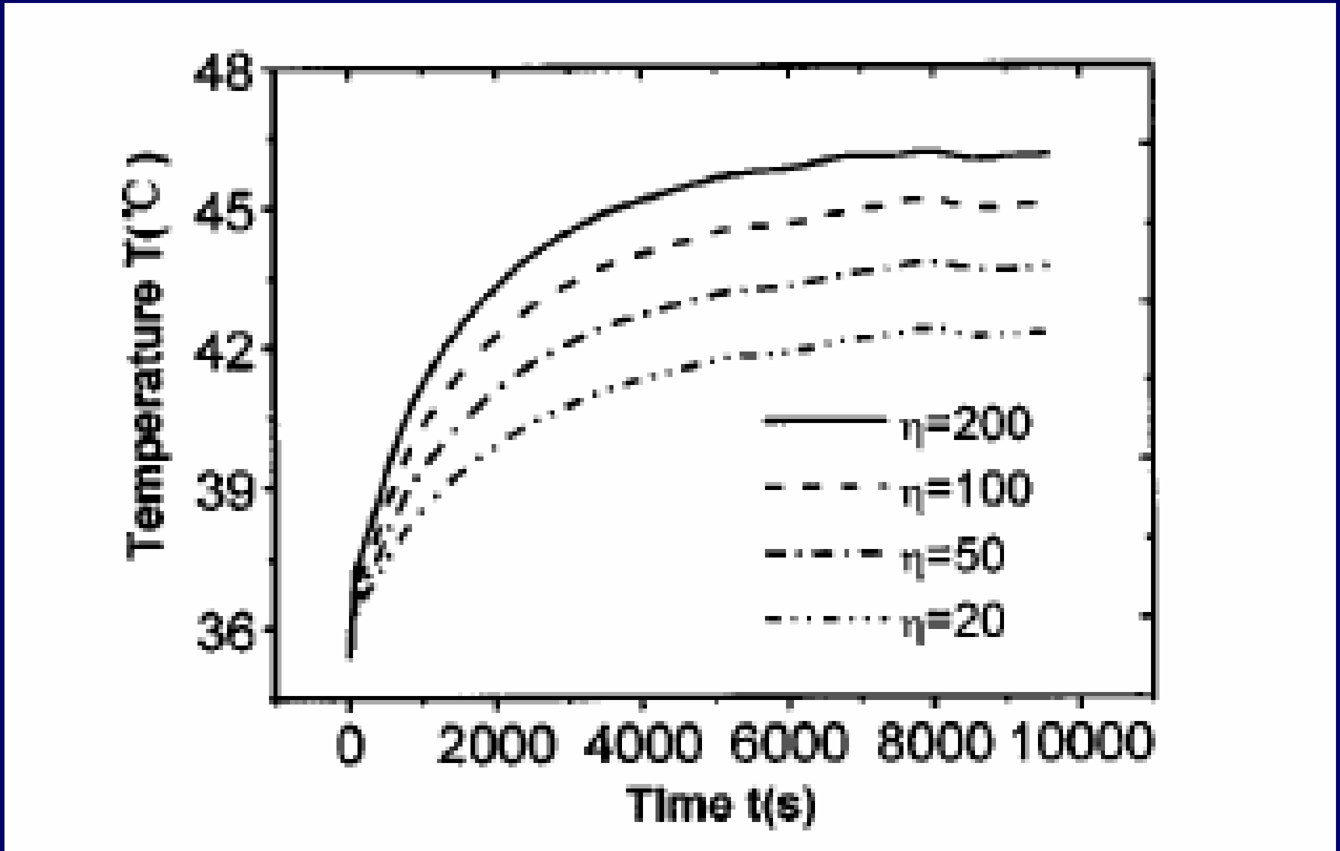
Materials at Interface	Reflectivity
Brain–skull bone	0.66
Fat–bone	0.69
Fat–blood	0.08
Fat–kidney	0.08
Fat–muscle	0.10
Fat–liver	0.09
Lens–aqueous humor	0.10
Lens–vitreous humor	0.09
Muscle–blood	0.03
Muscle–kidney	0.03
Muscle–liver	0.01
Soft tissue (mean value)–water	0.05
Soft tissue–air	0.9995
Soft tissue–PZT5 crystal	0.89

Bio-Effects

- Heating
- Cavitation

Ultrasound Heating

- Bio-transfer equation: $$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + \omega_b \rho_b c_b (T_a - T) + Q_m + Q_r(x,t)$$

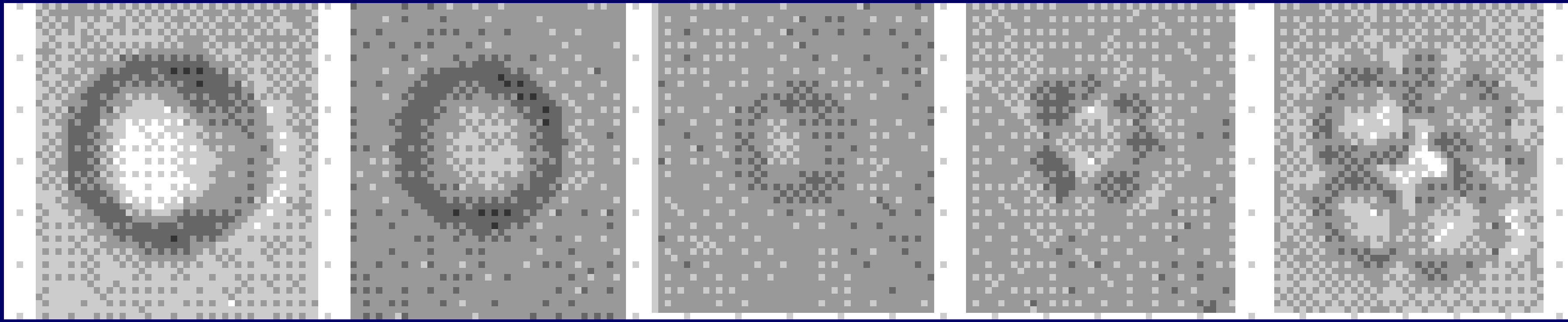


Bio-Effects

- Heating
- Cavitation

Cavitation

- Formation and behavior of gas bubbles in acoustic fields.
- Transient cavitation: sudden growth and collapse of bubbles, resulting shock waves and very high temperatures.

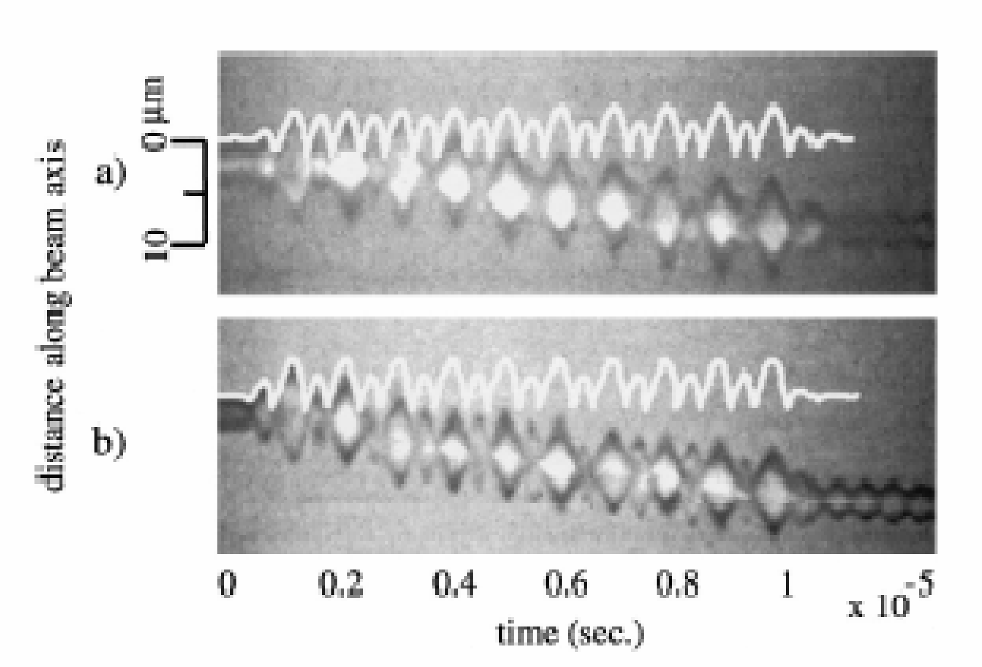


Other Acoustic Phenomena

- Radiation force.
- Sonoluminescence.
- …etc.

Radiation Force

- An ultrasonic wave exerts a static force on an interface or in a medium where there is a decrease in power in the wave propagation direction.

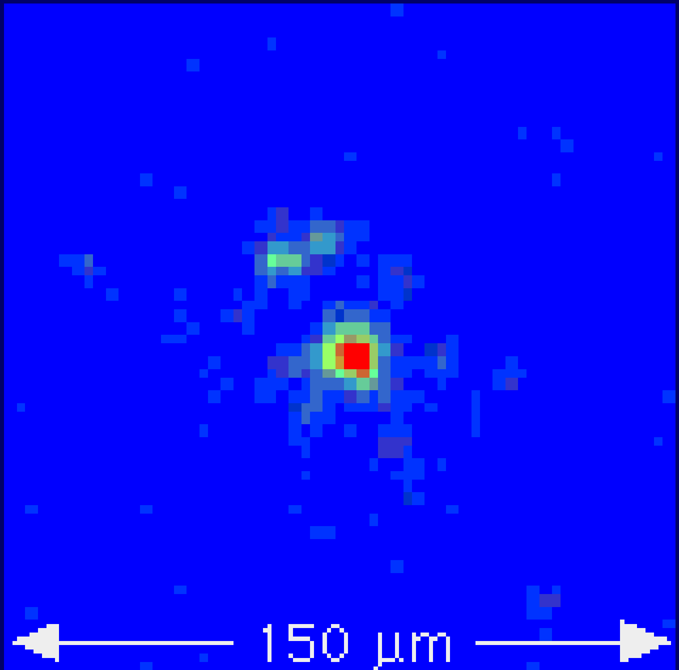


Other Acoustic Phenomena

- Radiation force.
- Sonoluminescence.
- …etc.

Sonoluminescence

- Weak emission of light observable when high intensity ultrasound passing through a medium containing dissolved gases.



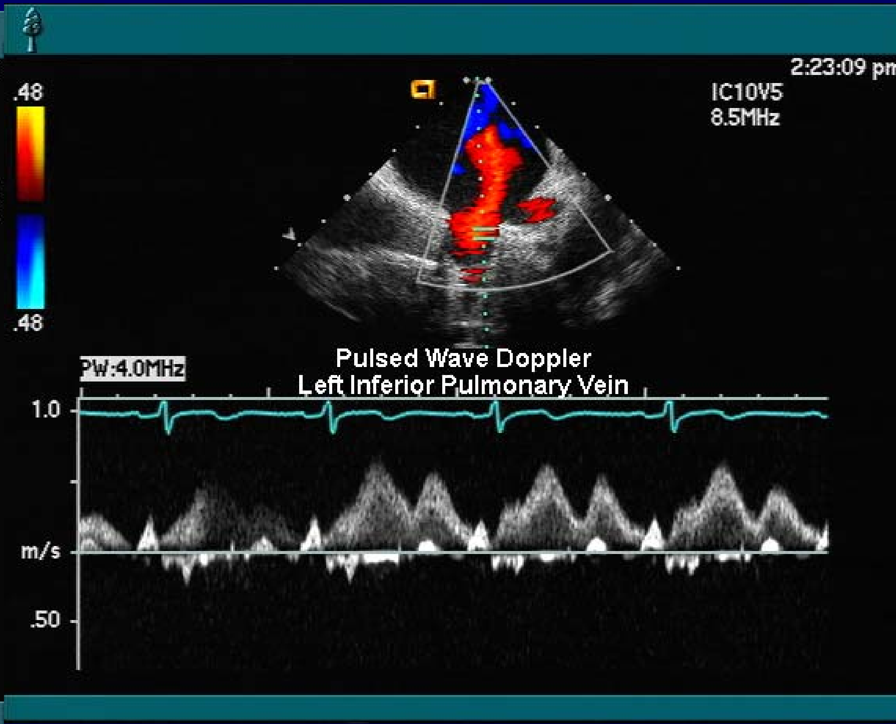
. . . ,etc.

What can ultrasound do in medicine and biology?

Ultrasound in Medicine and Biology

- Diagnostics (as a wave):
  - Imaging.
  - Blood flow measurements.
  - Bone density (indirect).
  - …etc.

Ultrasonic Imaging



Ultrasound in Medicine and Biology

- Therapeutics:
  - Heat generation:
    - Hyperthermia.
    - HIFU.
  - Shock wave
    - Lithotripsy.
  - …etc.

Hyperthermia

- Hyperthermia is a method of treating cancerous tissue by elevating the tissue temperature to 42.5°C or above, and maintaining this for 30-60 minutes.

Hyperthermia

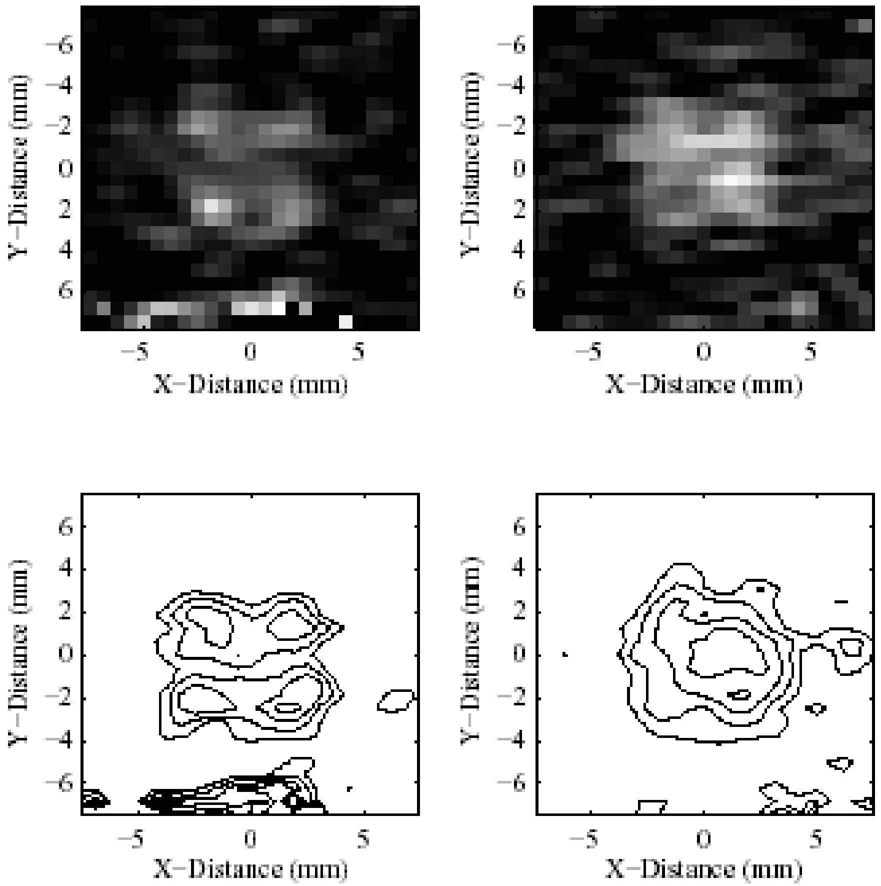


Figure 3: Thermal contour images for (left) non-switched and (right) switched sonications.

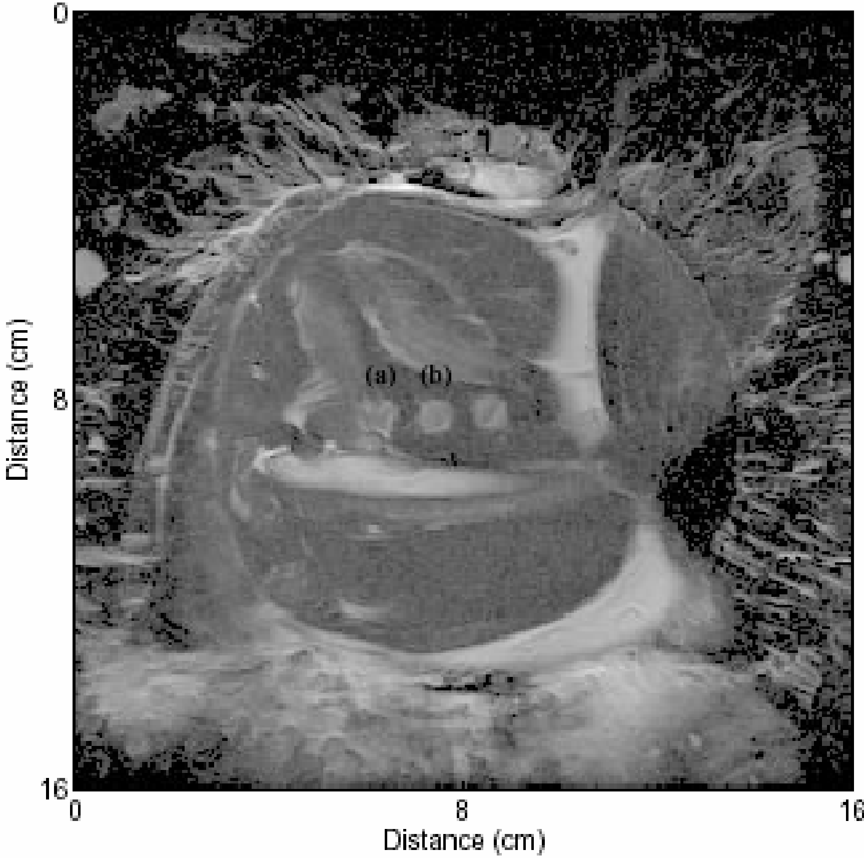


Figure 4: T2 weighted image of therma necrosis caused by (a) single four focus patter and (b) switched focus pattern across axis.

HIFU

- *High Intensity Focused Ultrasound.*
- In the focal point, the sudden and intense absorption of the ultrasound beam creates a sudden elevation of the temperature (from 85 to 100°C) which destroys the cells located in the targeted zone.

HIFU for Prostate Cancer

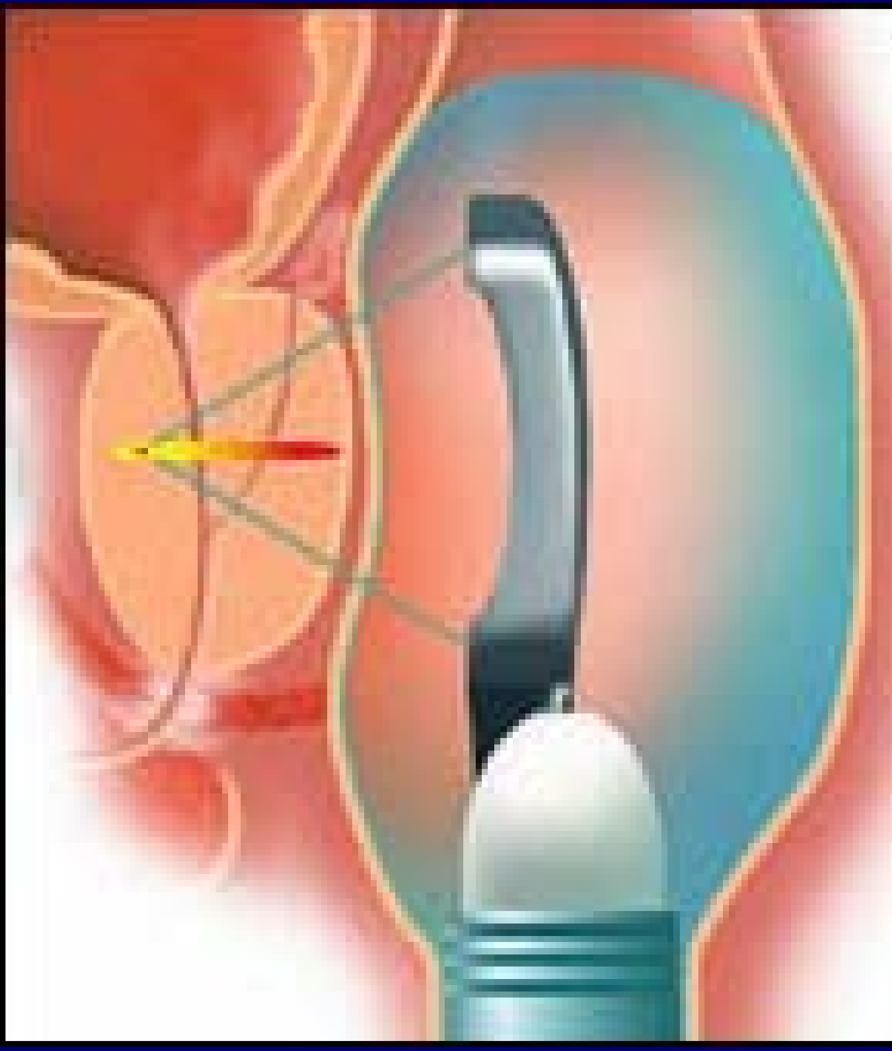


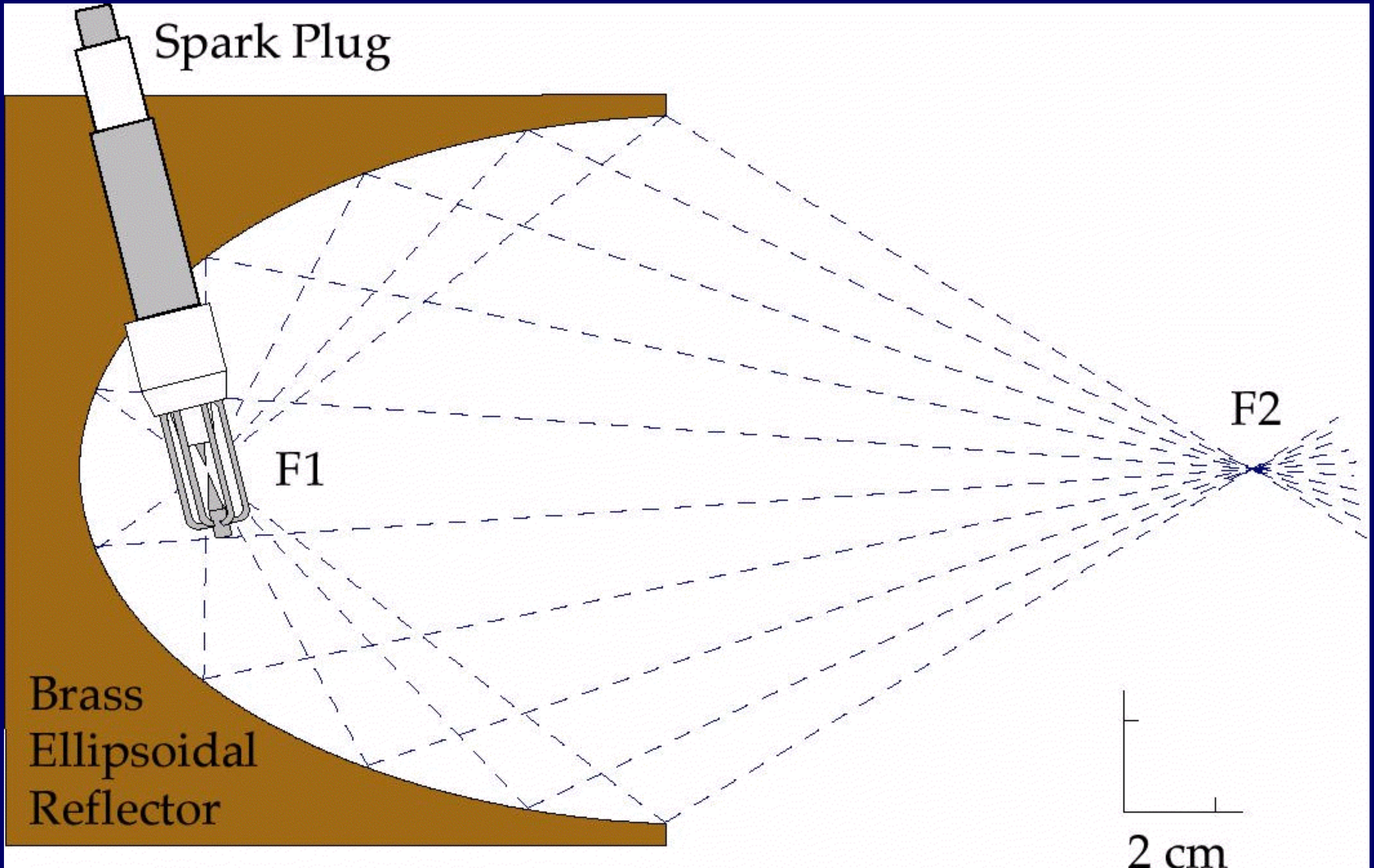
Image Guided HIFU

Ultrasound in Medicine and Biology

- Therapeutics:
  - Heat generation:
    - Hyperthermia.
    - HIFU.
  - Shock wave
    - Lithotripsy.
  - …etc.

Extracorporeal Lithotripsy

- The use of shock waves to destroy stones in the body.



Extracorporeal Lithotripsy

Ultrasound in Medicine and Biology

- Sonoluminescence.
- Radiation force.
- Cavitation.
- Cosmetics.
- …etc.

Bio-Effects and Safety Requirements

Basics

- Safety regulations.
- Physical parameters vs. Bio-effects.
- Measurement techniques.
- Dose: Energy absorption in tissue.
  - Temperature rise, cell damage.
  - Dosimetry: measurements of such effects.
- Exposure: Characteristics of ultrasound field.
  - Pressure, intensity, power.
  - Exposimetry: measurements of temporal/spatial characterisitics.

Bio-Effects

- Temperature rise and cell damage (cavitation).
- FDA Track I: Pre-amendments.
  - I_{SPTA} (720 mW/cm^2) and I_{SPPA} (190 W/cm^2).
- FDA Track III:
  - TI (Thermal Index) and MI (Mechanical Index).
- ALARA (as low as reasonably achievable).

Bio-Effects

- Thermal index (TI):
  - TIS, TIB, TIC.
  - Analytical.

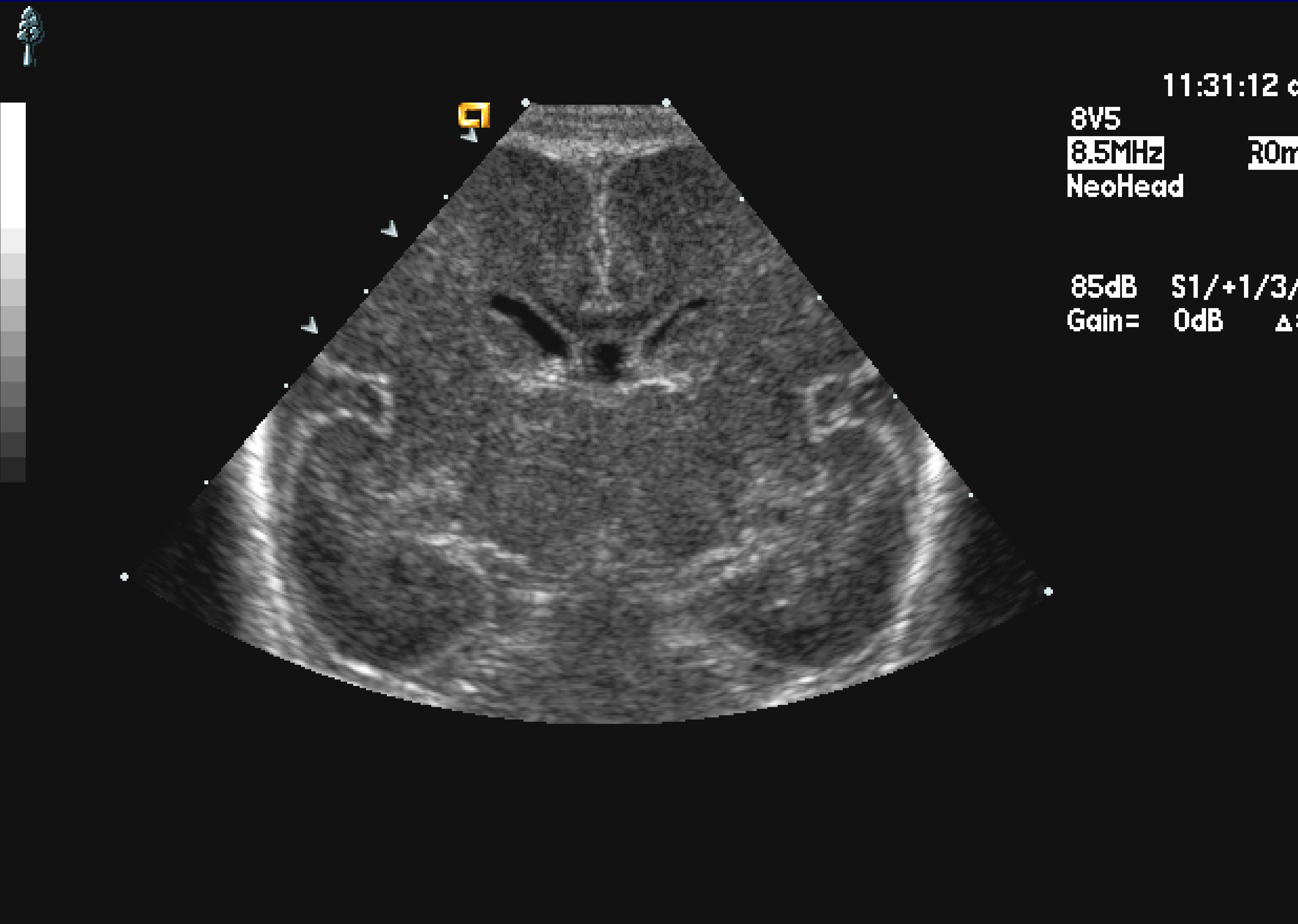
$$TI \equiv \frac{W_o}{W_{\text{deg}}}$$

- Mechanical Index (MI):
  - Experimental.
  - Destruction of bubble with different sizes at various frequencies.

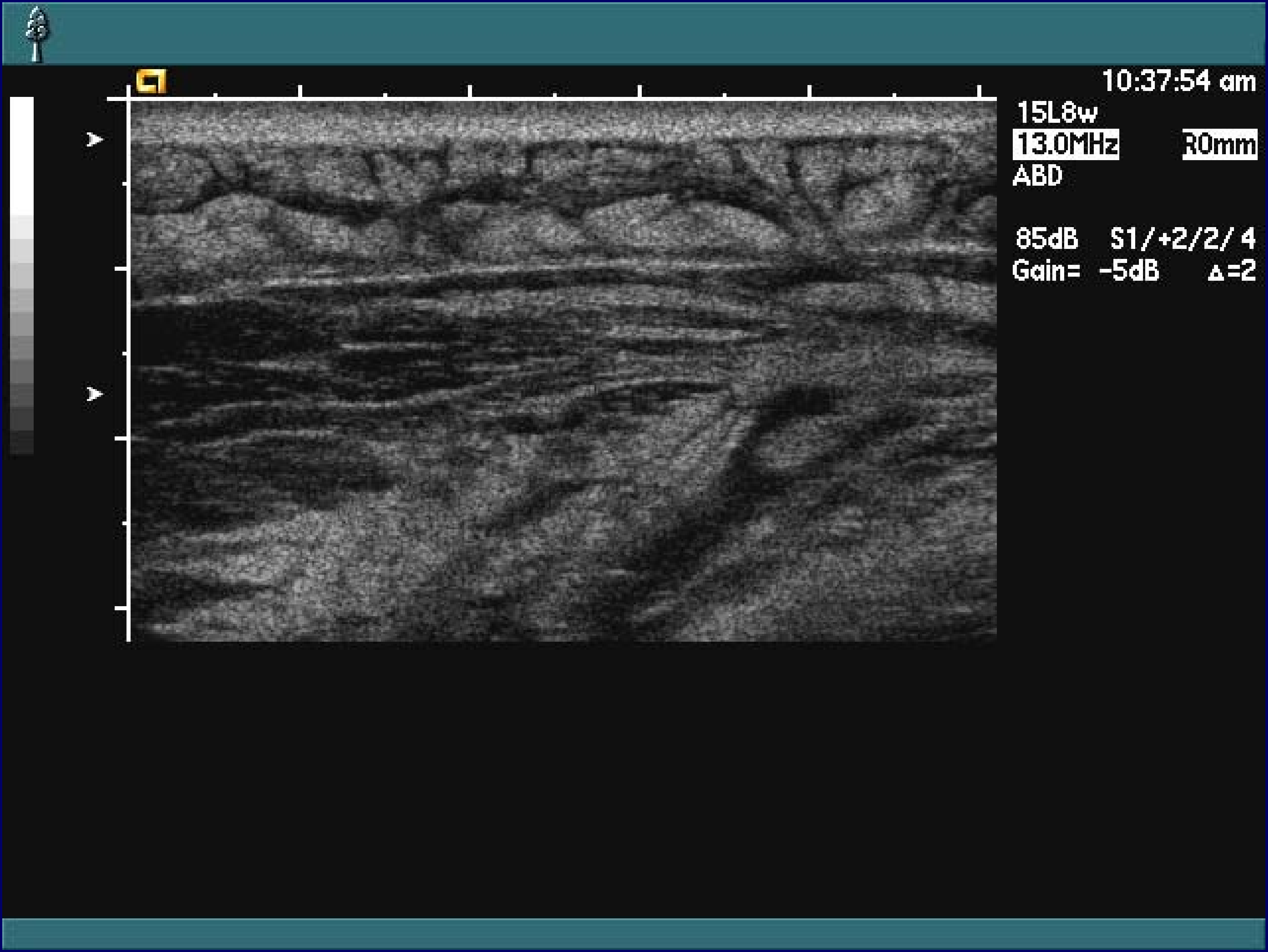
$$MI \equiv \frac{P_{0.3}}{\sqrt{f_c}}$$

Imaging and Focusing

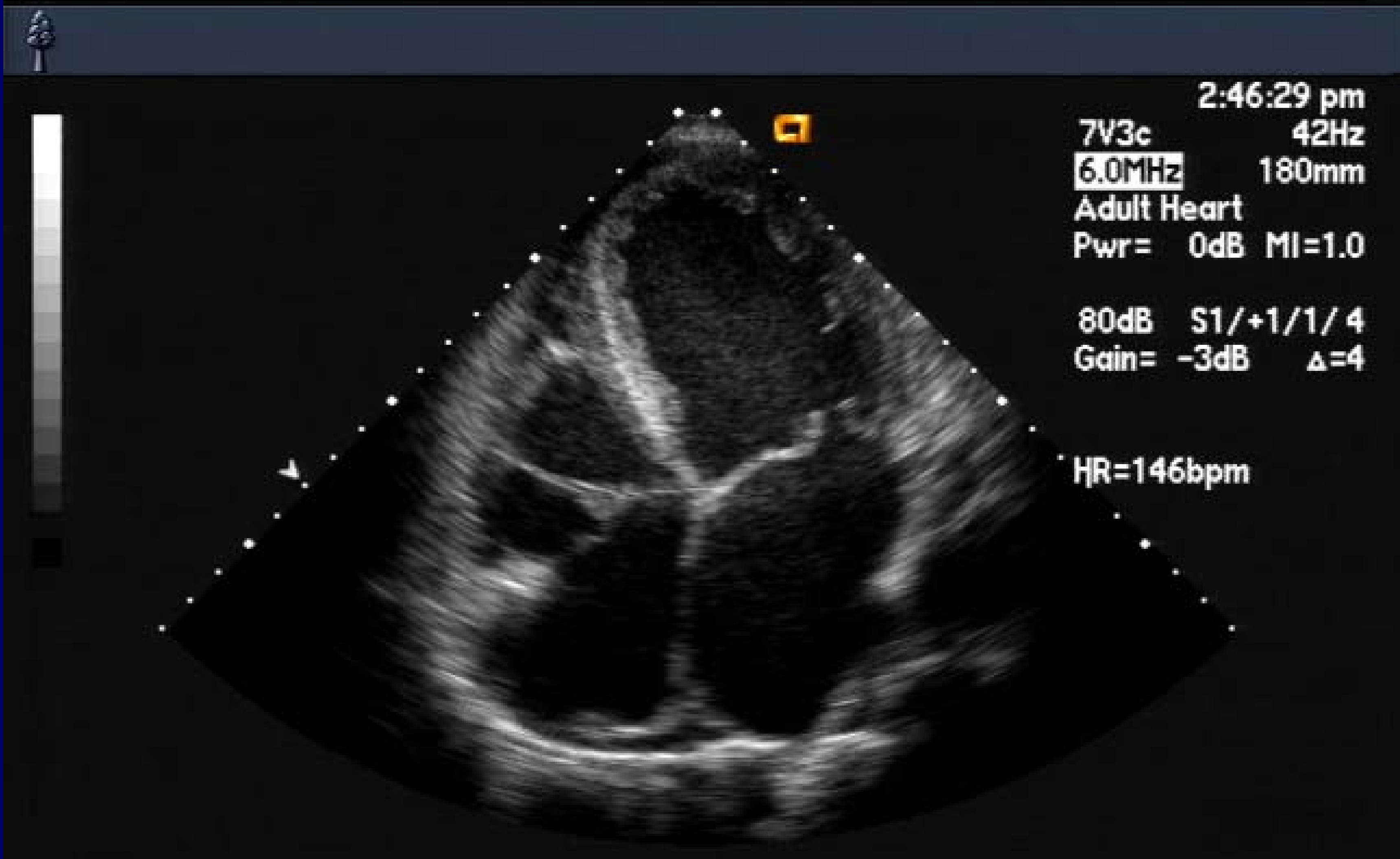

2:07:06 pm
8C4
H8.0MHz
75dB S1/+1/1/ 4
Gain= -6dB ▵=2



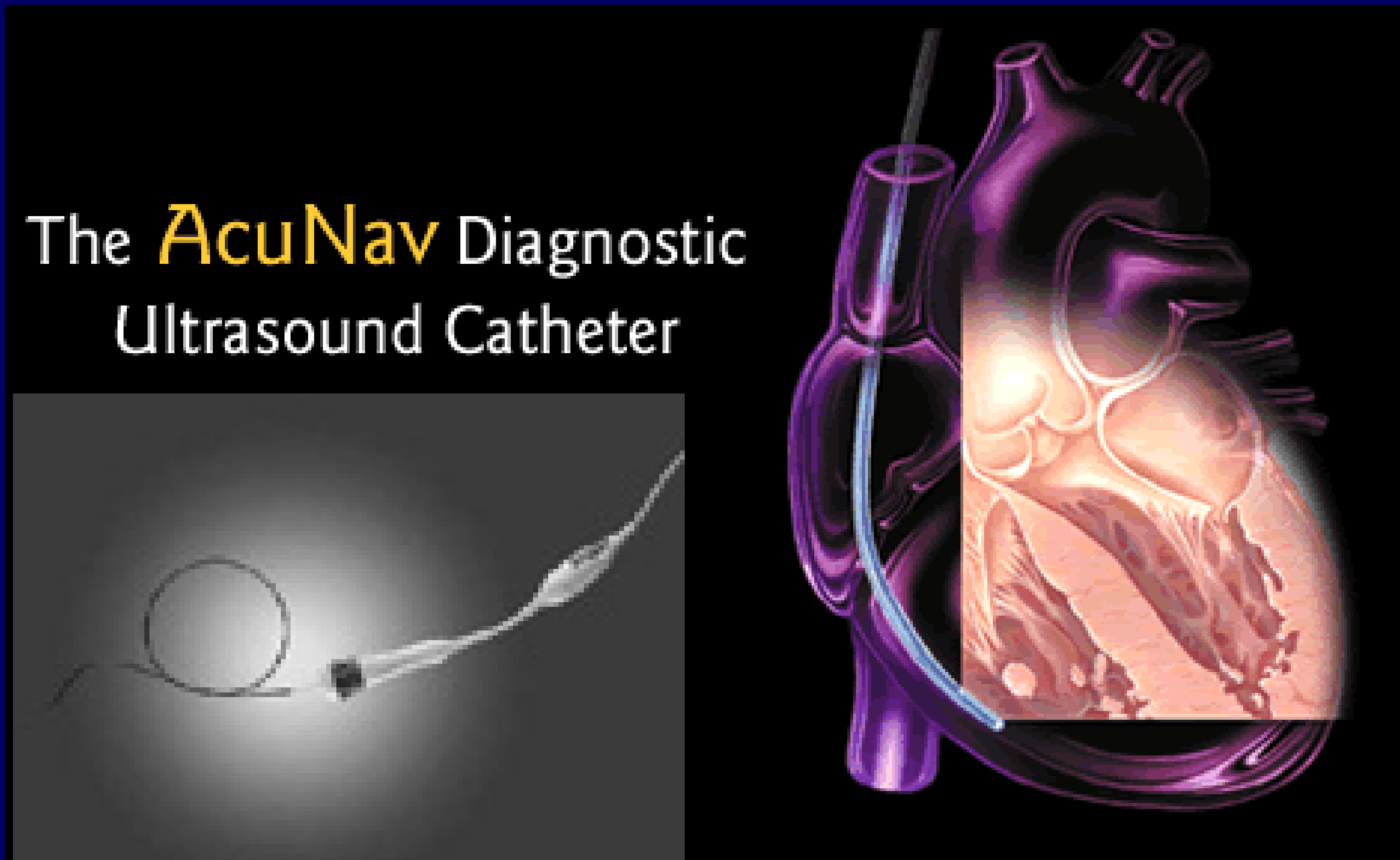
11:31:12
8V5
8.5MHz
NeoHead
85dB
Gain= 0dB

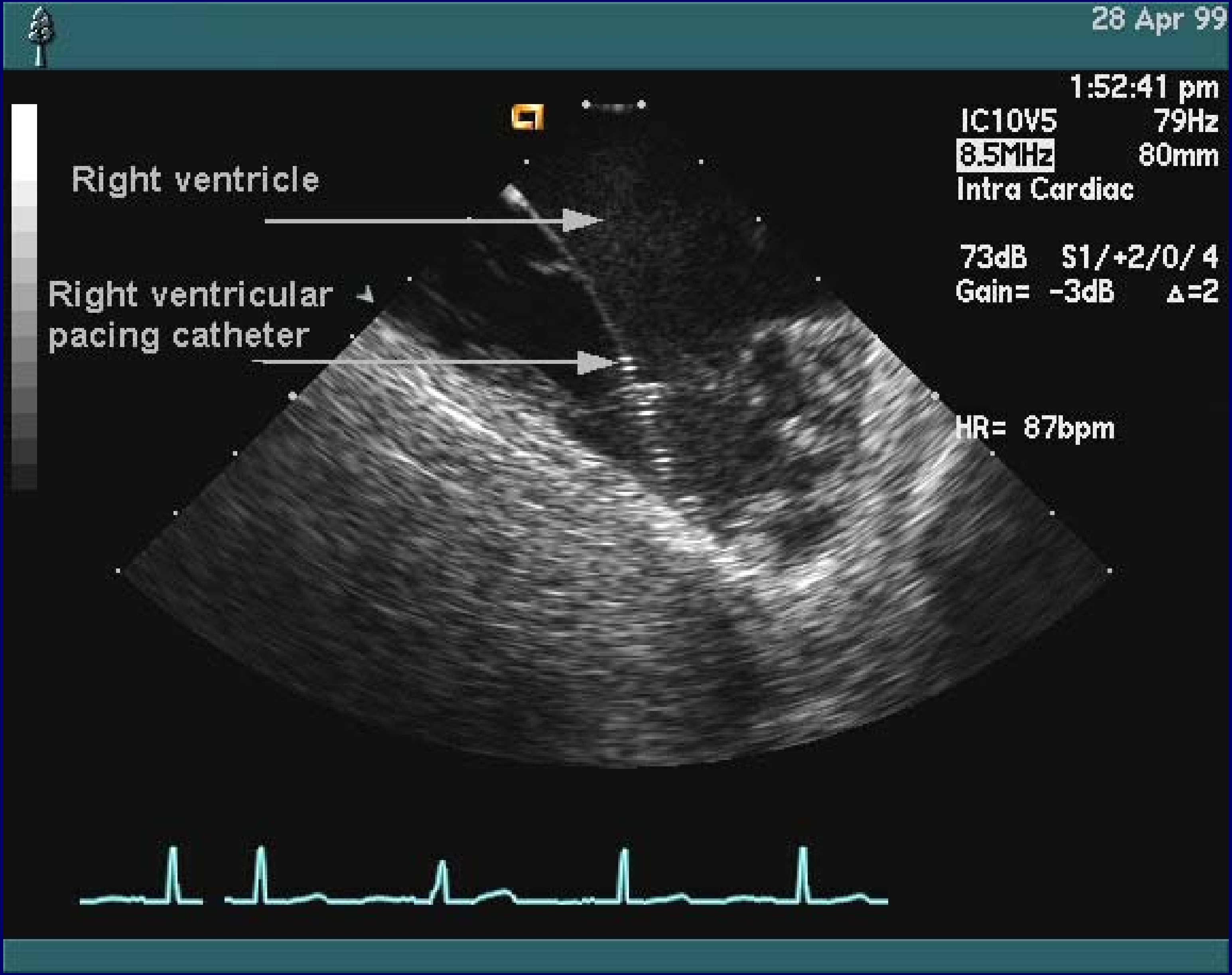

10:37:54 am
15L8w
13.0MHz
R0mm
ABD
85dB S1/+2/2/4
Gain= -5dB ▵=2

Real-Time Imaging

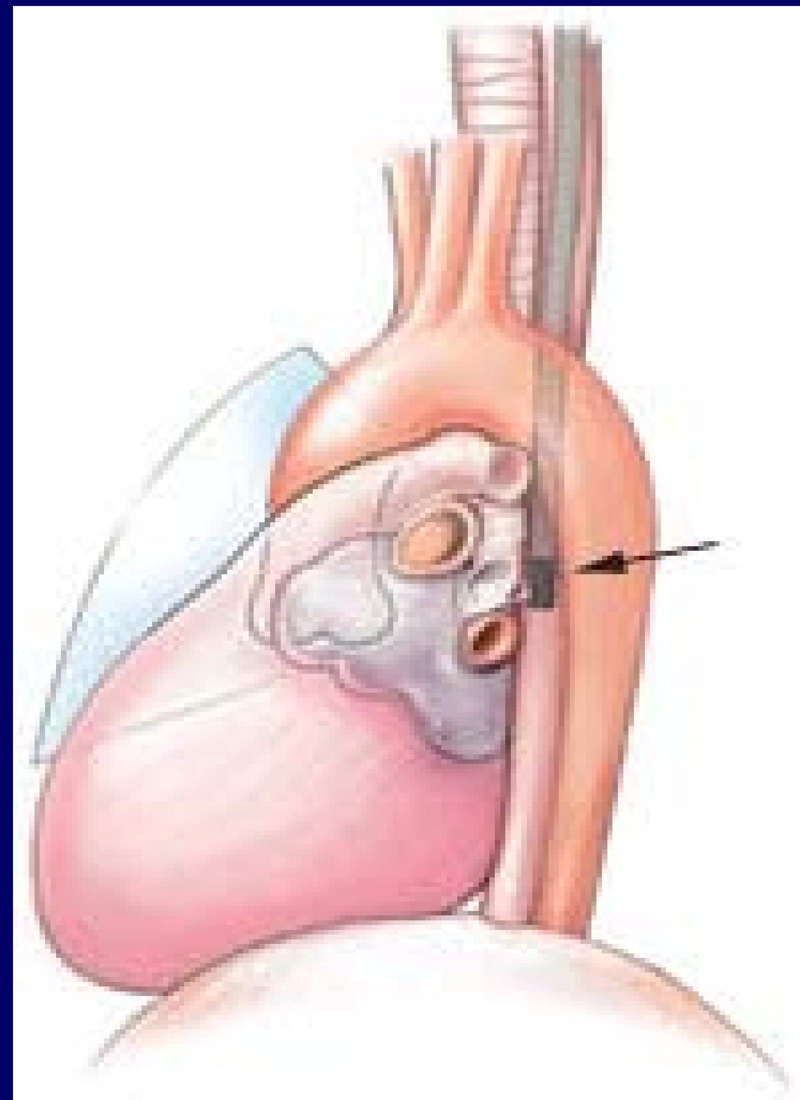


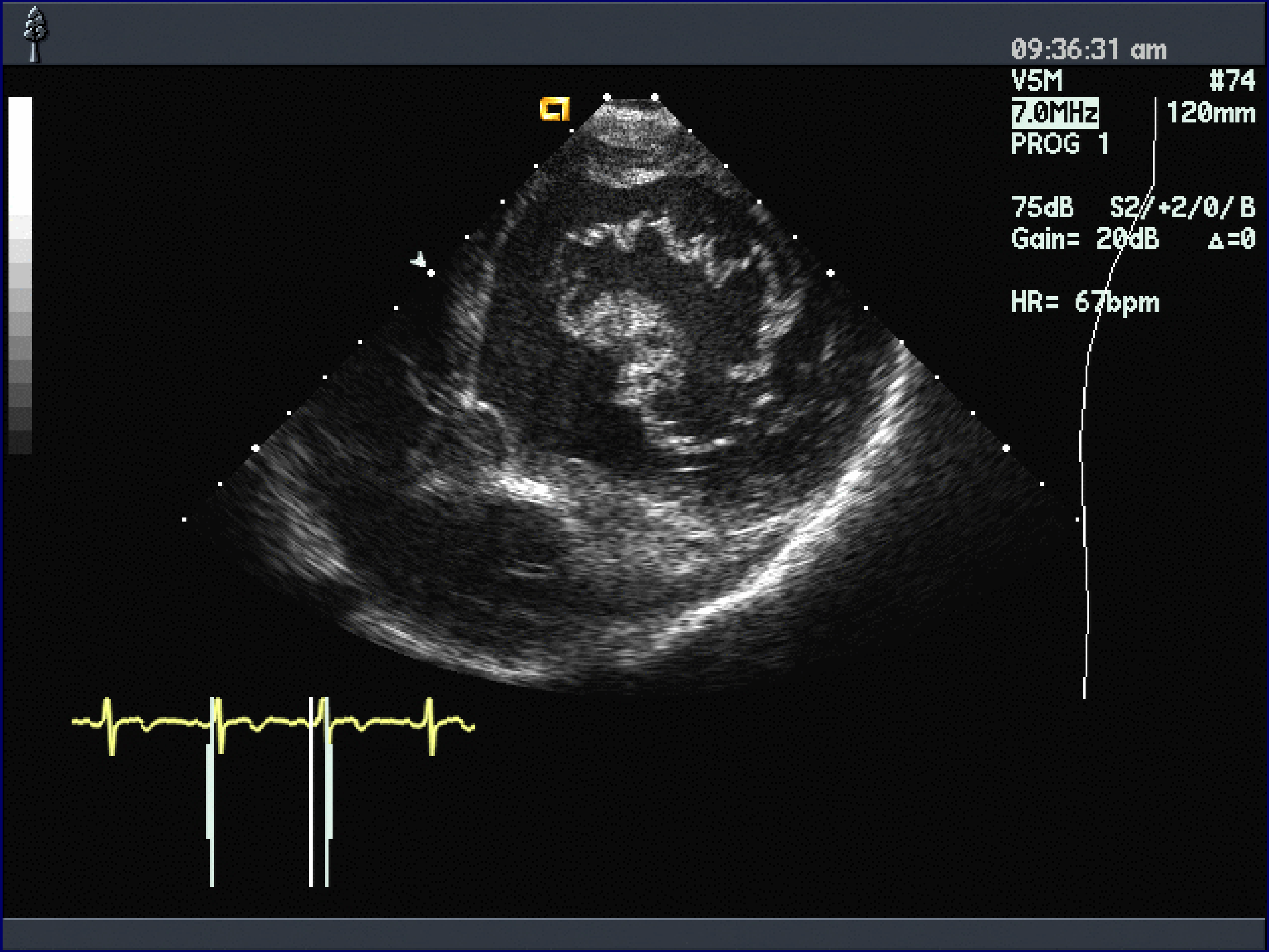
Apical 4 Chamber


The AcuNav Diagnostic
Ultrasound Catheter


28 Apr 99
1:52:41 pm
IC10V5 79Hz
8.5MHz 80mm
Intra Cardiac
73dB S1/+2/0/ 4
Gain= -3dB Δ=2
HR= 87bpm
Right ventricle
Right ventricular
pacing catheter

TransEsophageal Echocardiogram (TEE)

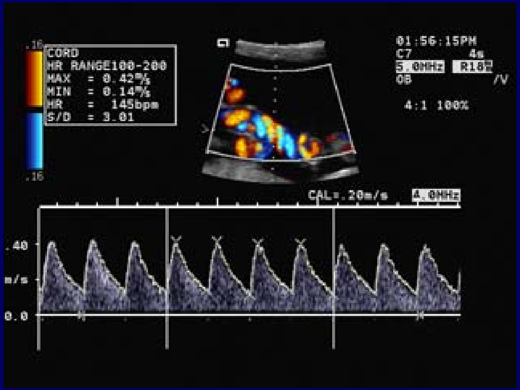



09:36:31 am
V5M #74
7.0MHz 120mm
PROG 1
75dB S2/+2/0/B
Gain= 20dB Δ=0
HR= 67bpm

8 Week Fetus

Works-in-Progress

Clinical Applications



(From www.acuson.com)

- OB/GYN, vascular, cardiac, transcranial, abdominal, musculoskeletal, endo-vaginal, endo-rectal, ocular, intra-vascular, …etc.

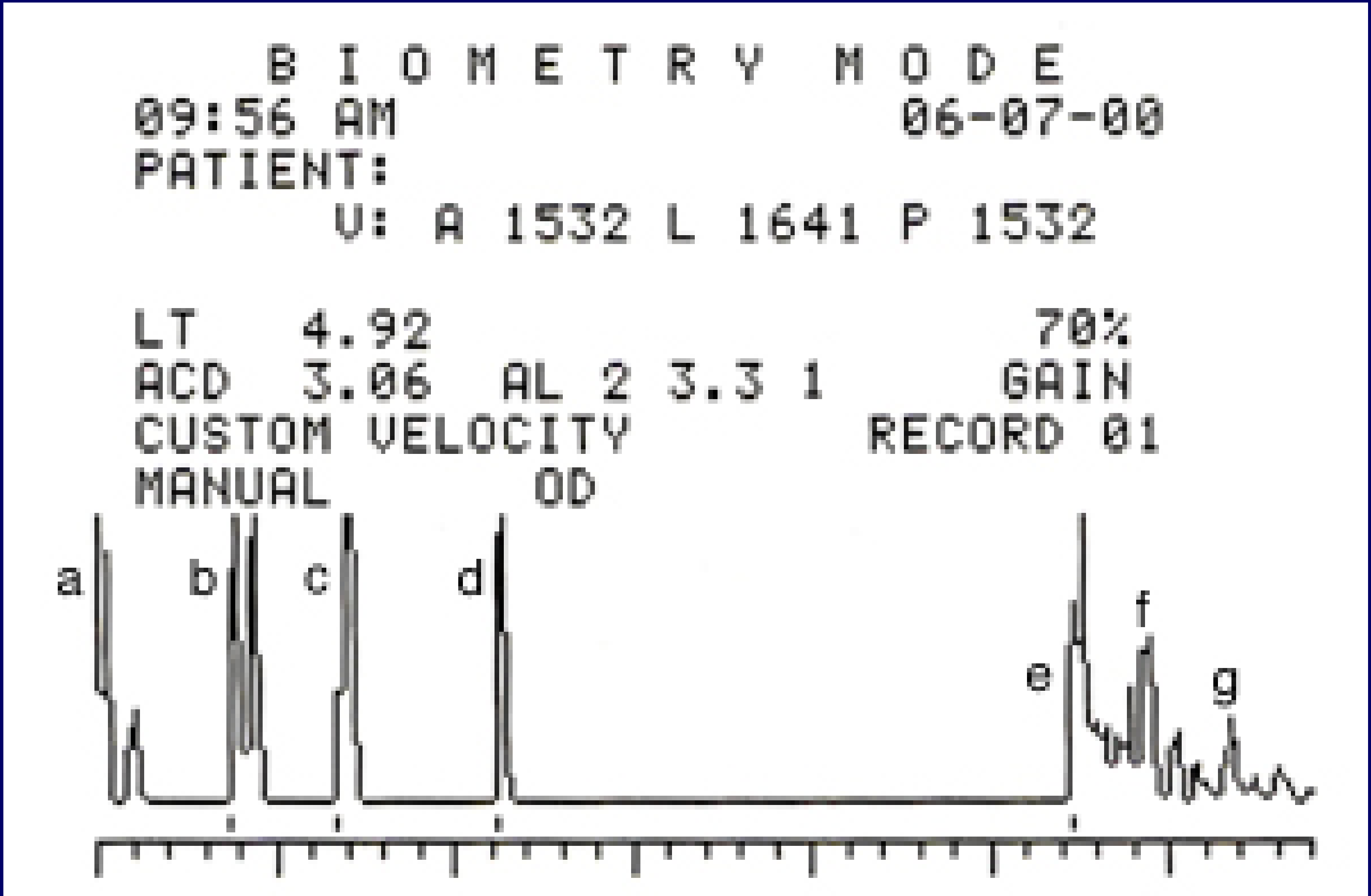
Characteristics of Diagnostic Ultrasound

- Non-invasive.
- Safe (under regulations).
- Real-time.
- Reflection mode (similar to RADAR).
- Blood flow imaging.
- Access.
- Portable.
- Body type dependent.

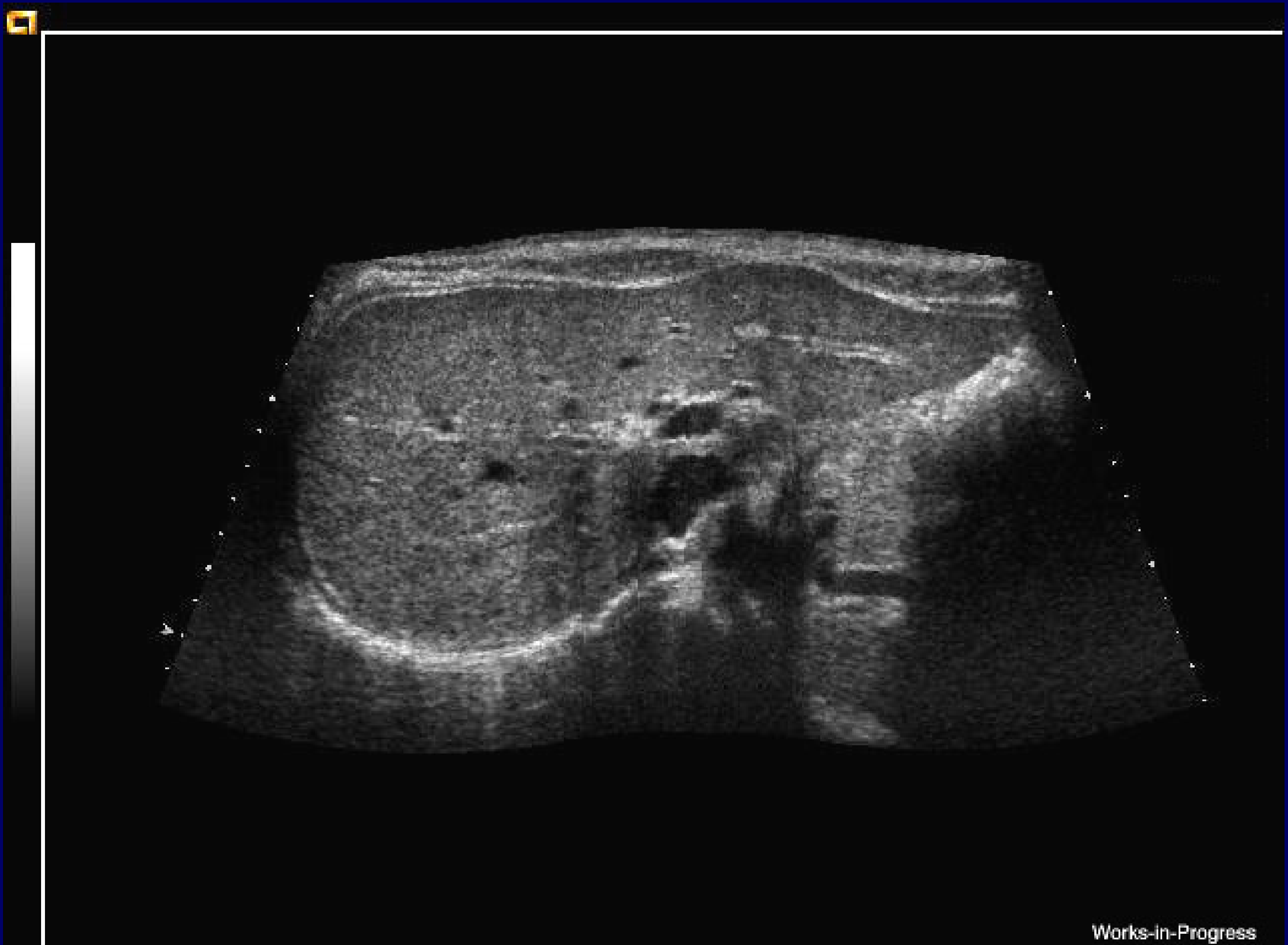
Function Modes

- A-mode (A-scan, 1D).
- B-mode (Gray scale, 2D).
- 3D ultrasound.
- M-mode (motion)
- Color Doppler (2D, blood flow).
- Spectral Doppler (localized, blood flow).
- Audio Doppler.

A-Scan (Amplitude, 1D)

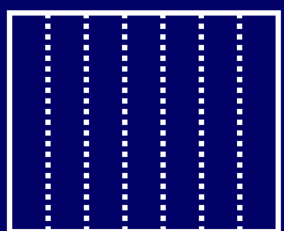


B-Scan (Brightness, 2D)



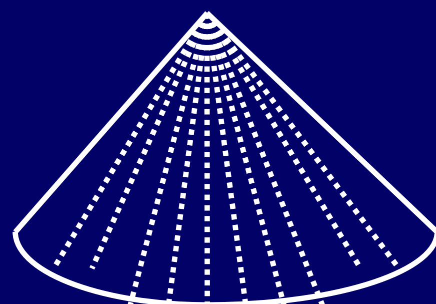
2D Scan Formats

linear



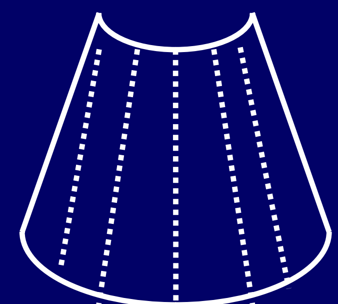
easy access
limited view

sector



limited access
wide view

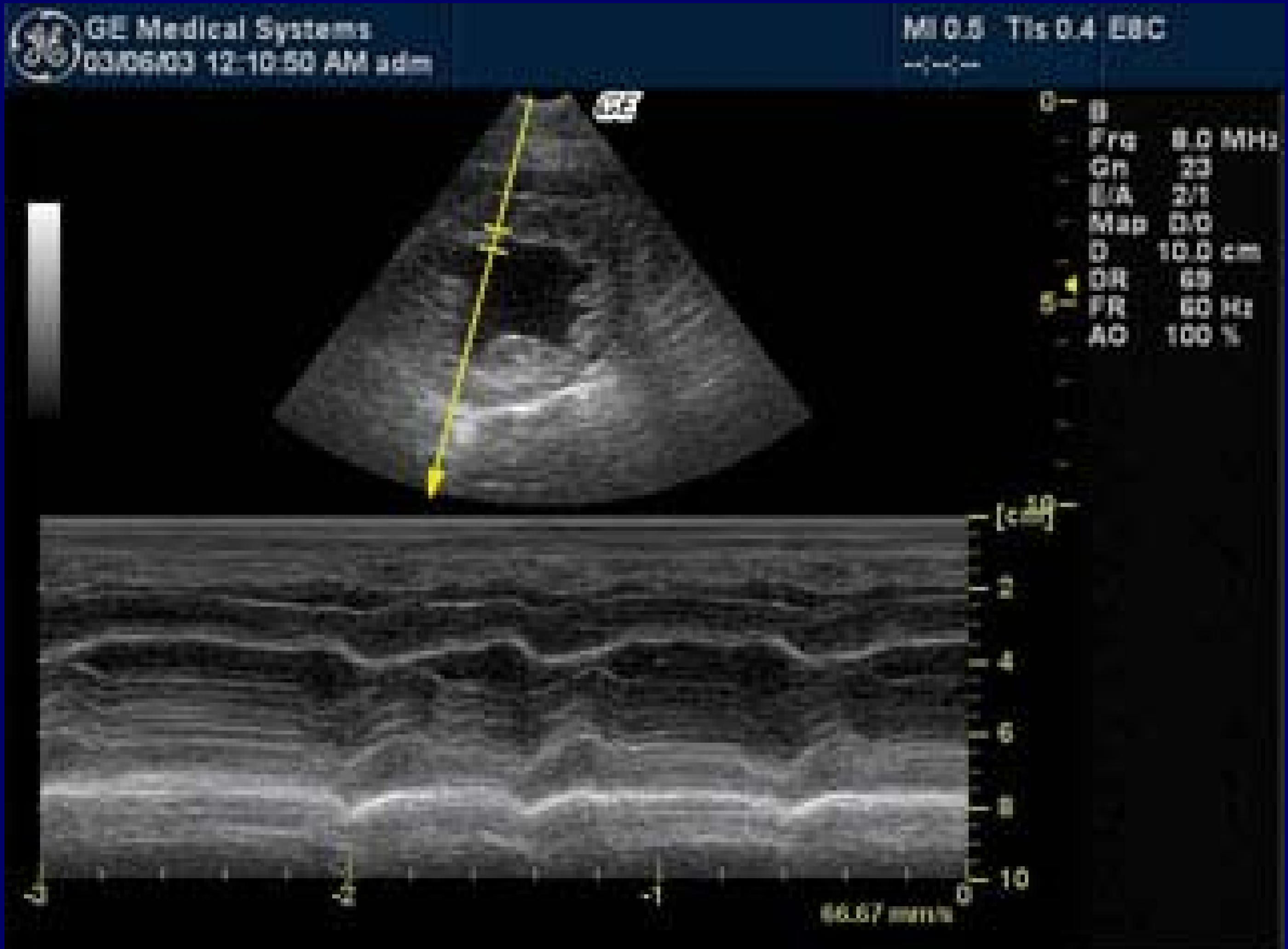
curved linear



easy access
wide view

3D Ultrasound

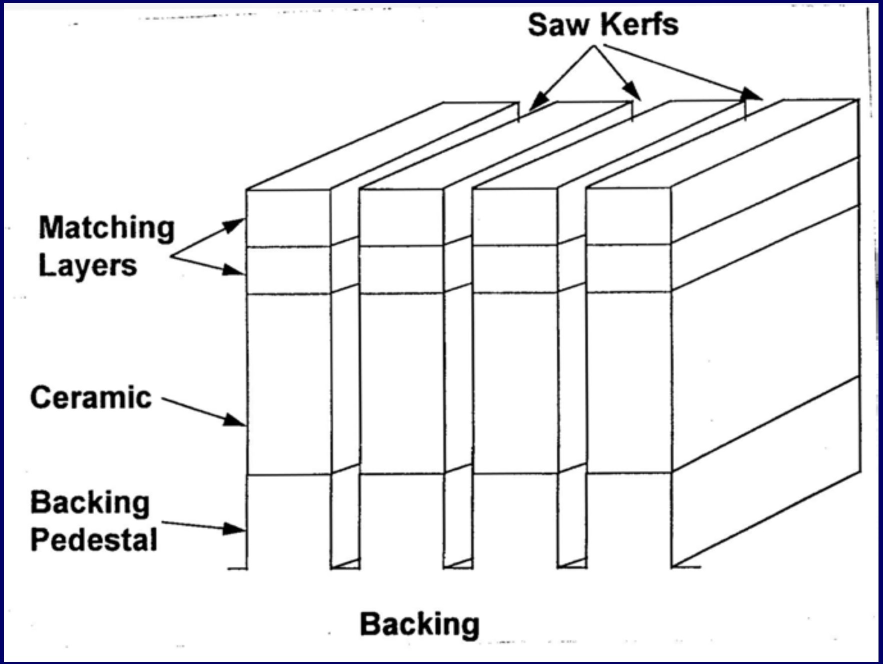
M-Mode (Motion)



Transducers: Generation and Detection of Sound Waves

Ultrasonic Array Transducers

(From www.acuson.com)

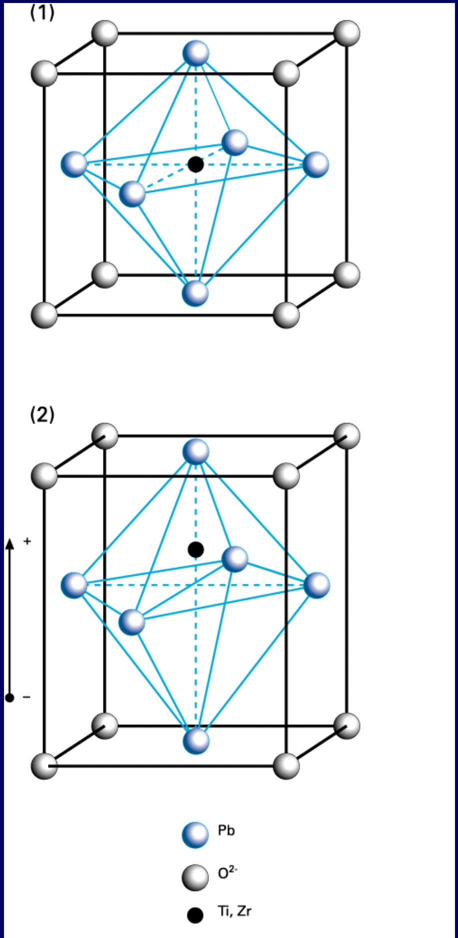


Transducer

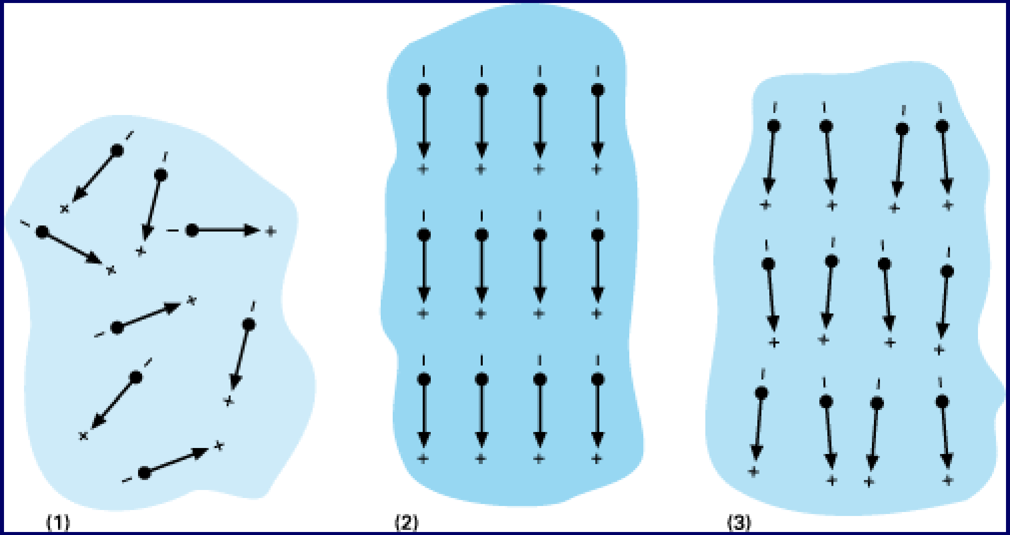
- Energy conversion: electrical ↔ mechanical.
- Generation and detection (speaker and microphone).
- Medical ultrasound: same device in MHz range.
- Piezoelectricity: electrical polarization ↔ mechanical strain.
- PZT, PVDF and composite materials are commonly used.

Piezoelectricity

Anisotropy

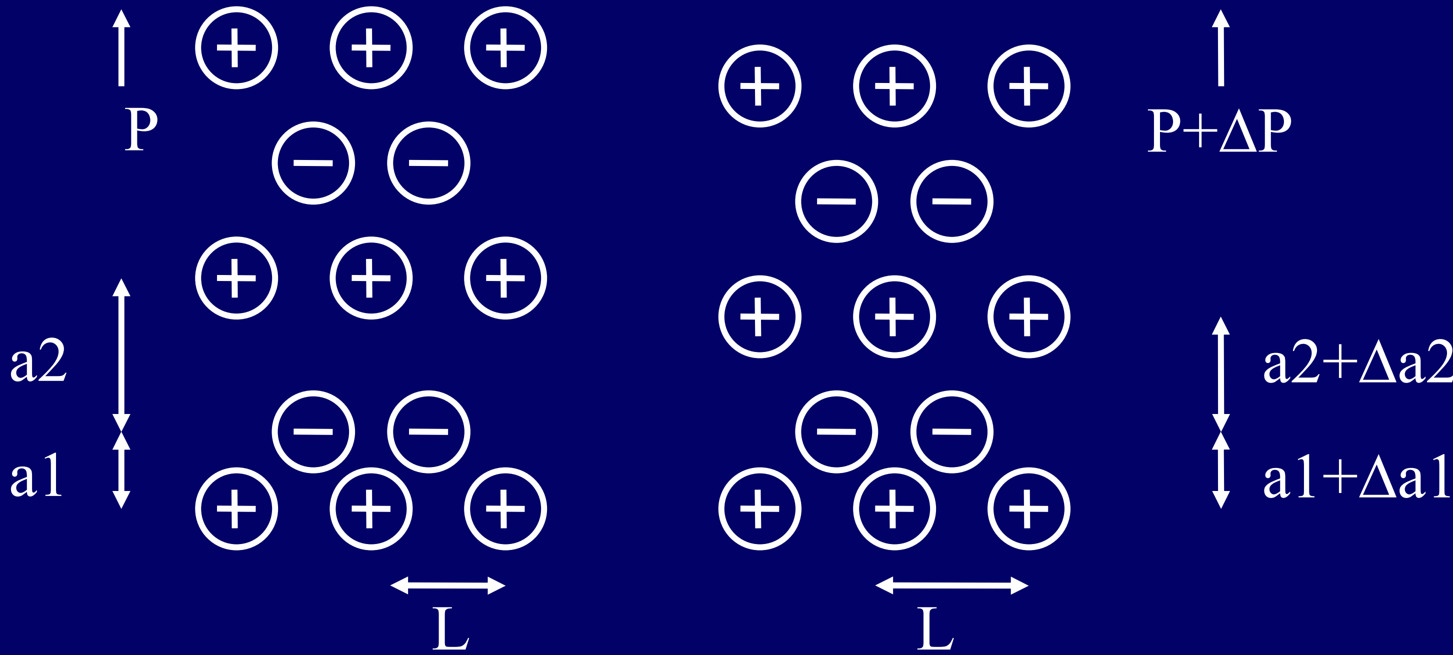


Poling



Curie temperature: 320^0 – 370^0C.

Piezoelectricity



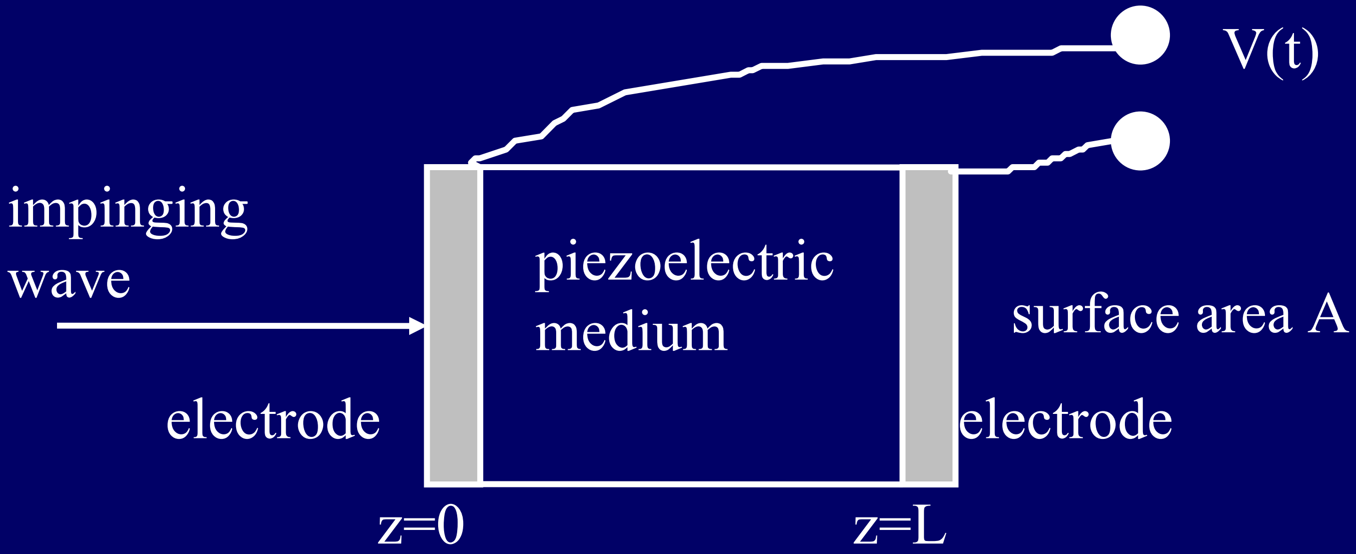
$$P \equiv \frac{\text{dipole strength of unit cell}}{\text{volume of unit cell}} = \frac{q\,(a2 - a1)}{L^2\,(a2 + a1)}$$

$$\Delta P \approx PS \equiv eS$$

e: Piezoelectric stress constant

Detection of Ultrasound

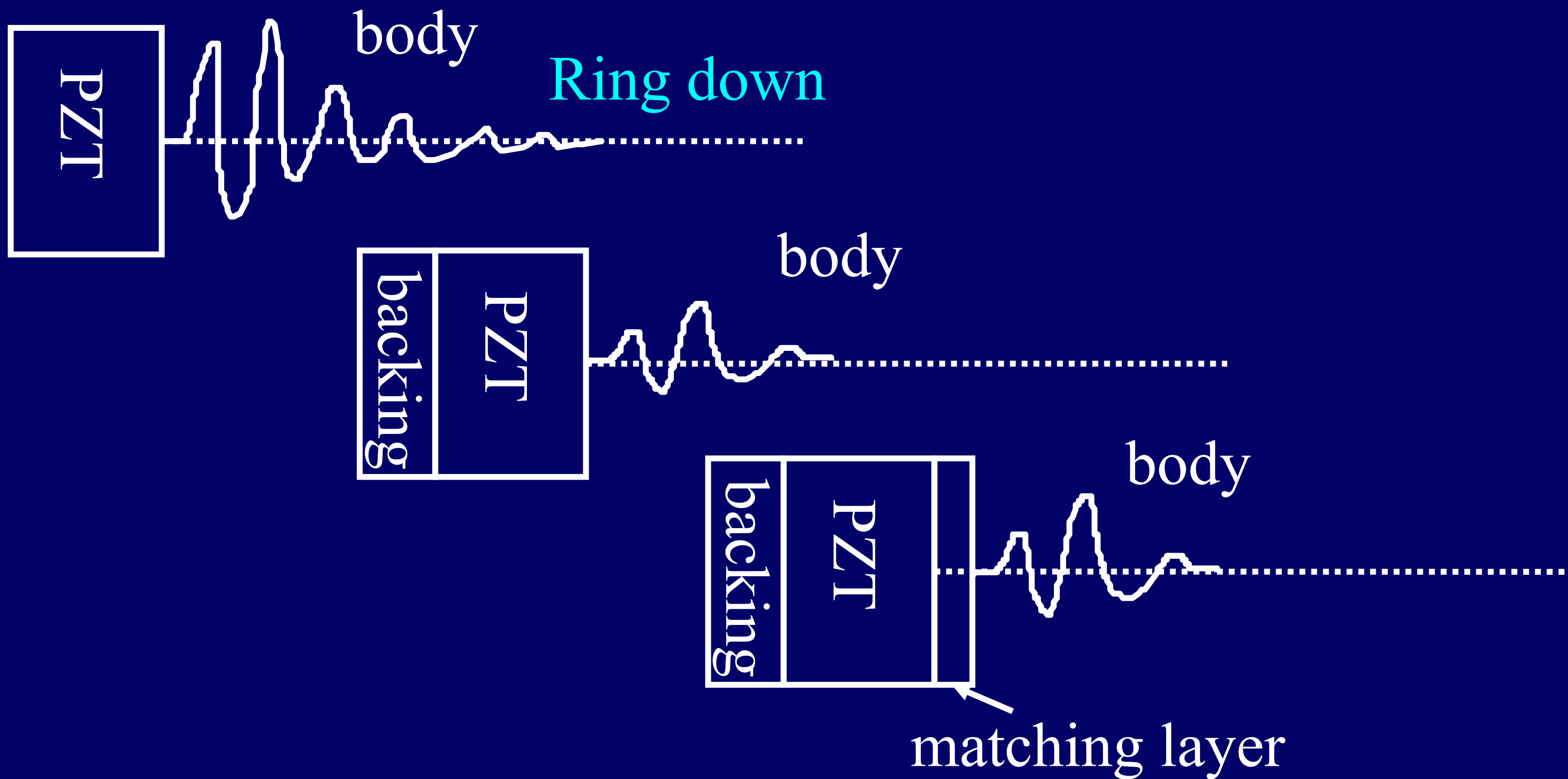
- Reciprocal to generation.



$$V(t) = \int_0^L E(z,t)\,dz$$

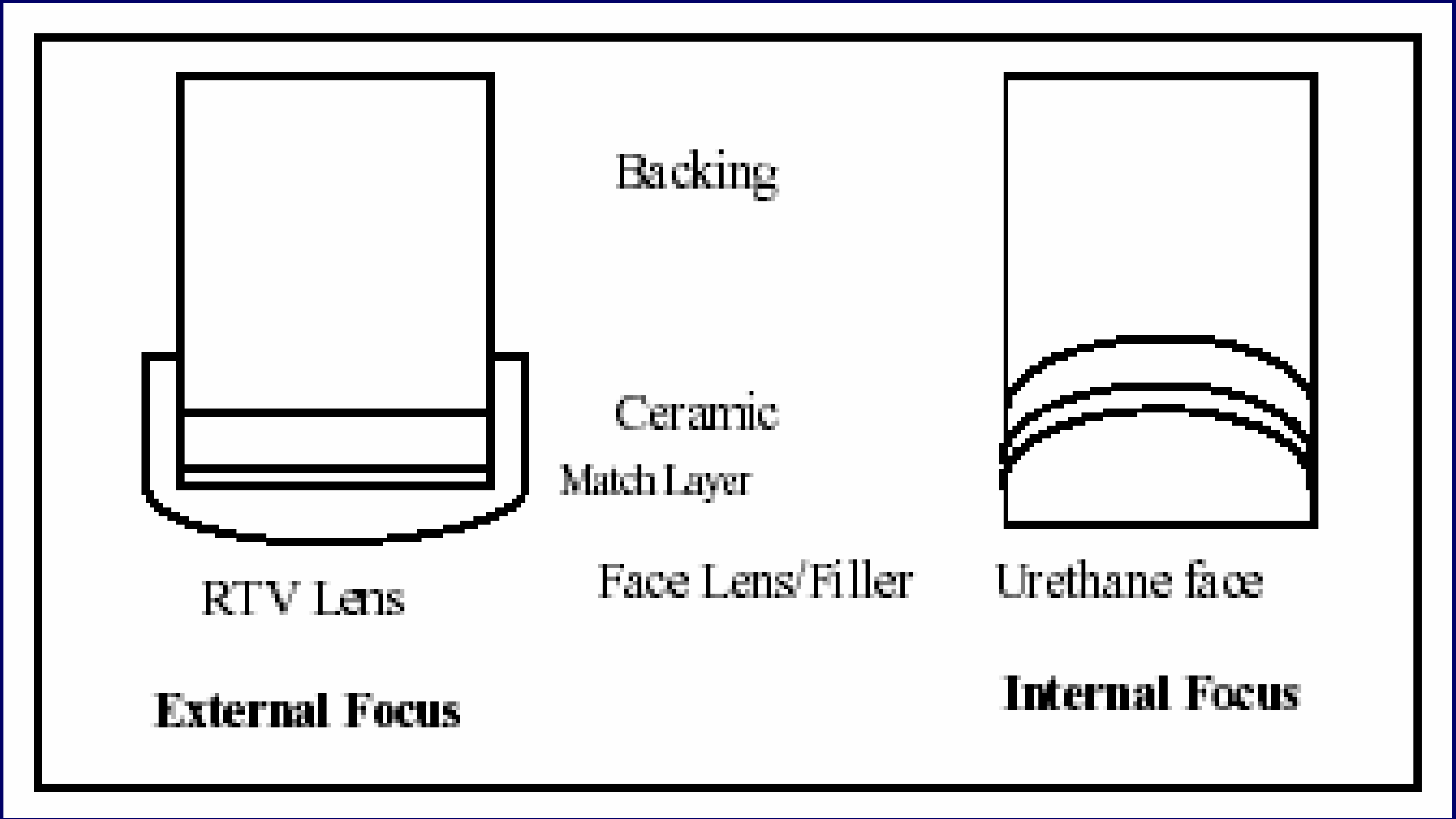
Design Considerations

- Bandwidth and sensitivity.

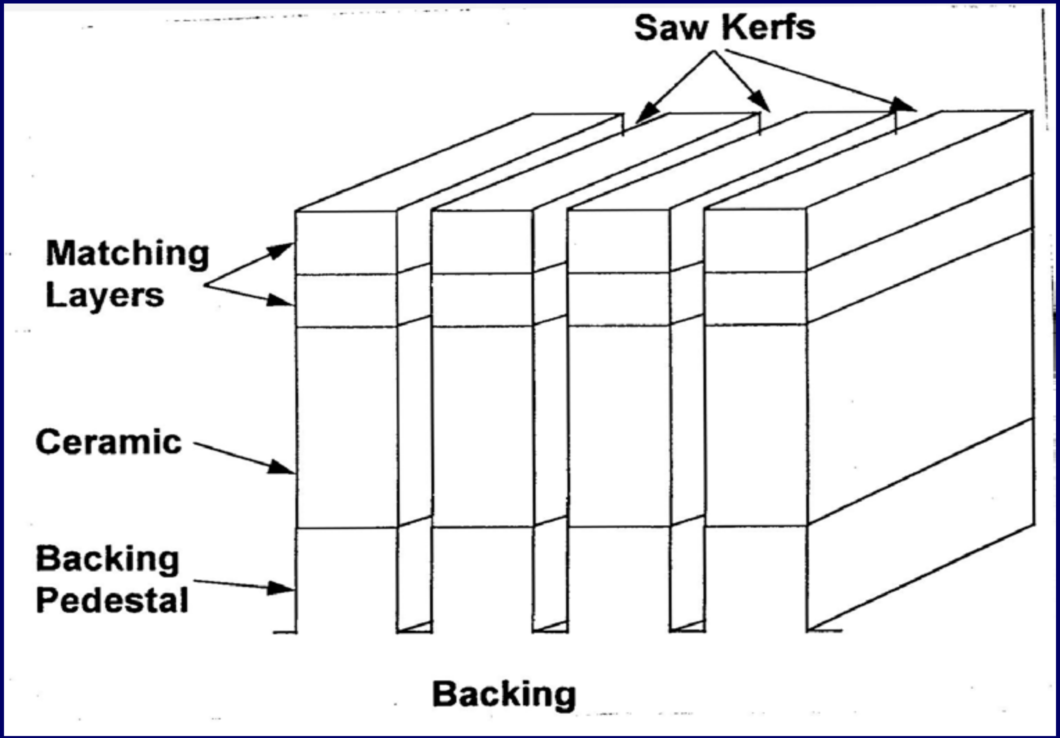


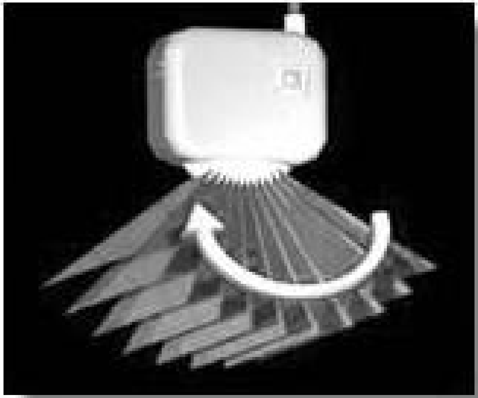
Acoustic Lens

- Fixed geometric elevational focusing.

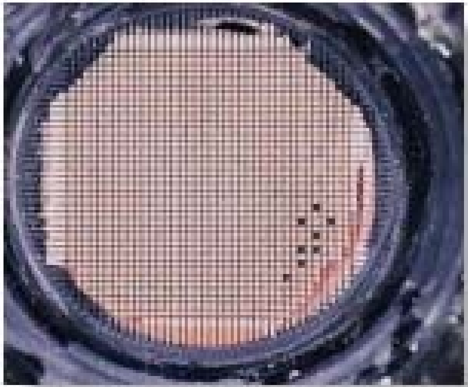


1-D and 2-D Arrays





Hand-held 3-D probe from Kretztechnik

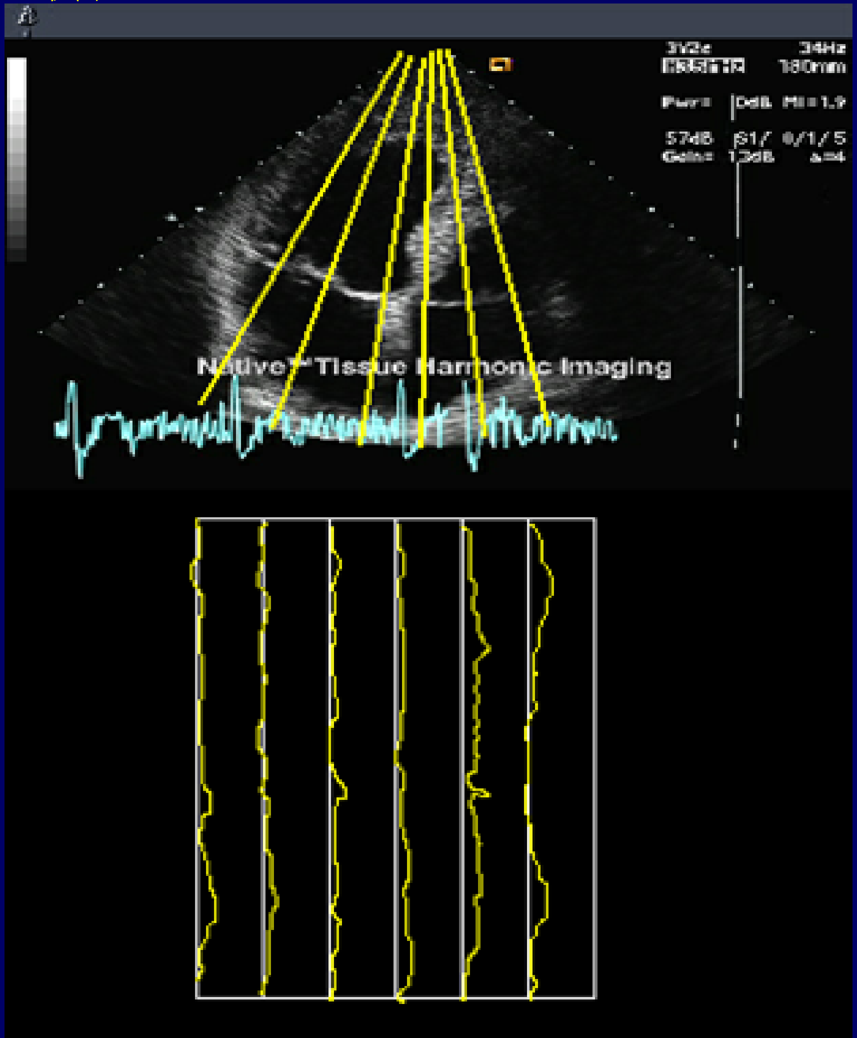


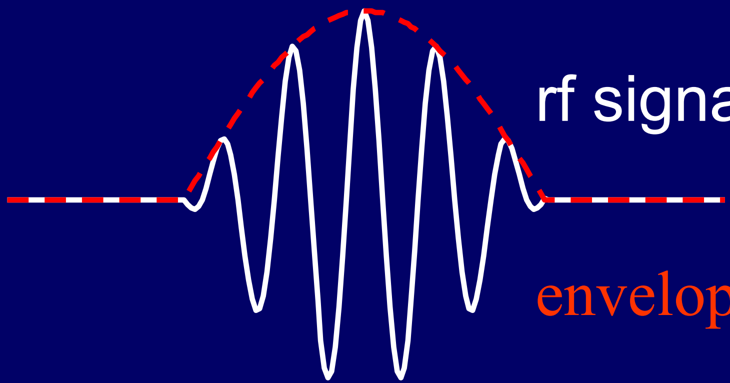
2-D matrix-array at Duke

Focusing and Diffraction

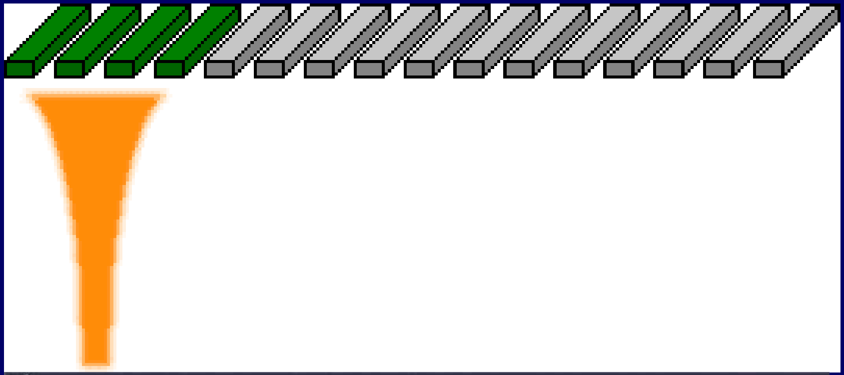
B-mode Imaging

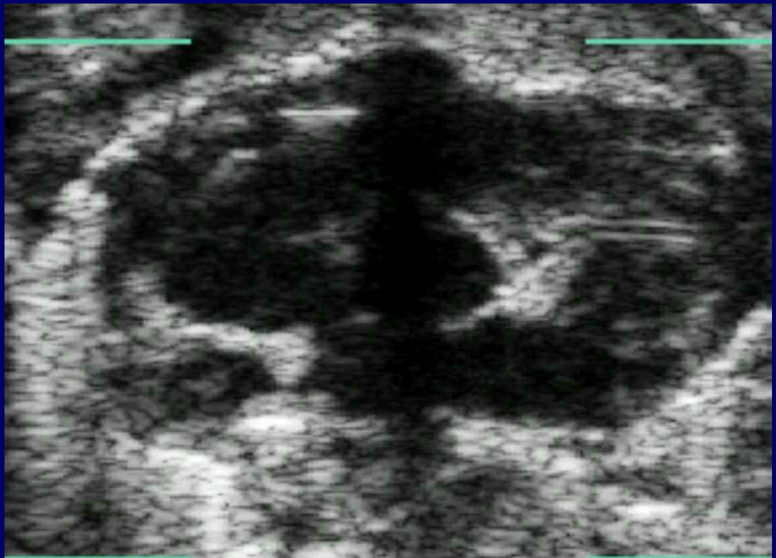
取自www.acuson.com

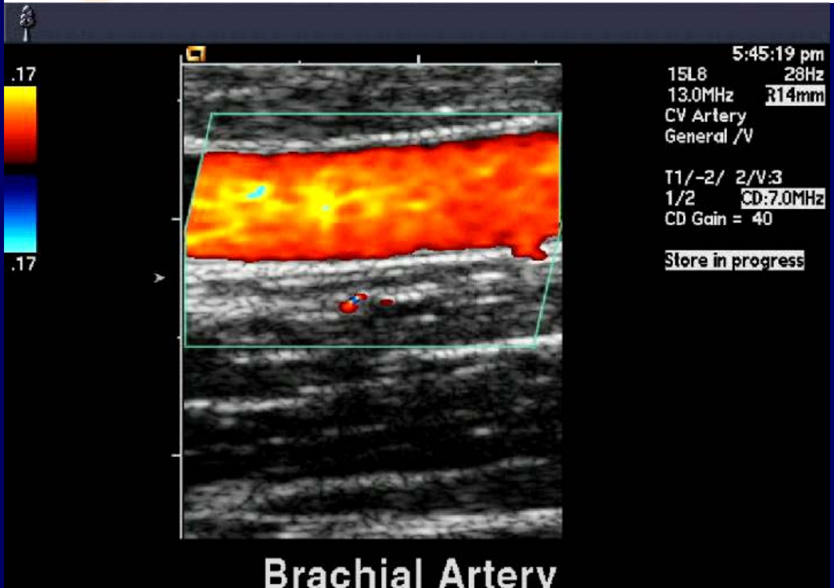




Linear Scanning

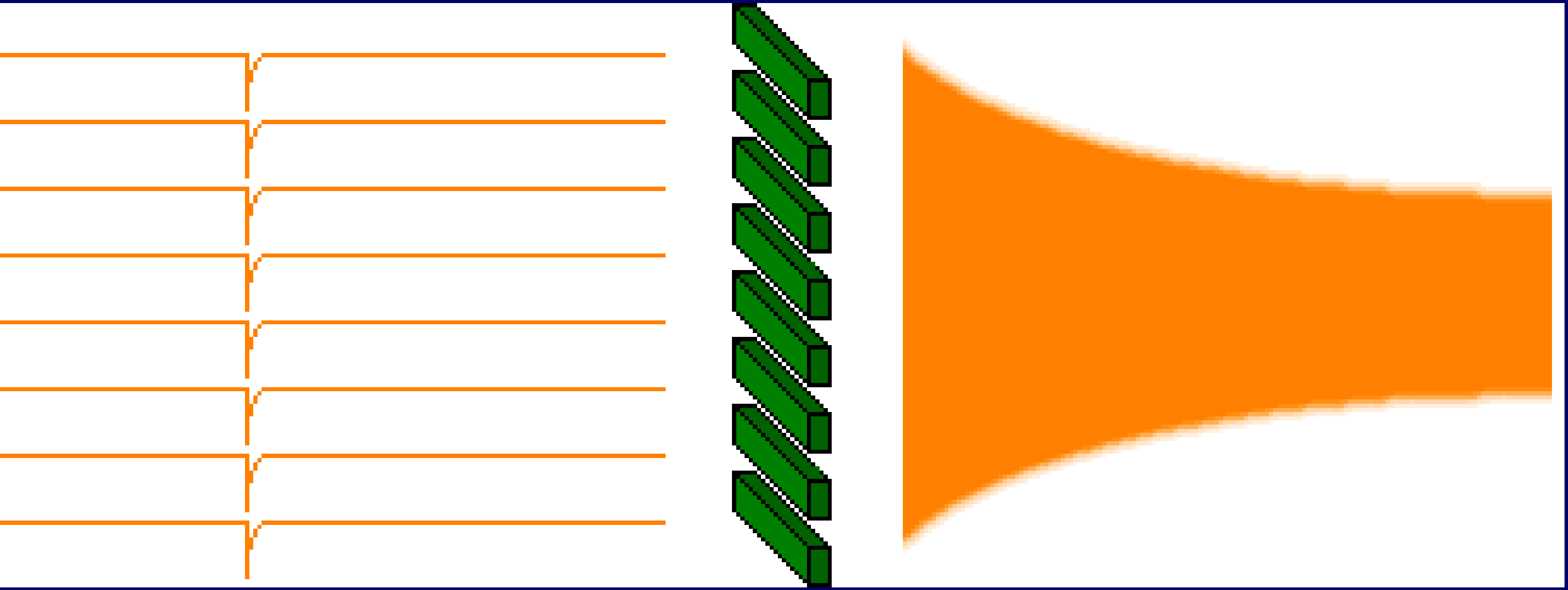




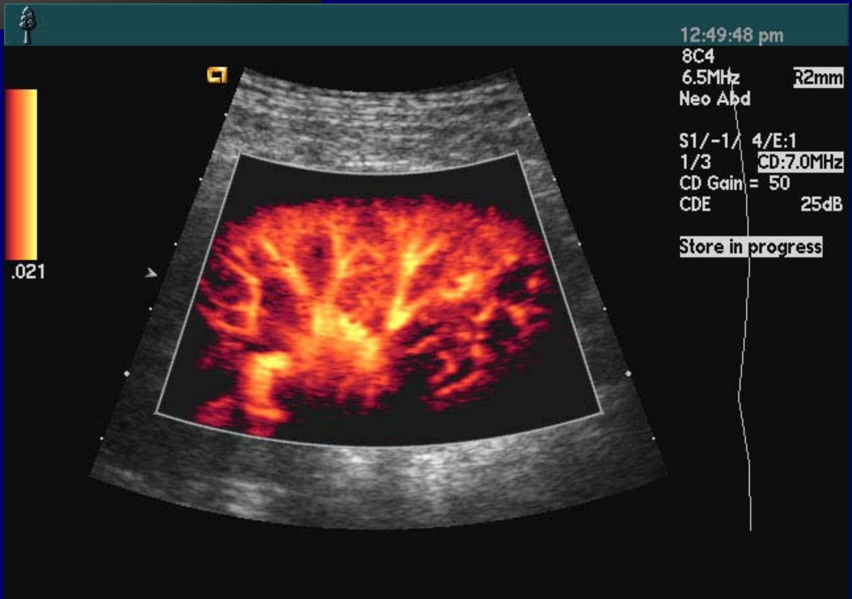


Beam Formation Using Arrays

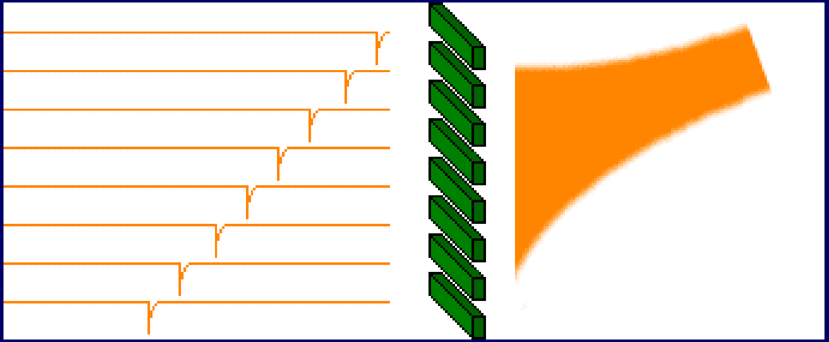
Focusing:

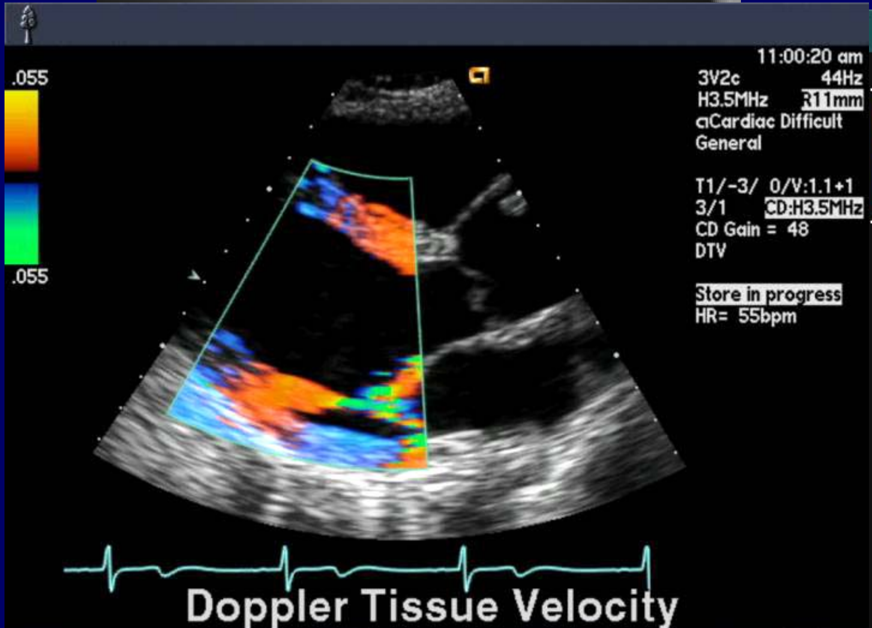


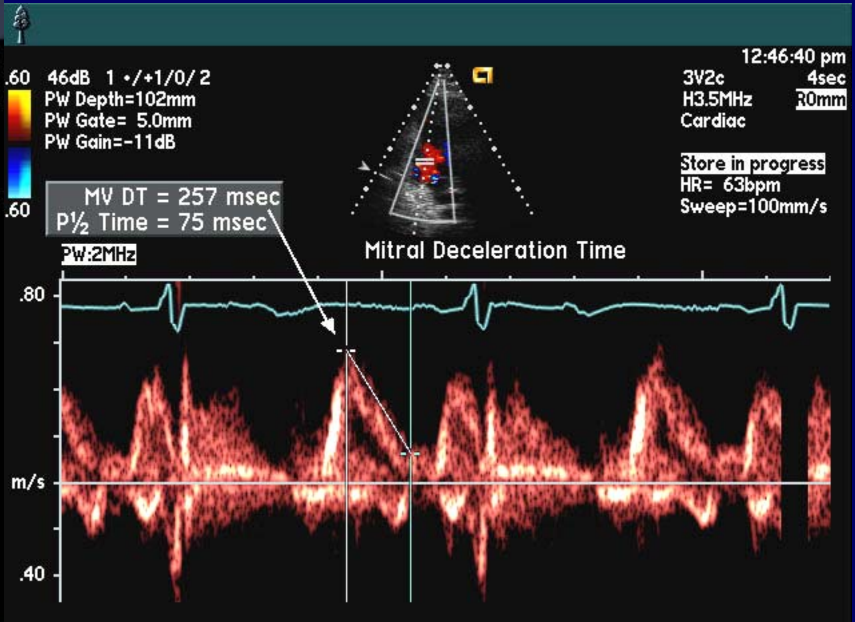
Curved Linear Scanning



Sector Steering

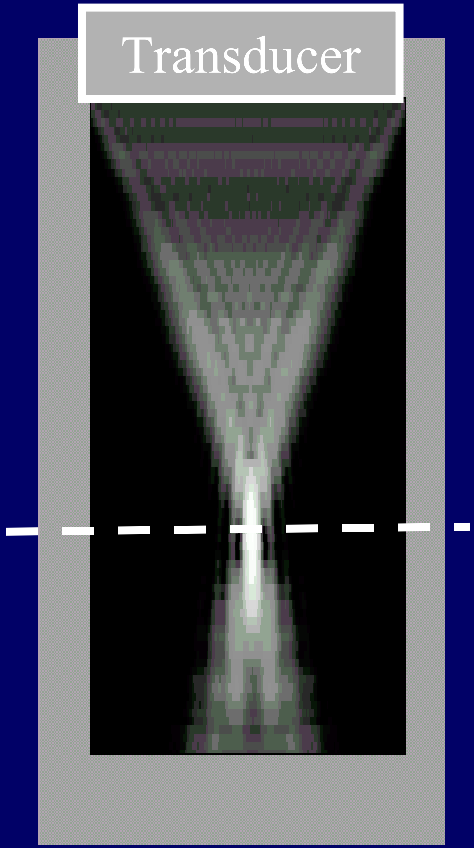




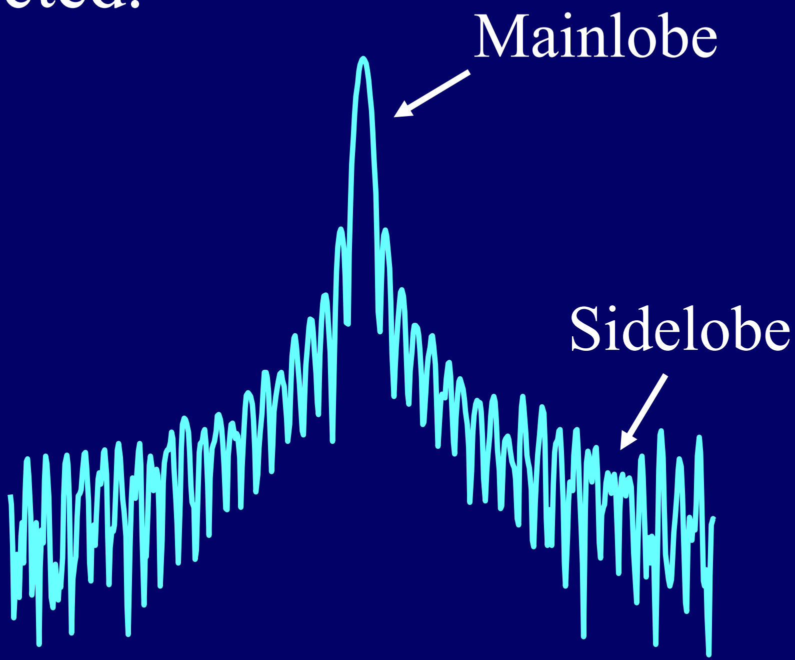


How is the resolution determined?

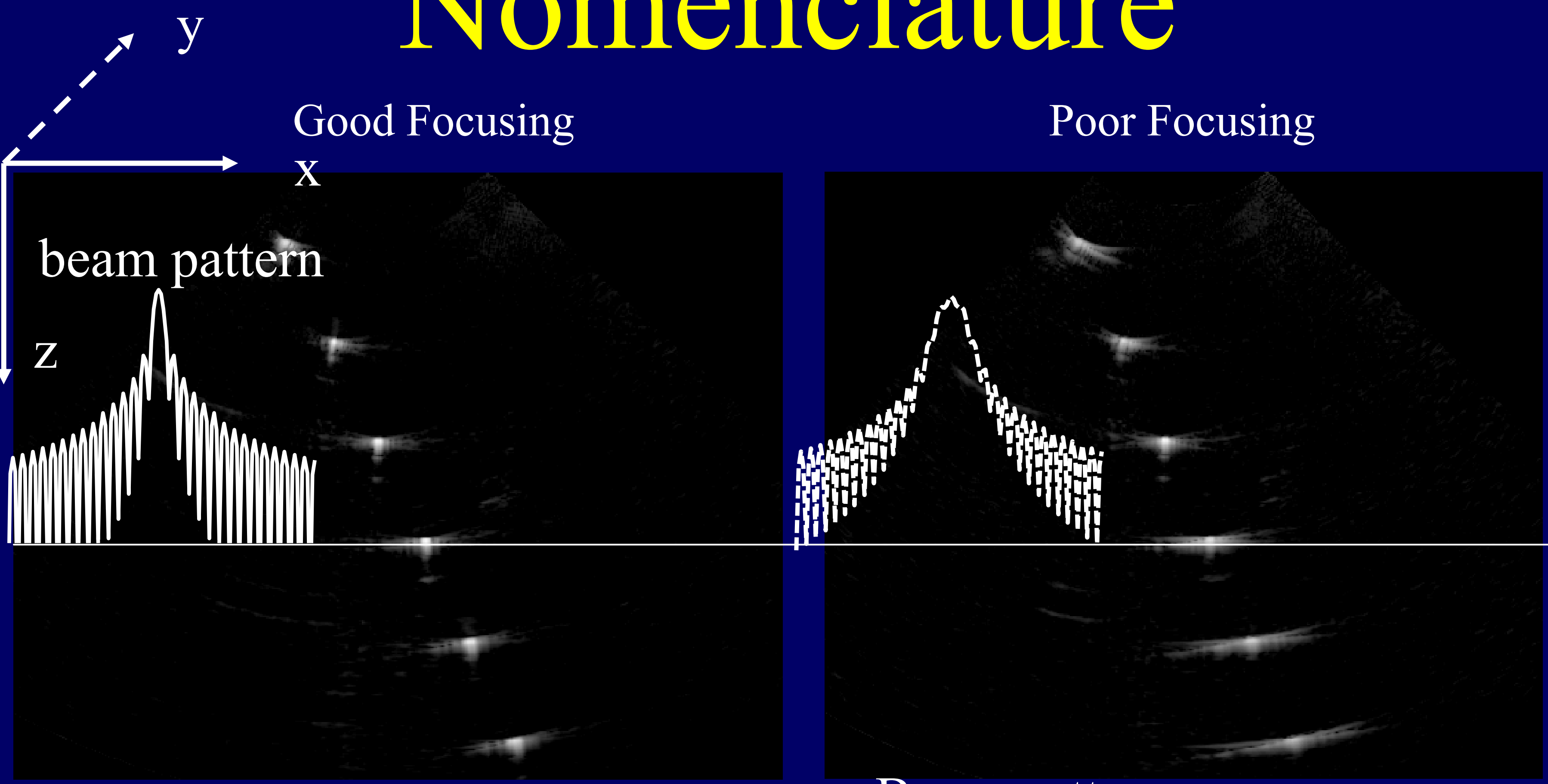
Focusing ←→ Beam Formation



- To form a beam of sound wave such that only the objects along the beam direction are illuminated and possibly detected.



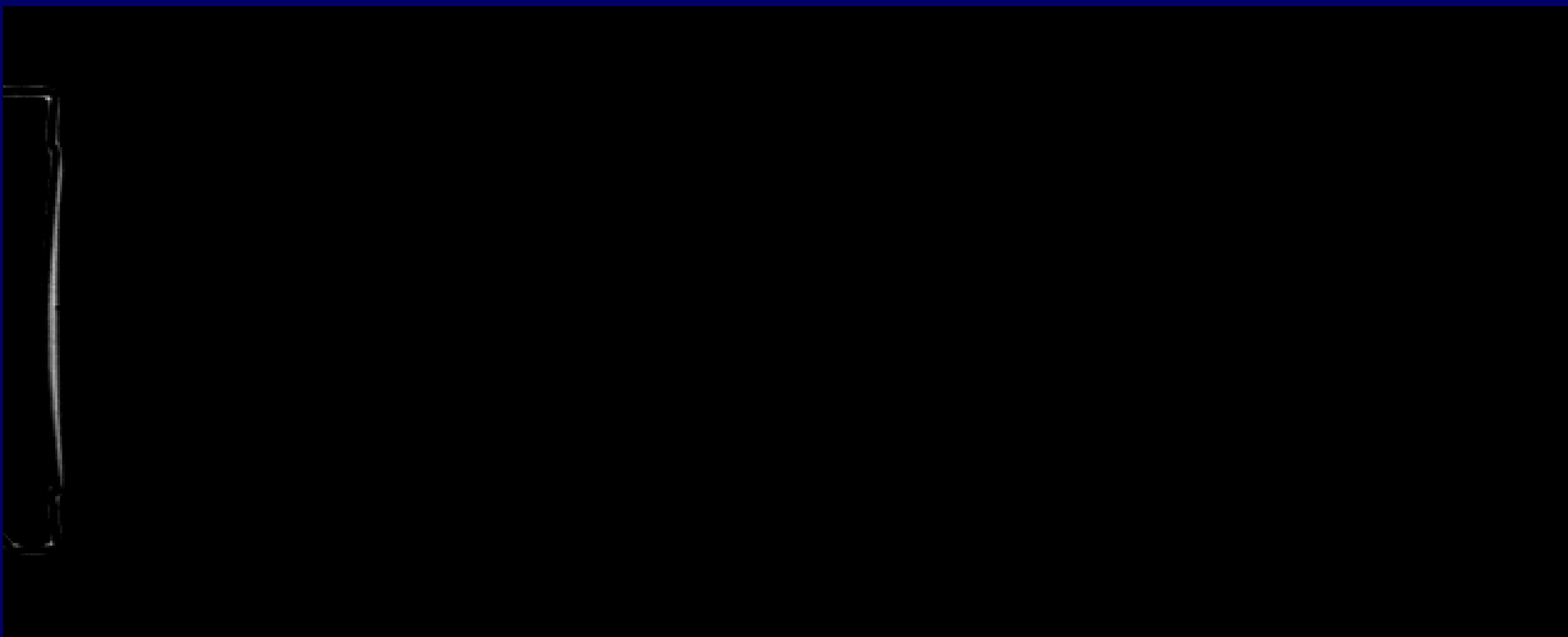
Nomenclature



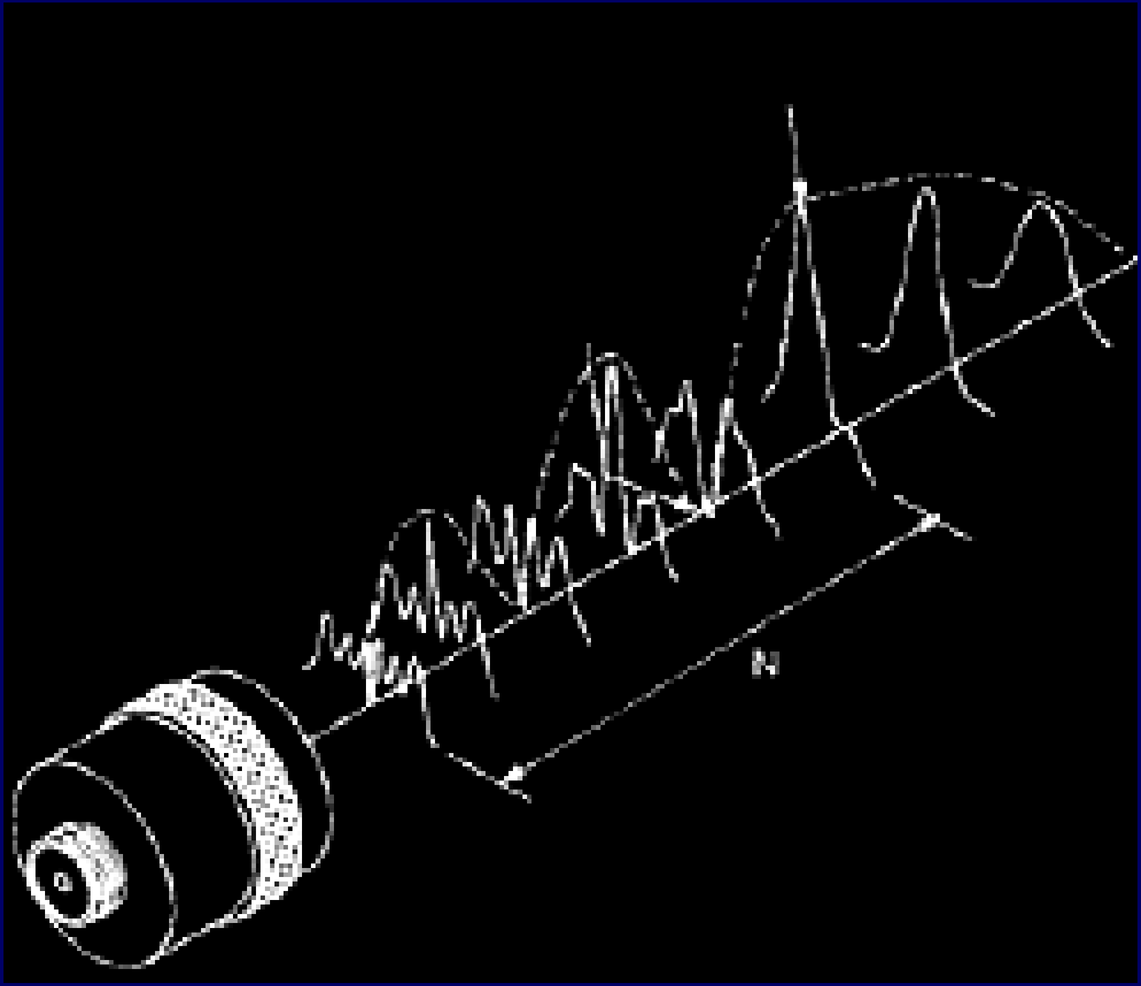
x: Lateral, azimuthal, scan
y: Elevational, non-scan
z: Axial, range, depth

Beam pattern
Radiation pattern
Diffraction pattern
Focusing pattern

Pulsed Wave (PW) vs. Continuous Wave (CW)



Radiation Pattern

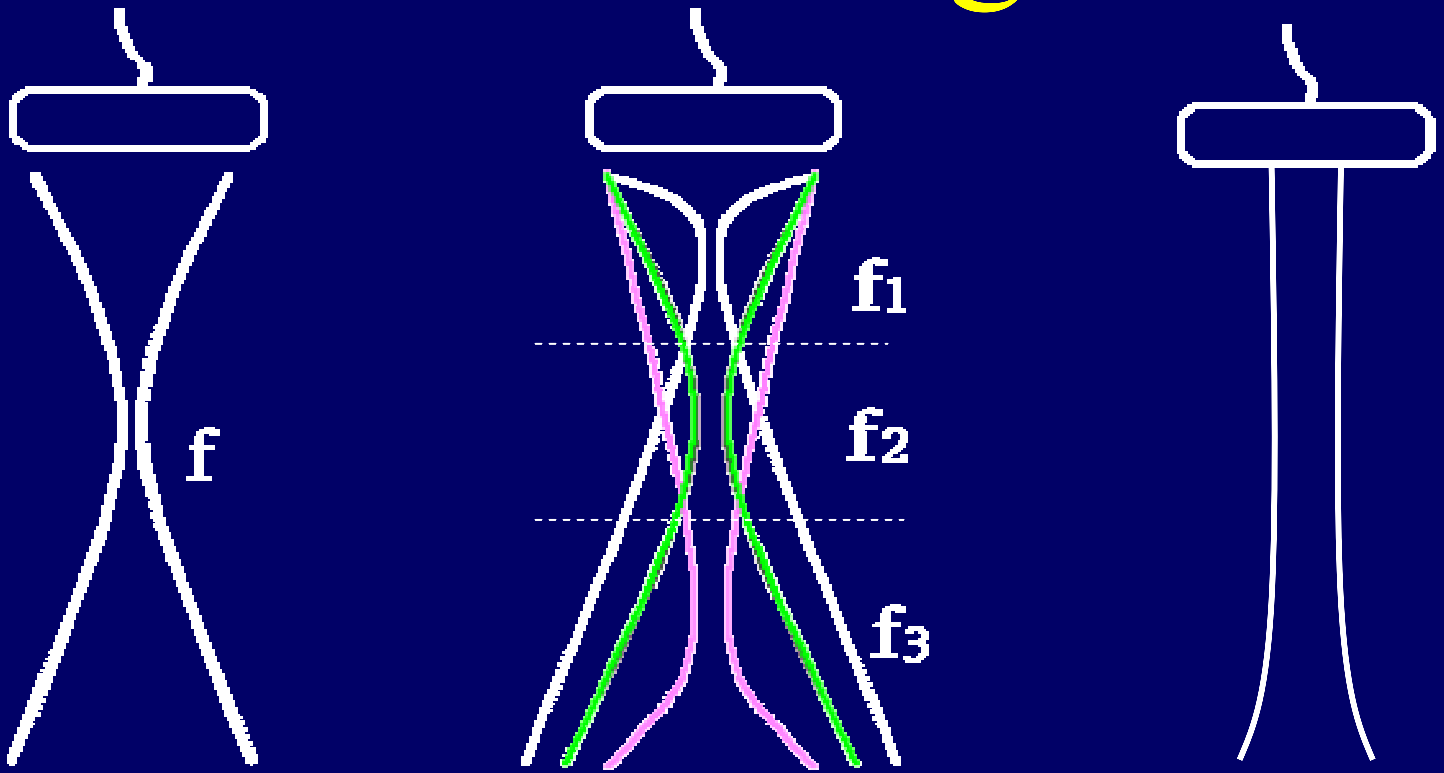


How to focus?

Beamforming

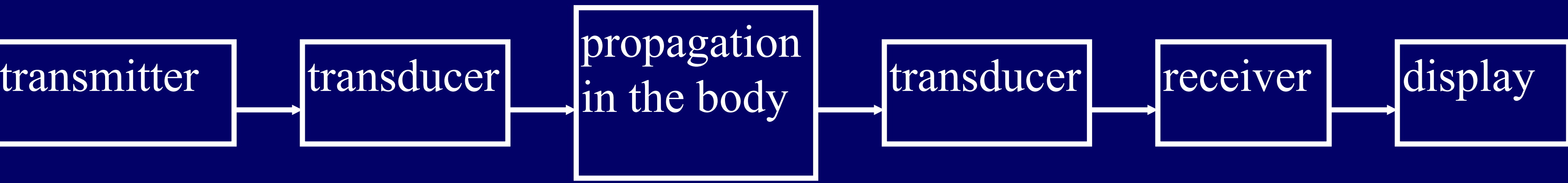
- Manipulation of transmit and receive apertures.
- Trade-off between performance/cost to achieve:
  - Steer and focus the transmit beam.
  - Dynamically steer and focus the receive beam.
  - Provide accurate delay and apodization.
  - Provide dynamic receive control.

Focusing



Single Zone Focusing   Multi-Zone Focusing   Dynamic Focusing

Imaging Model



A-scan:

$$V(t) = k\iiint \frac{R(x',y',z')e^{-2\beta z'}}{z'} B(x',y',z')\, p(t-\frac{2z'}{c})\, dx'dy'dz'$$

B-scan:

$$S(x,t) = k\iiint R(x',y',z')B(x'-x,y',z')\, p(t-\frac{2z'}{c})\, dx'dy'dz'$$

Scanning → Convolution

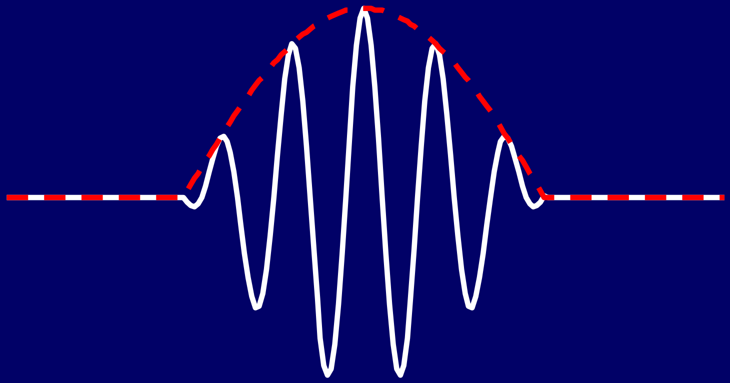
(Correlation vs. Convolution)

Imaging Model

$$p(t-\frac{2z'}{c}) = A(t-\frac{2z'}{c})\cos(2\pi f_0(t-\frac{2z'}{c}))$$

Ideally,

$$S(x,t) = R(x, y_0, ct/2)$$

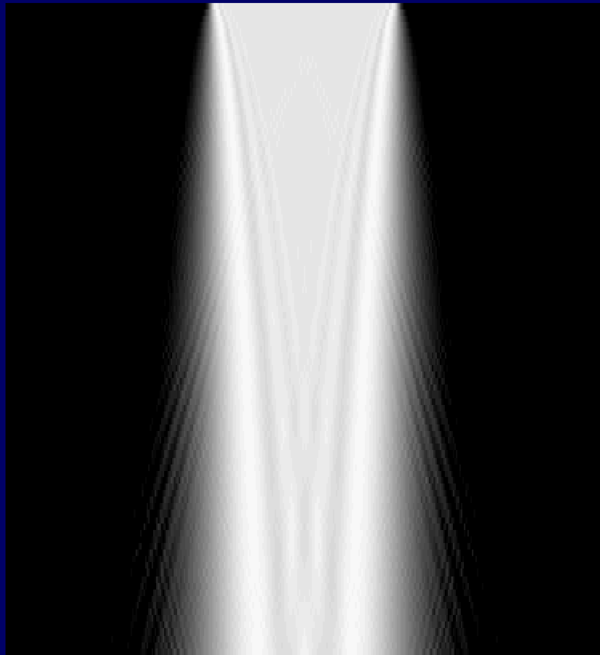


In practice,

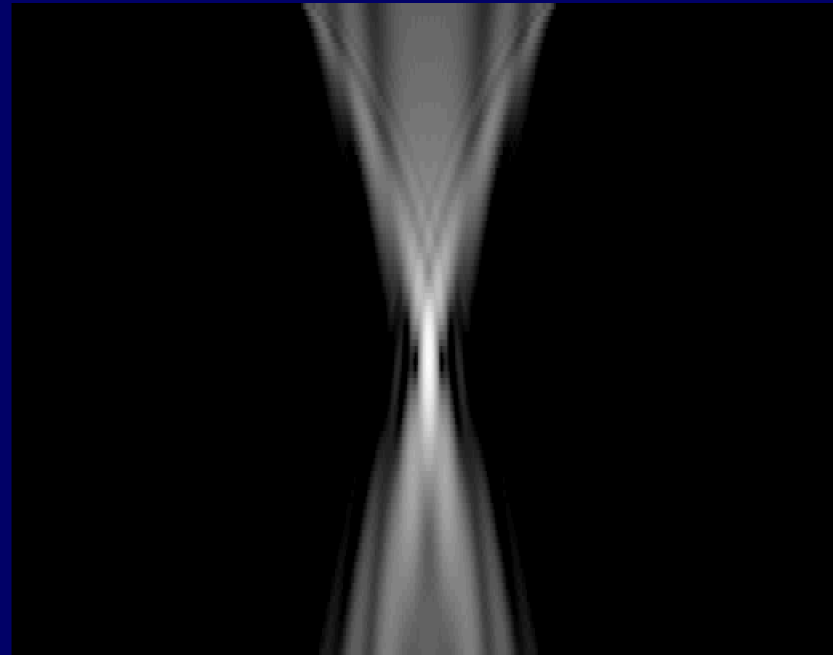
$B(\cdot)$: determined by diffraction

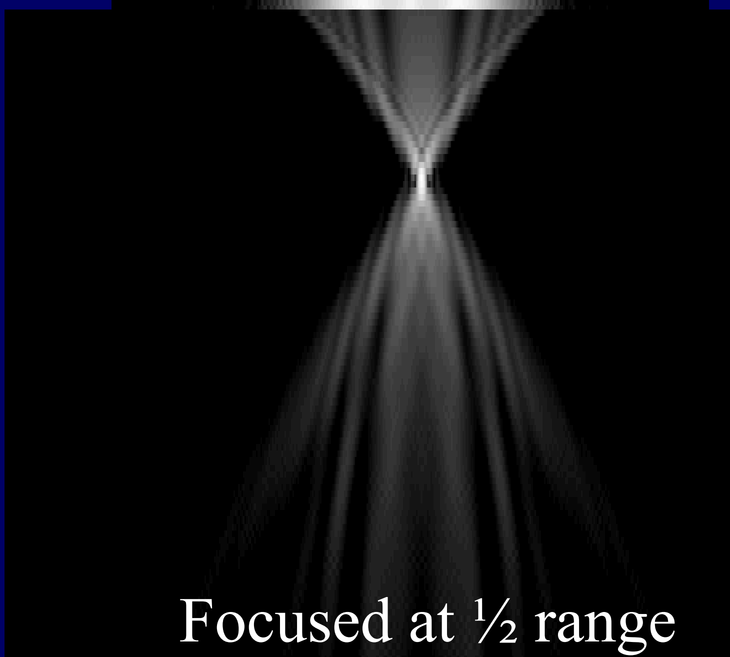
$A(\cdot)$: determined by transducer bandwidth

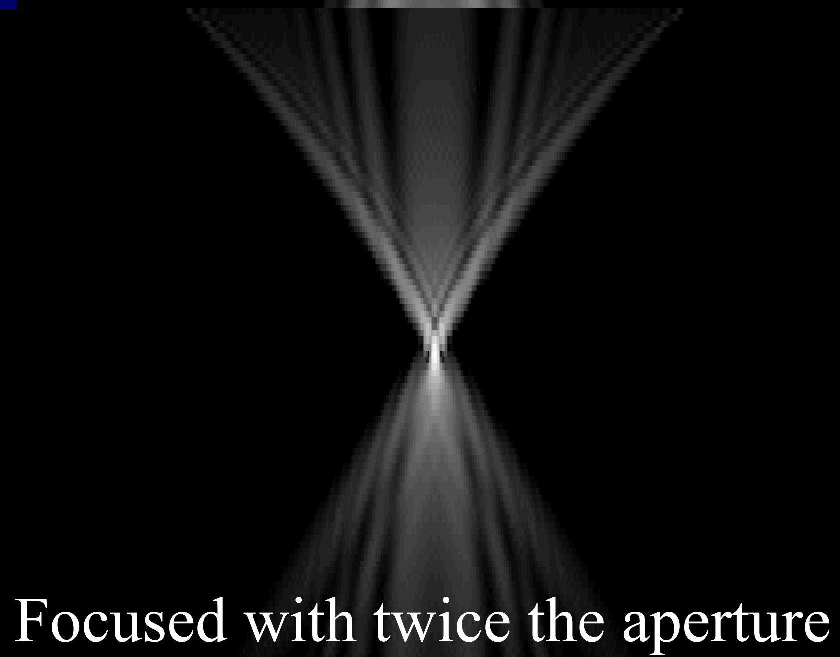
Unfocused



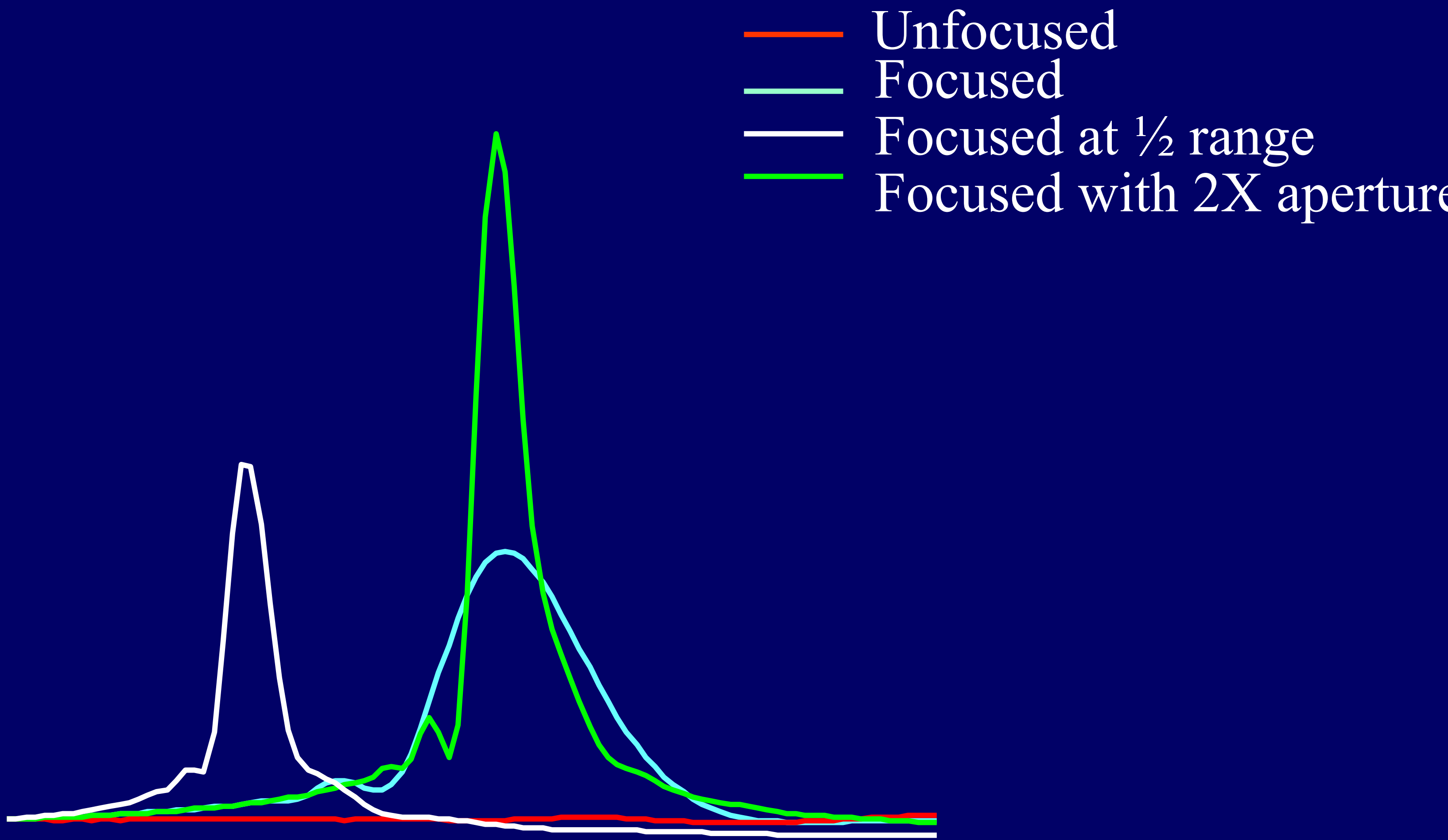
Focused





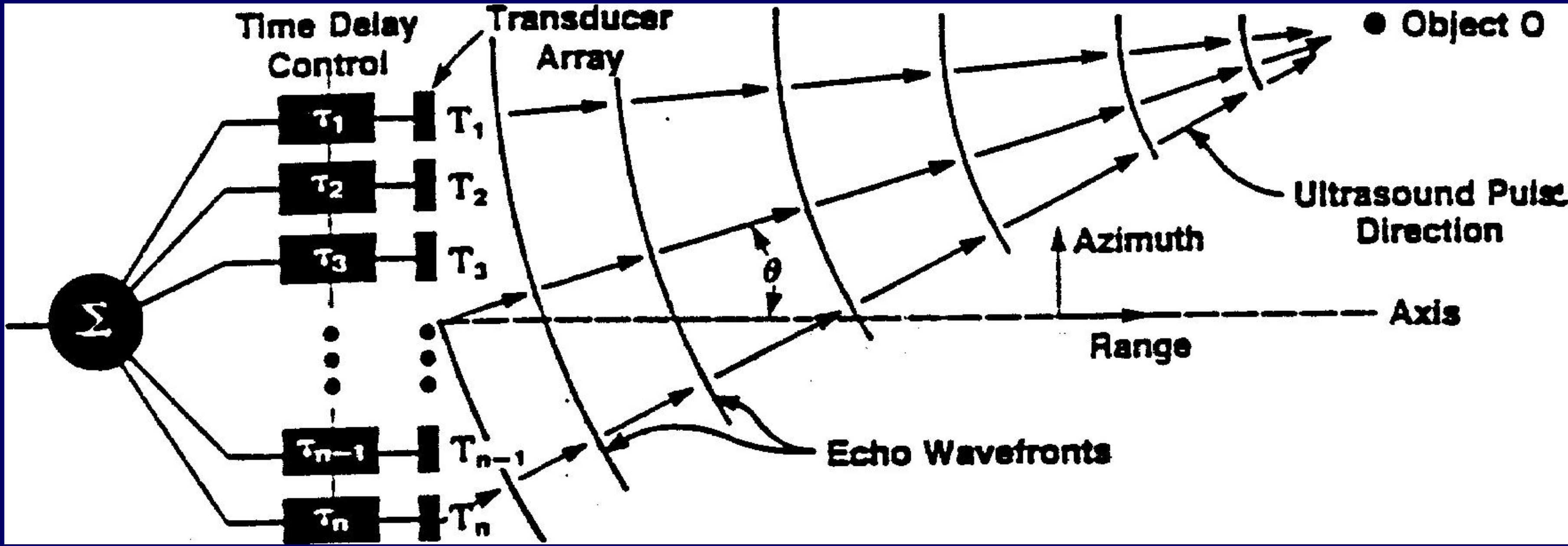


Axial Intensity



Implementation of Focusing Using Arrays

Beam Formation Using Arrays



$$O(t) = \sum_{i=1}^{N} S_i(t - \tau(x_i, R, \theta))$$ ← Delay and Sum

Propagating Delays

$$\tau(x_i, R, \theta) = \frac{\left(\left(x_i - R\sin\theta\right)^2 + R^2\cos^2\theta\right)^{1/2}}{c} = \frac{R}{c}\left(1 + \frac{x_i^2}{R^2} - \frac{2x_i}{R}\sin\theta\right)^{1/2}$$

In Fresnel region

$$\tau(x_i, R, \theta) \approx \frac{R}{c}\left(1 + \frac{x_i^2}{2R^2} - \frac{x_i}{R}\sin\theta - \frac{x_i^2}{2R^2}\sin^2\theta\right)$$

$$= \frac{R}{c}\left(1 - \frac{x_i}{R}\sin\theta + \frac{x_i^2}{2R^2}\cos^2\theta\right) = \frac{R}{c} - \frac{x_i\sin\theta}{c} + \frac{x_i^2\cos^2\theta}{2Rc}$$

Effective aperture size: $2a \to 2a\cos\theta$

Propagating Delays

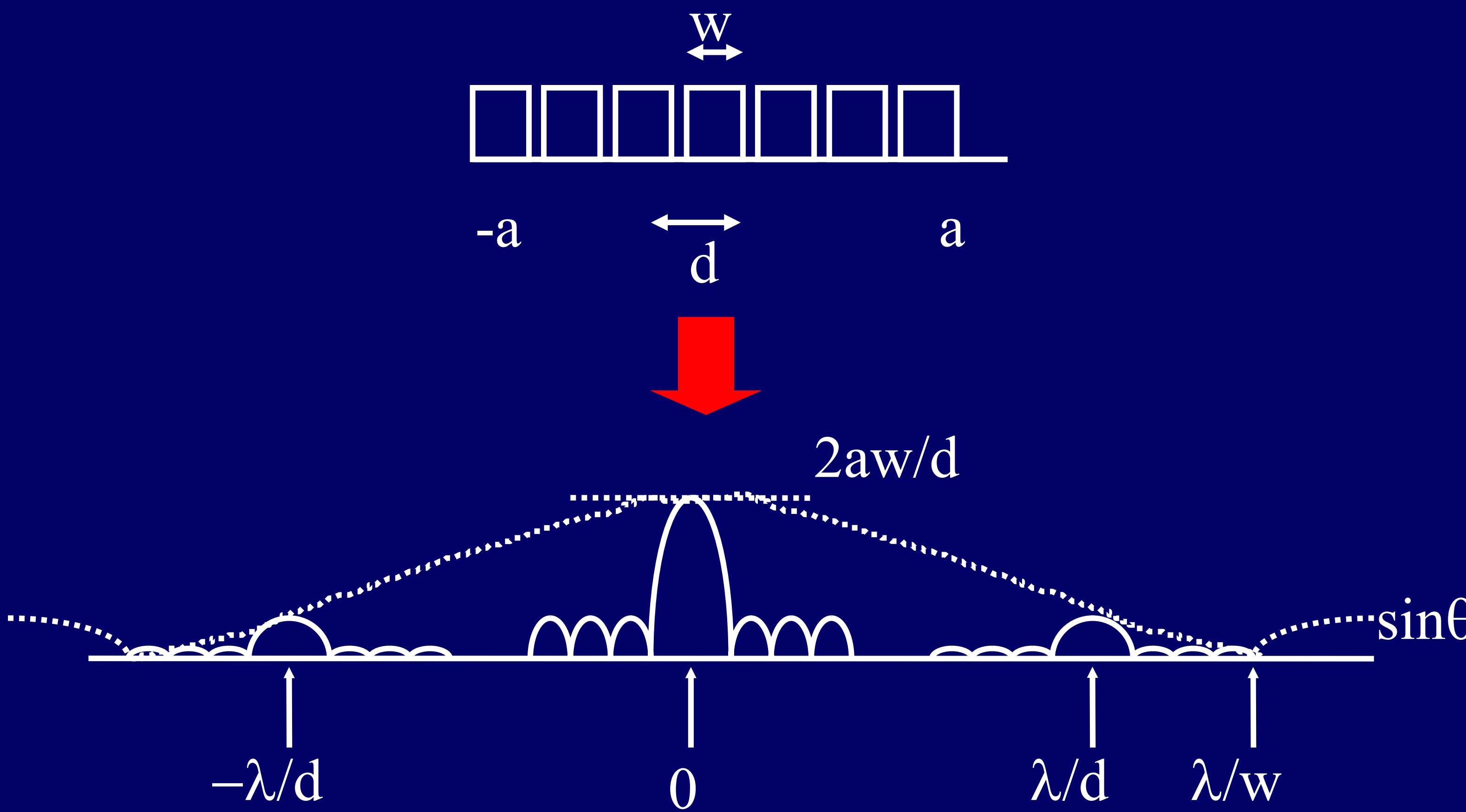
Transmit:

$$\tau^{T}(x_i, R, \theta) = -\frac{x_i \sin\theta}{c} + \frac{x_i^2 \cos^2\theta}{2Rc}$$

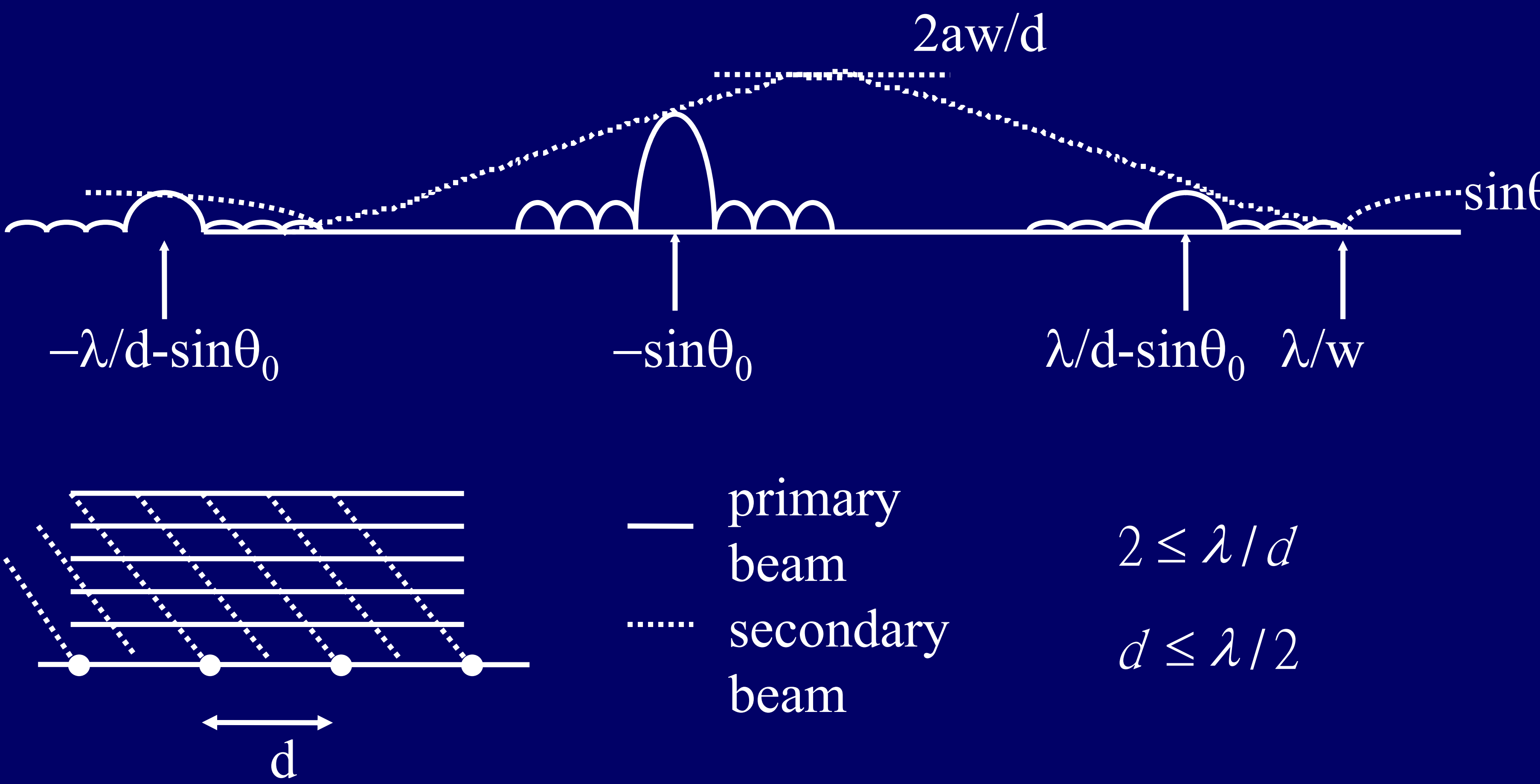
Receive:

$$\tau^{R}(x_i, R, \theta) = \frac{2R}{c} - \frac{x_i \sin\theta}{c} + \frac{x_i^2 \cos^2\theta}{2Rc}$$

Array → Sampled Aperture



Array Steering and Grating Lobes



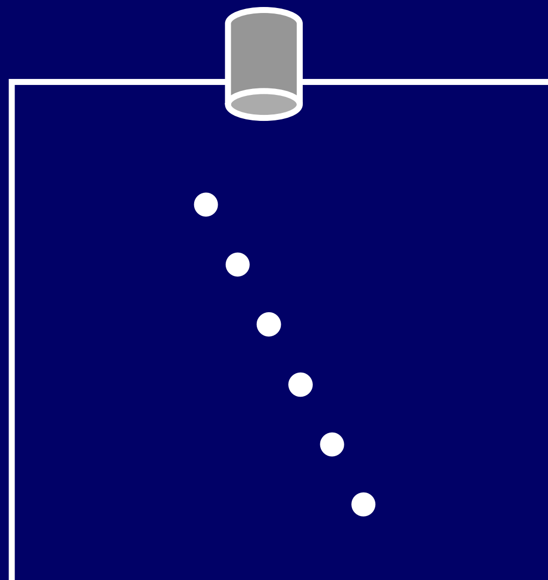
$$2 \le \lambda / d$$

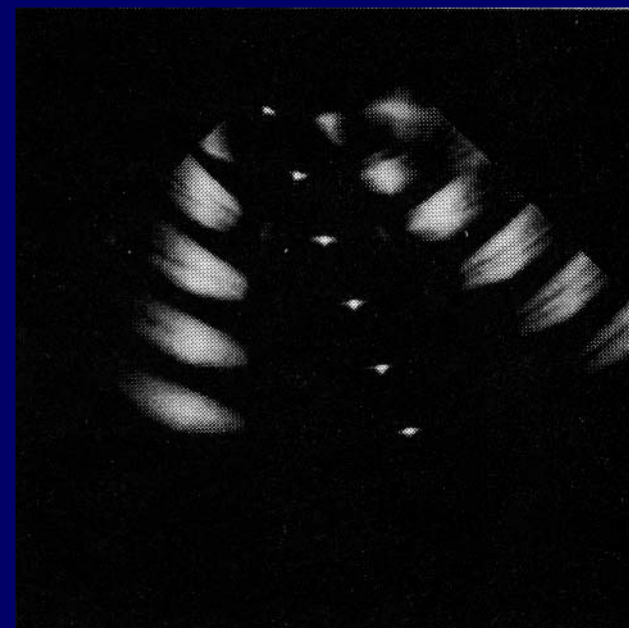
$$d \le \lambda / 2$$

Grating Lobes

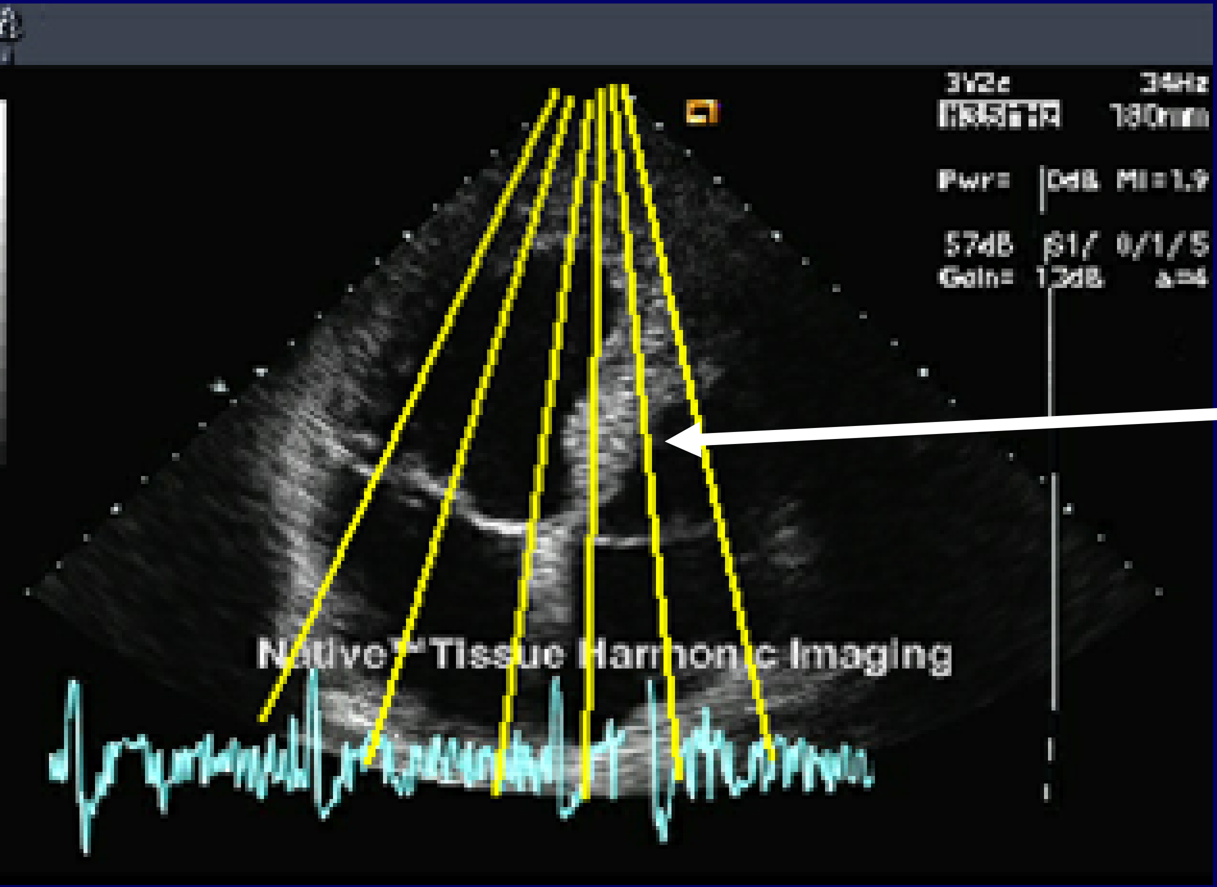
No Grating Lobes

With Grating Lobes





Beam Sampling

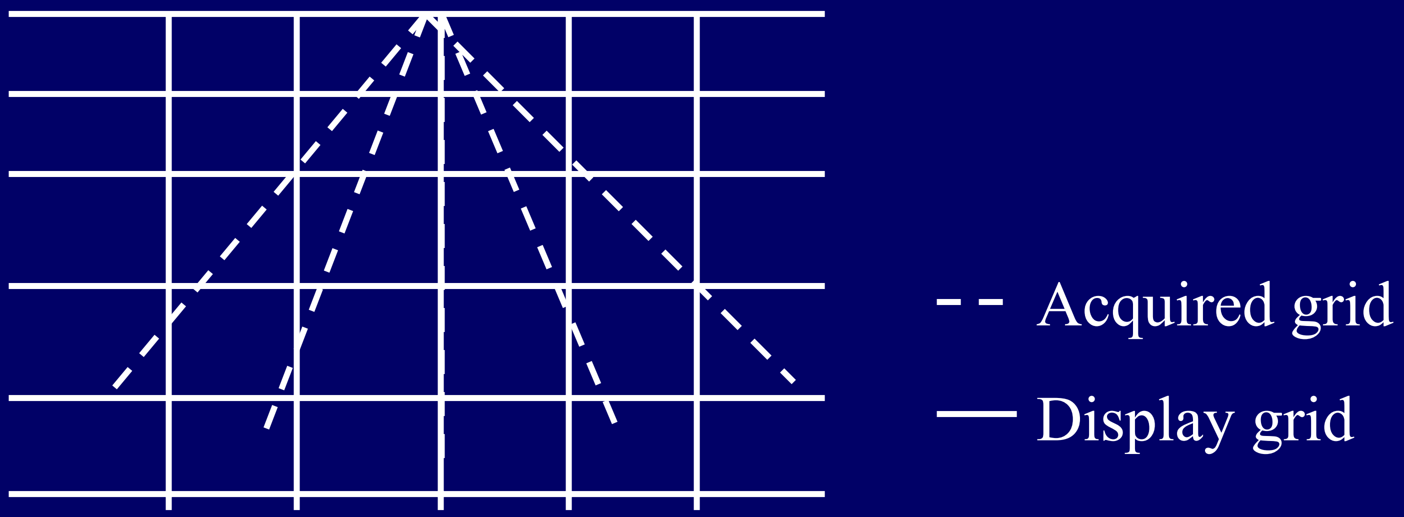


$$\Delta \sin\theta \le \frac{\lambda}{4a}$$

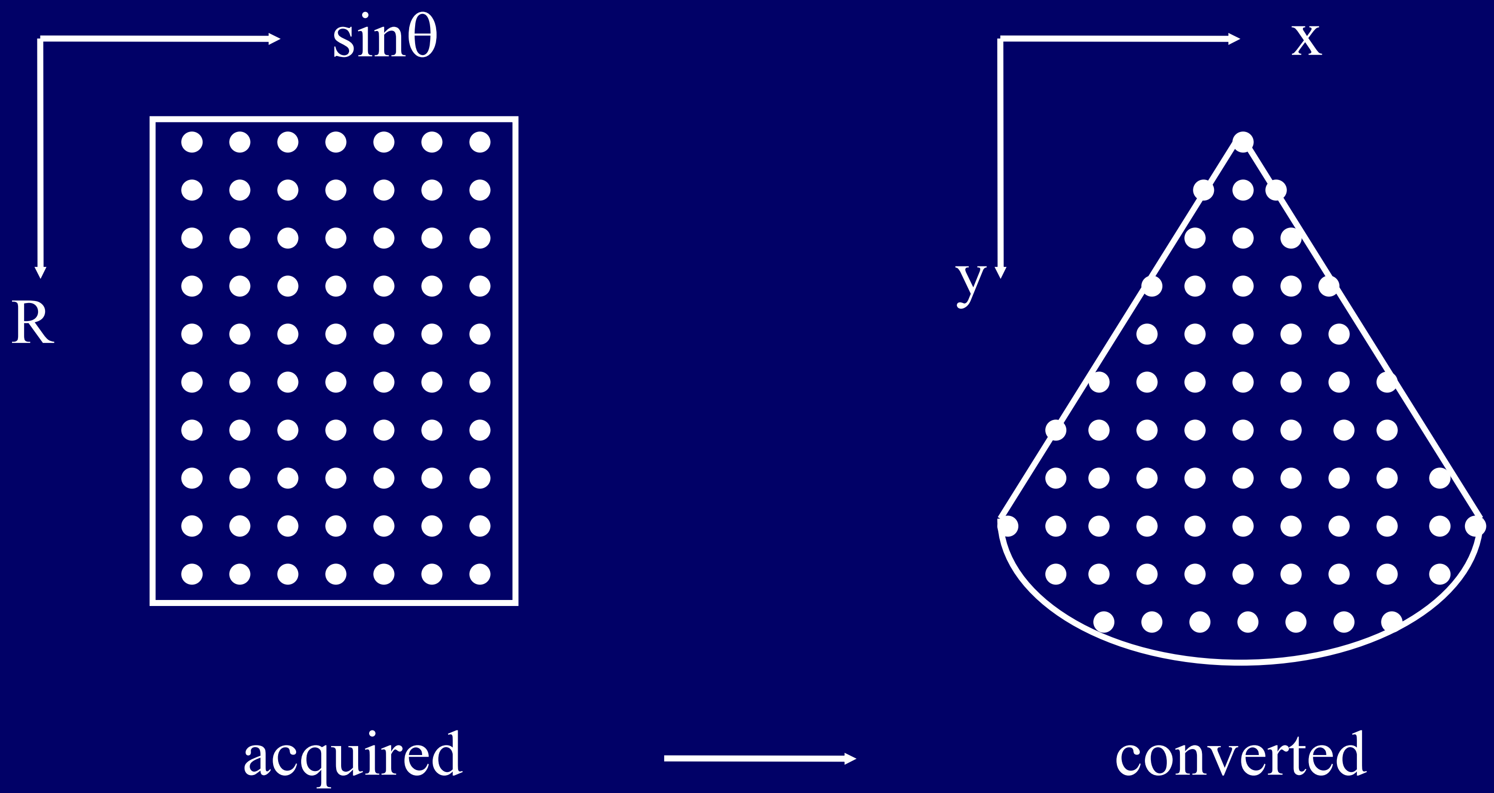
Real-Time Image Formation

Scan Conversion

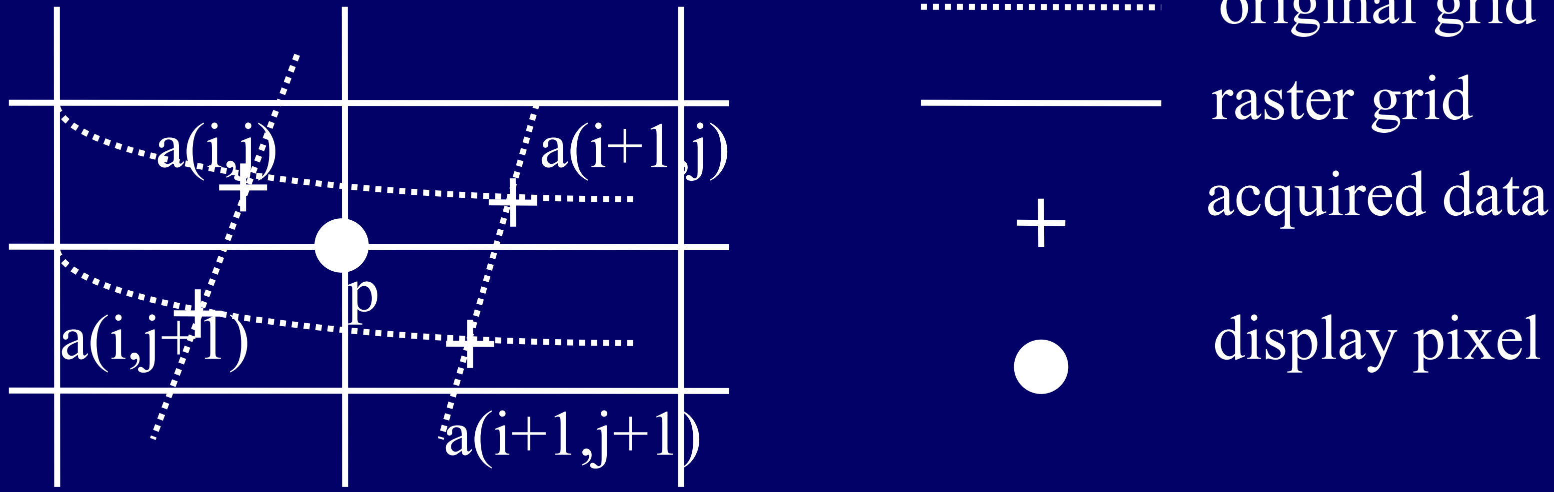
- Acquired data may not be on the display grid.



Scan Conversion

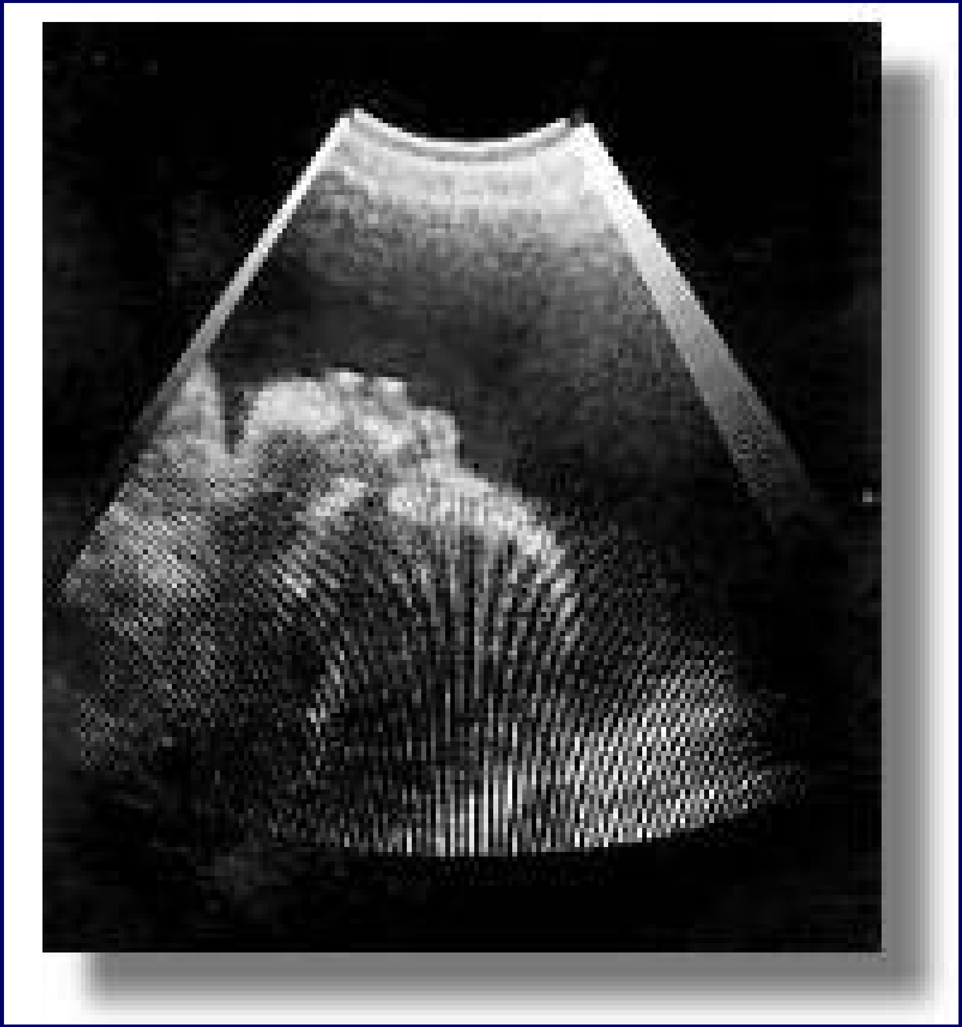


Scan Conversion



$$p(m,n) = c_{m,n,i,j}a(i,j) + c_{m,n,i+1,j}a(i+1,j) + c_{m,n,i,j+1}a(i,j+1) +$$
$$c_{m,n,i+1,j+1}a(i+1,j+1)$$

Moiré Pattern



Temporal Resolution (Frame Rate)

- Frame rate=1/Frame time.
- Frame time=number of lines * line time.
- Line time=(2*maximum depth)/sound velocity.
- Sound velocity is around 1540 m/s.
- High frame rate is required for real-time imaging.

Temporal Resolution

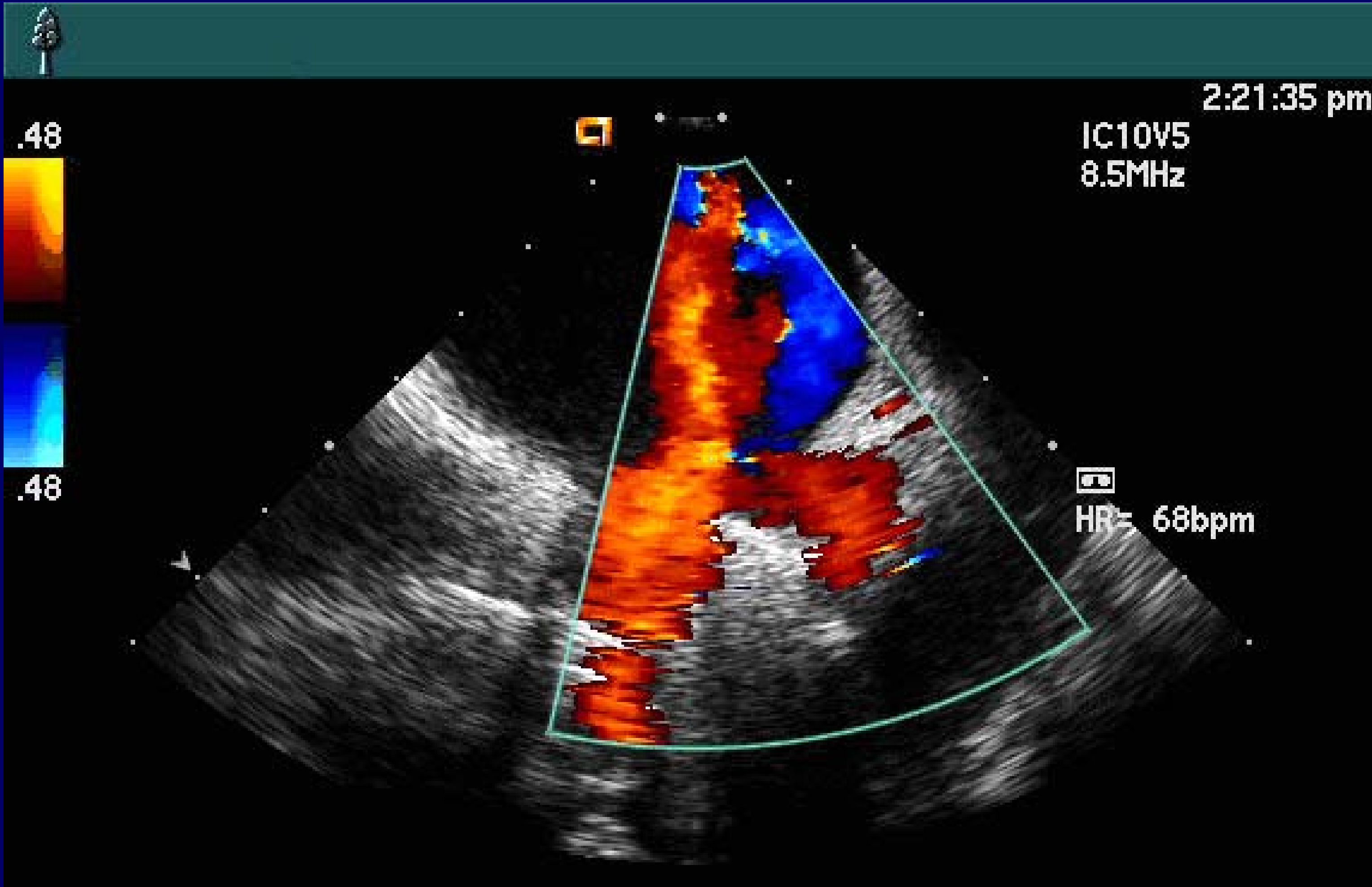
- Display standard: NTSC: 30 Hz. PAL: 25 Hz (2:1 interlace). 24 Hz for movie.
- The actual acoustic frame rate may be higher or lower. But should be high enough to have minimal flickering.
- Essence of real-time imaging: direct interaction.

Temporal Resolution

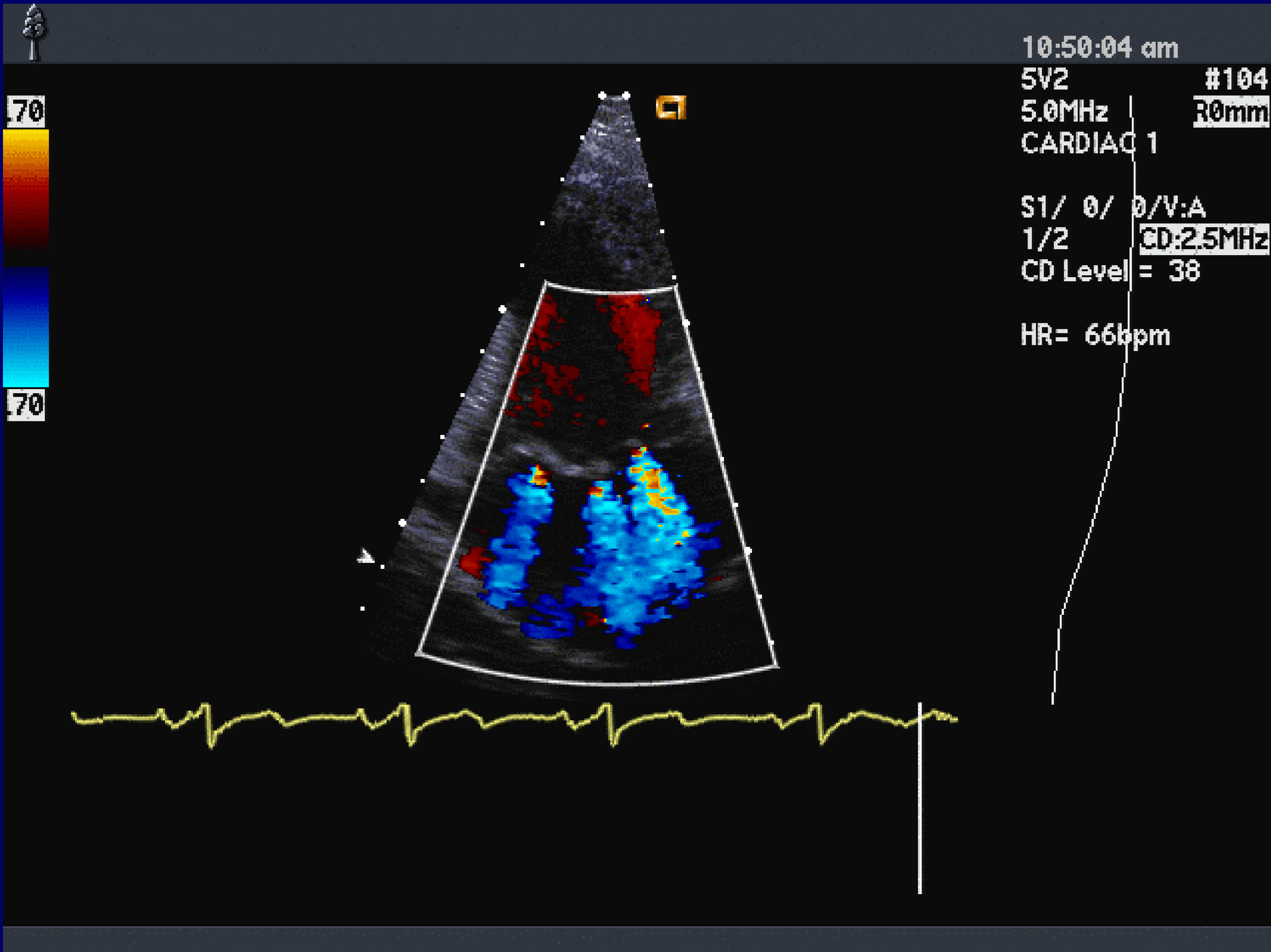
- For an actual frame rate lower than 30 Hz, interpolation is used.
- For an actual frame rate higher than 30 Hz, information can be displayed during playback.
- Even at 30 Hz, it is still possibly undersampling.

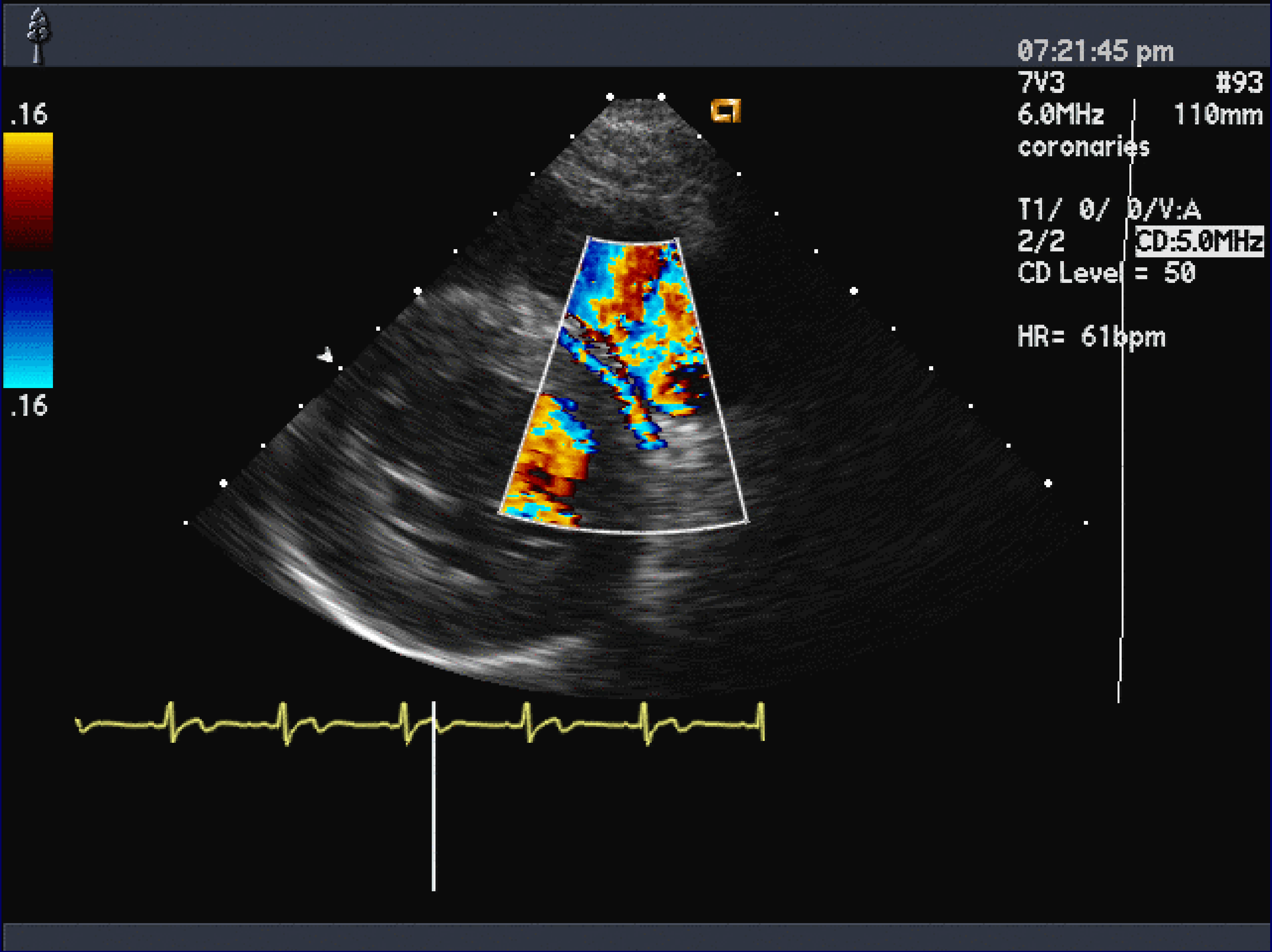
Doppler Techniques for Motion Estimation

Color Doppler Mode



Color Doppler
Left Pulmonary Veins

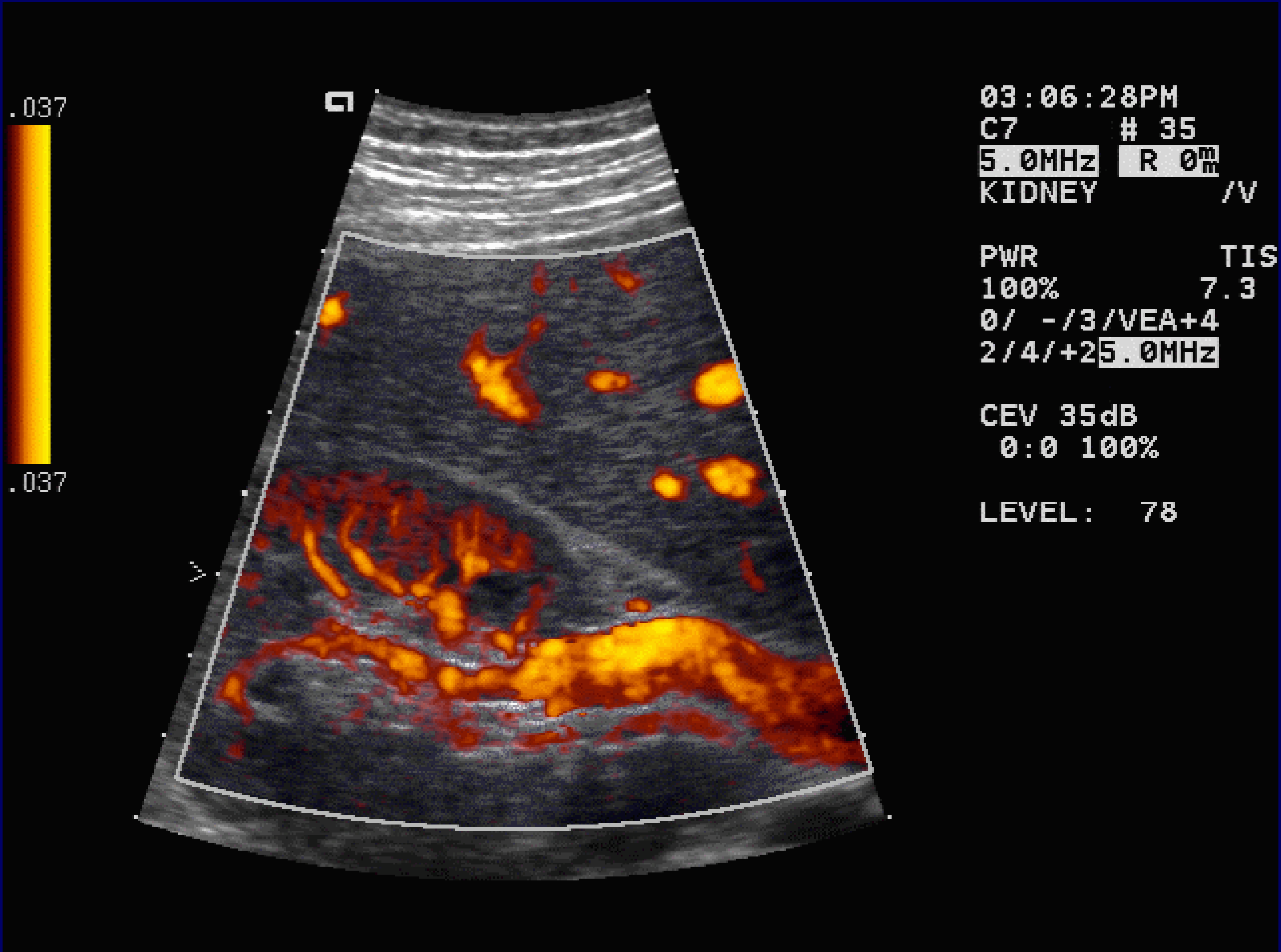

10:50:04 am
5V2
#104
5.0MHz
R0mm
CARDIAC 1
S1/ 0/ 0/V:A
1/2
CD:2.5MHz
CD Level = 38
HR= 66bpm
.70
.70



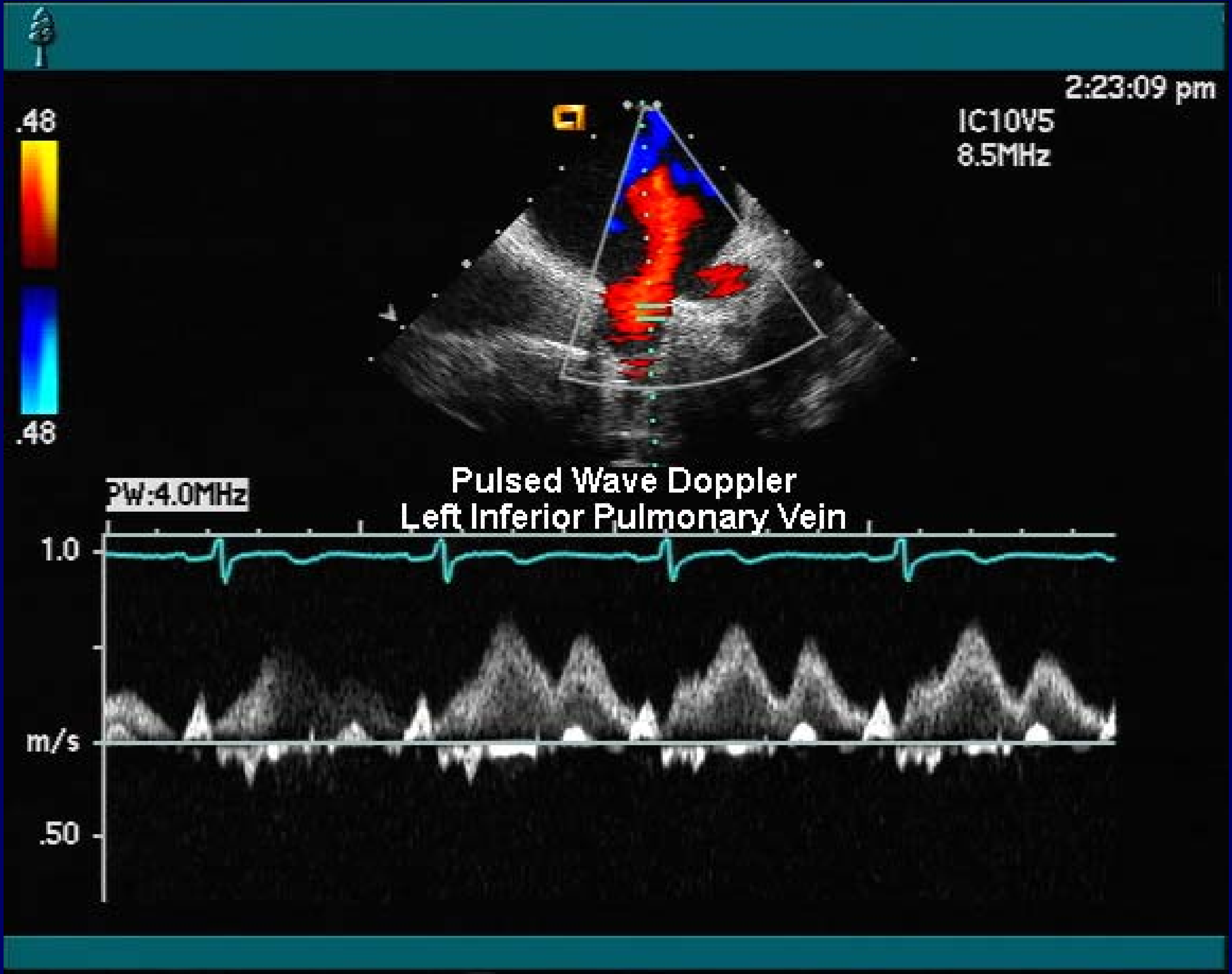
07:21:45 pm
7V3
#93
6.0MHz
110mm
coronaries
T1/ 0/ 0/V:A
2/2
CD:5.0MHz
CD Level = 50
HR= 61bpm
.16
.16

Power Doppler


6C2
.029

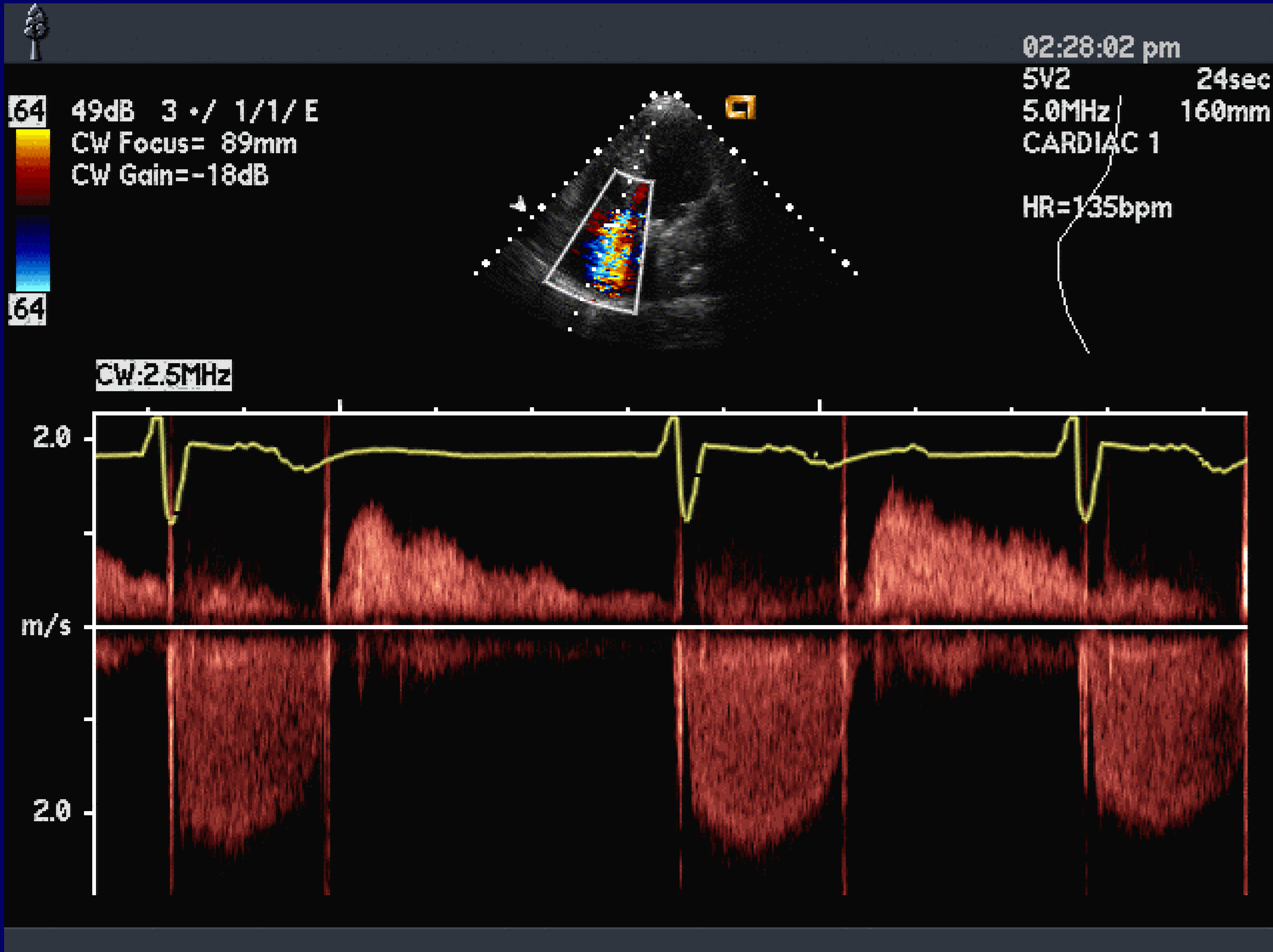

.037
.037
03:06:28PM
C7 # 35
5.0MHz R 0mm
KIDNEY /V
PWR TIS
100% 7.3
0/ -/3/VEA+4
2/4/+25.0MHz
CEV 35dB
0:0 100%
LEVEL: 78

PW Doppler (Spectral Doppler)

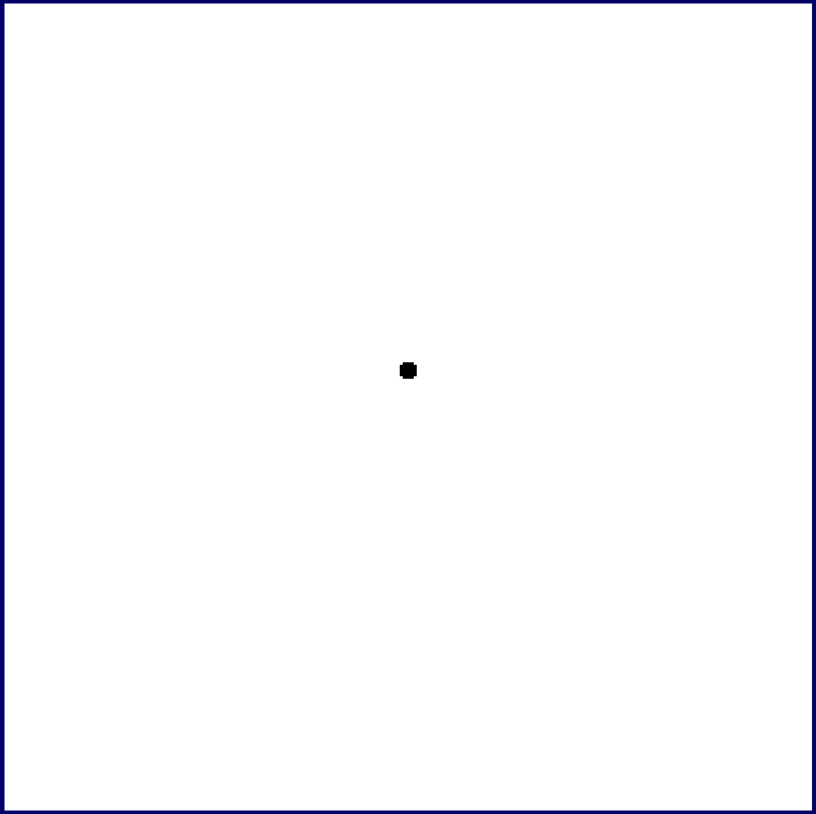


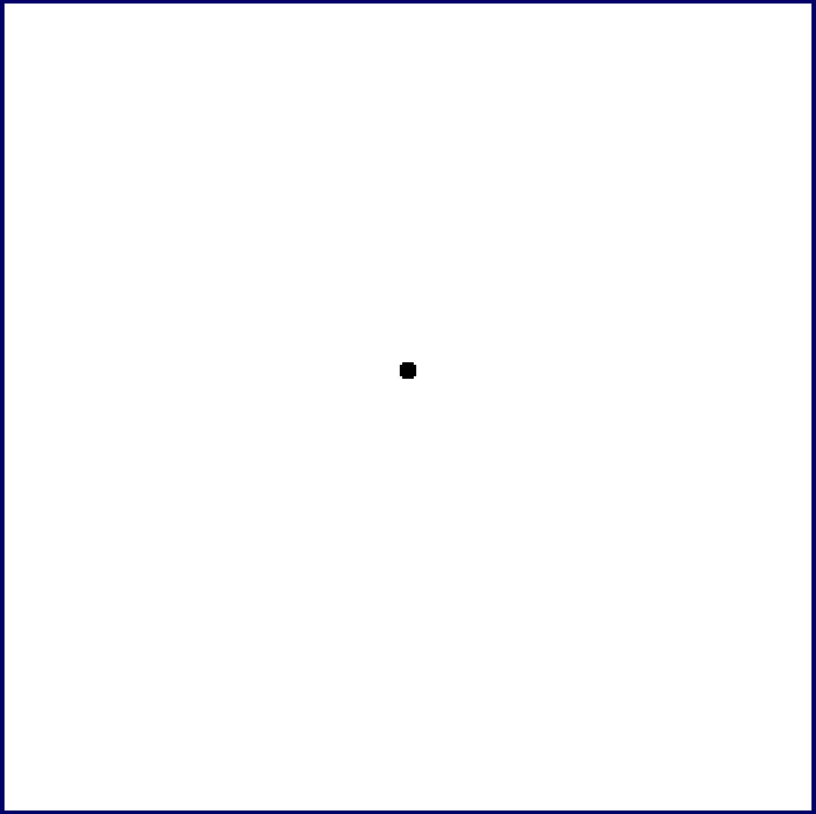
2:23:09 pm
IC10V5
8.5MHz
.48
.48
Pulsed Wave Doppler
Left Inferior Pulmonary Vein
PW:4.0MHz
1.0
m/s
.50

CW Doppler (Spectral Doppler)

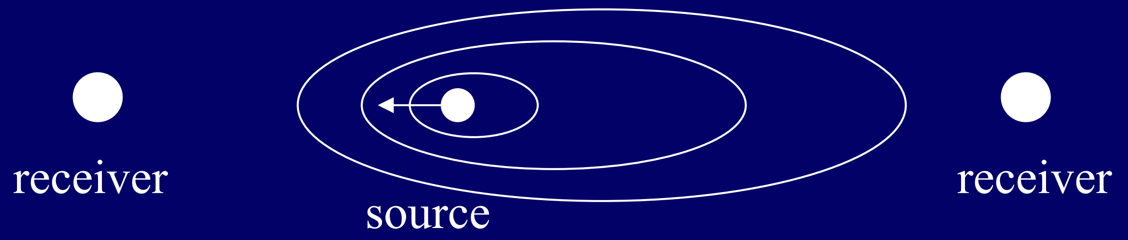

02:28:02 pm
5V2 24sec
5.0MHz 160mm
CARDIAC 1
HR=135bpm
64
49dB 3 •/ 1/1/ E
CW Focus= 89mm
CW Gain=-18dB
64
CW:2.5MHz
2.0
m/s
2.0

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.

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,

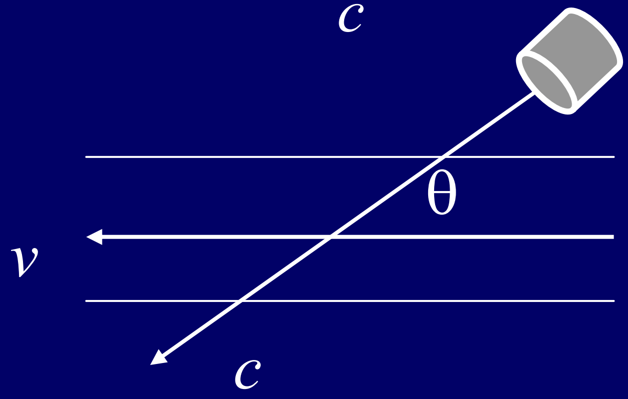
v_s and v_r are source and receiver velocities.

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.

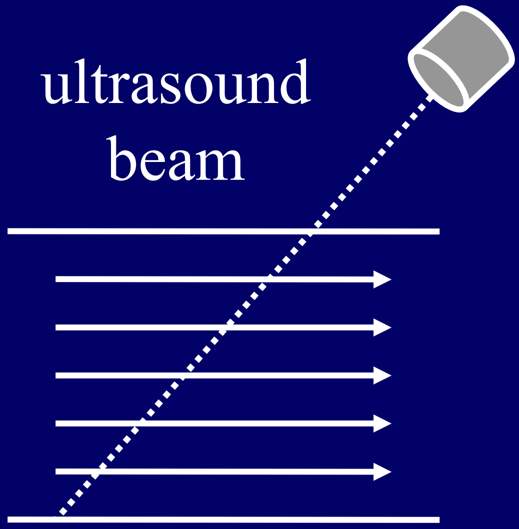
Doppler Equations

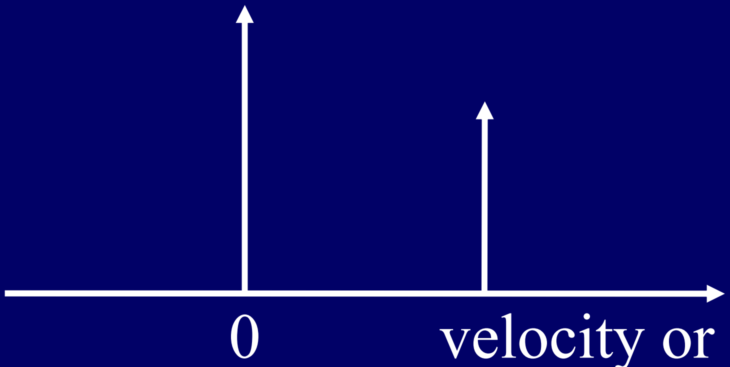
$$f_d = \frac{2vf_s}{c}\cos\theta$$



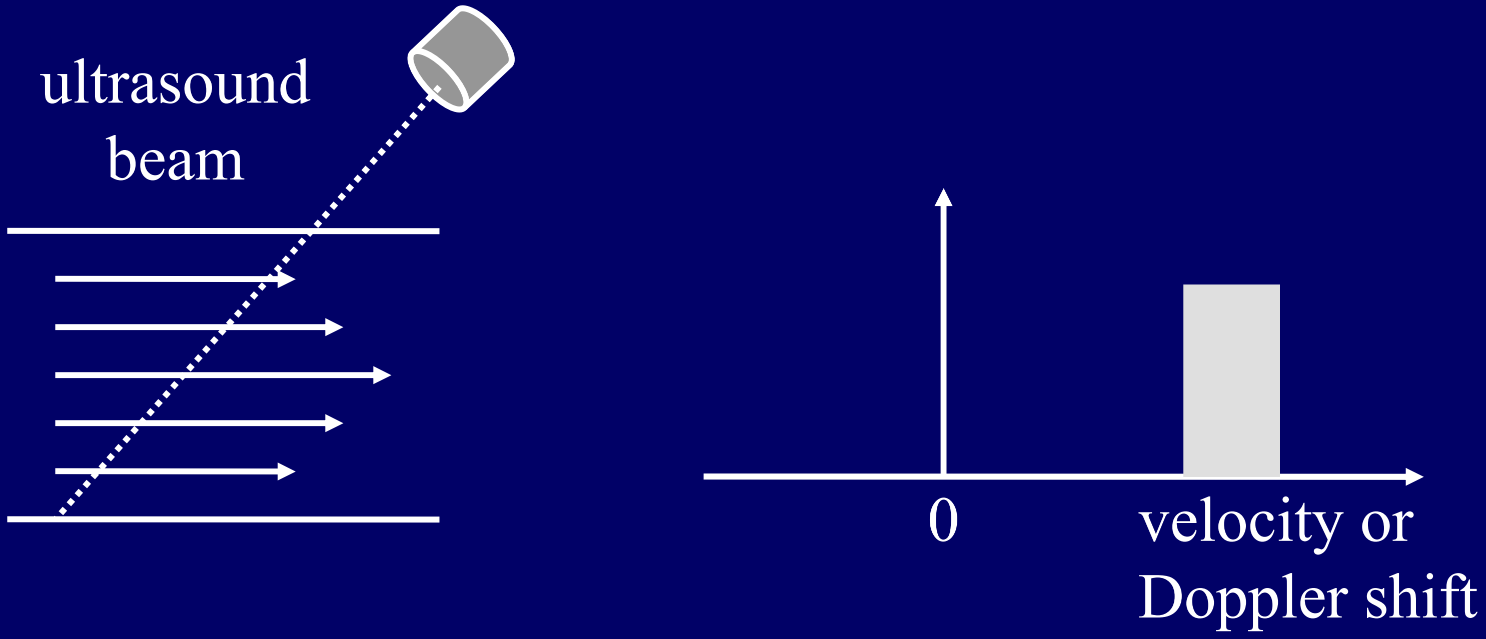
- Typical physiological flows (5-10m/sec at most) are much slower than sound velocity in the body (~1500m/sec).
- Doppler shift is doubled due to round-trip propagation.
- Only parallel flows can be detected.

Flow Pattern vs. Velocity Profile

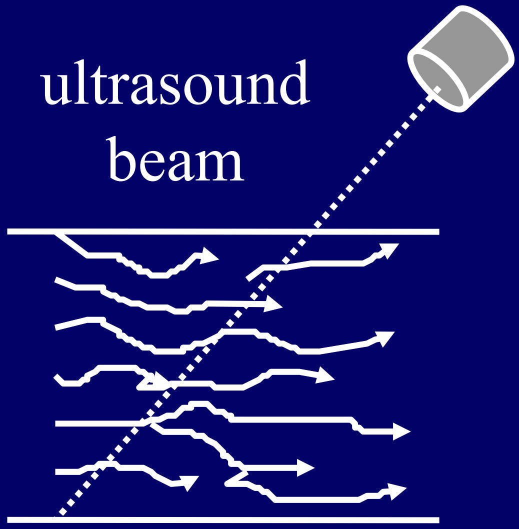


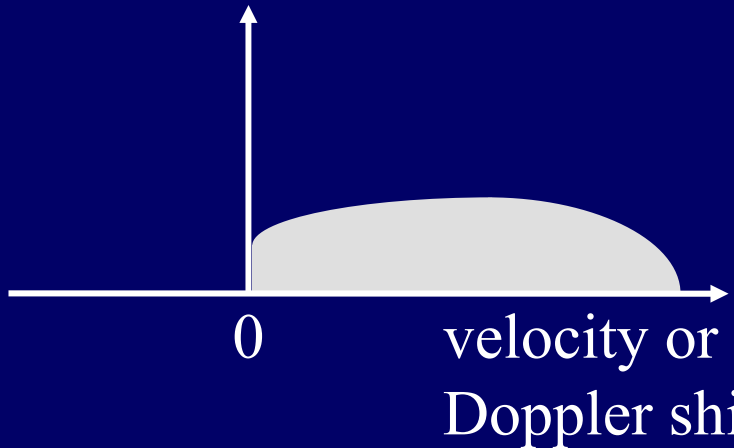


Flow Pattern vs. Velocity Profile

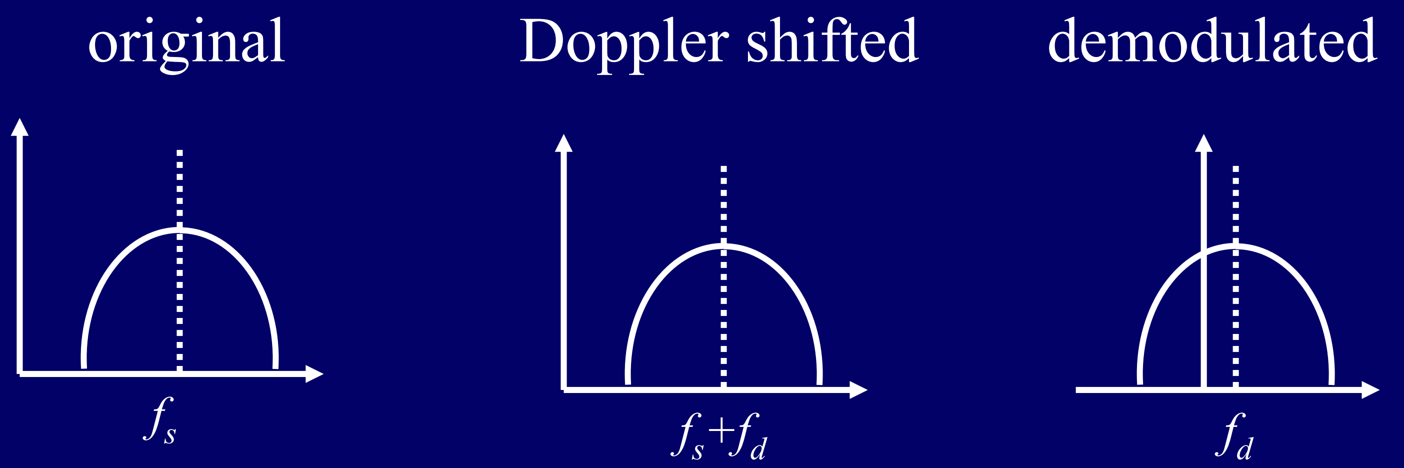


Flow Pattern vs. Velocity Profile



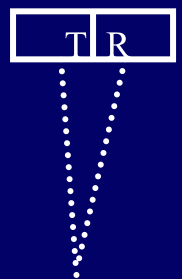


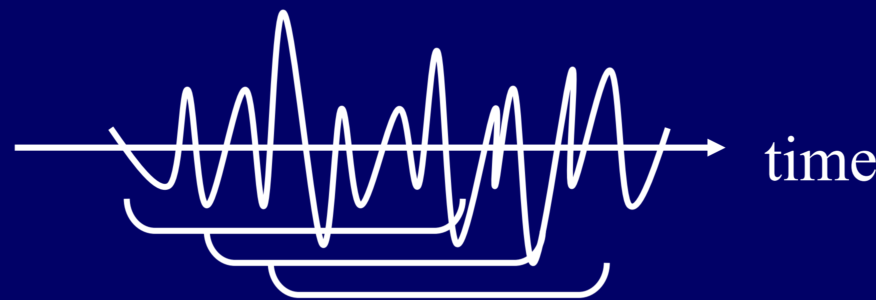
Doppler Spectrum Estimation

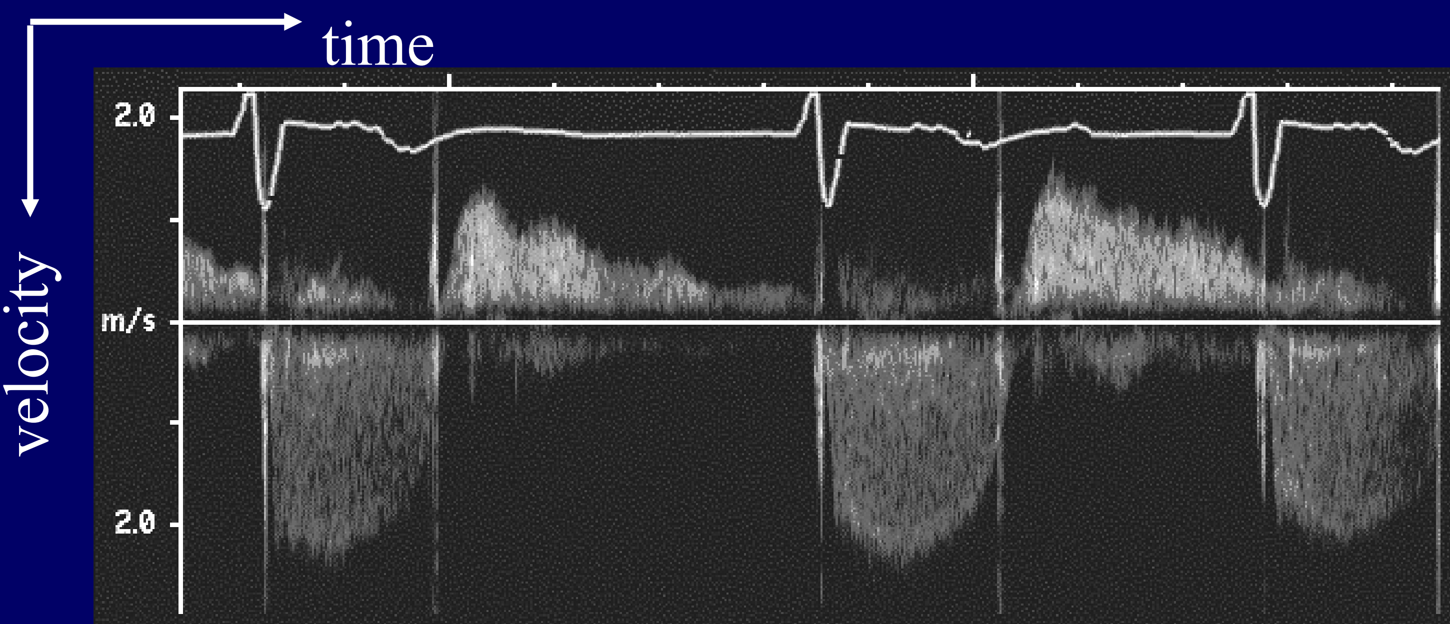


- Short-time Fourier transform (Spectral Doppler).
- Correlation based estimation (Color Doppler).

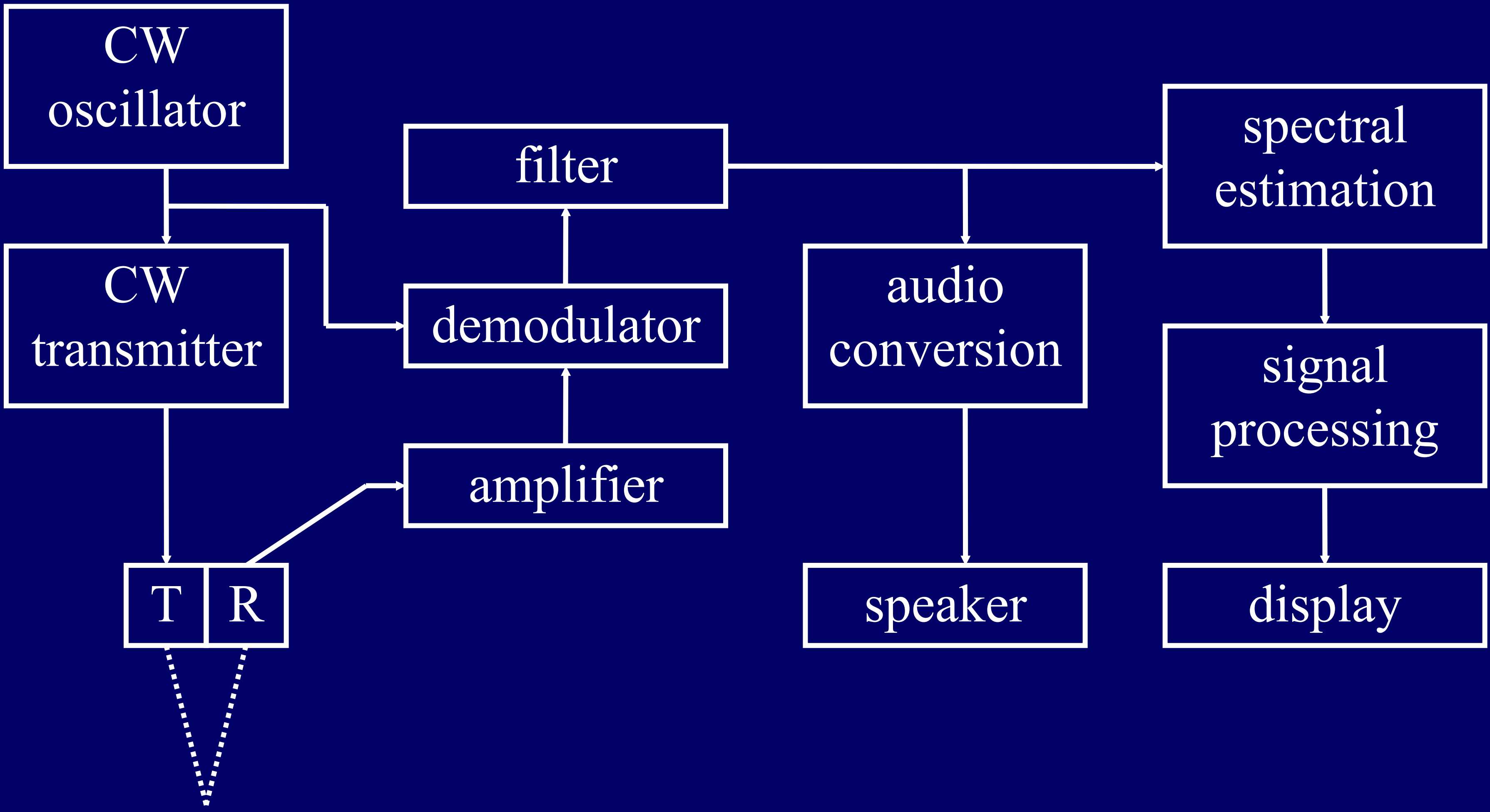
Continuous Wave (CW) Doppler







CW Doppler


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

CW Doppler

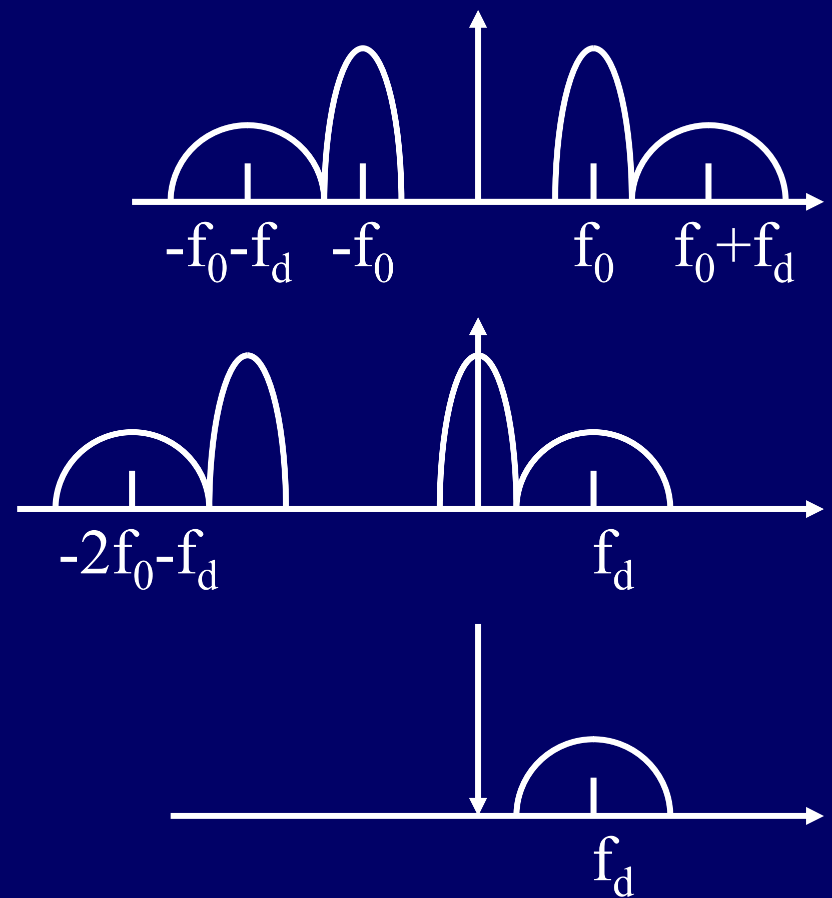
- Array CW and AUX CW (half transmit, half receive).
- Mainly for Cardiology.
- Good velocity (frequency) resolution.
- No range resolution. Flows along the same direction are all detected.
- Frequency downshift due to attenuation can be ignored.

CW Doppler Processing

original spectrum

demodulated

demodulated and filtered

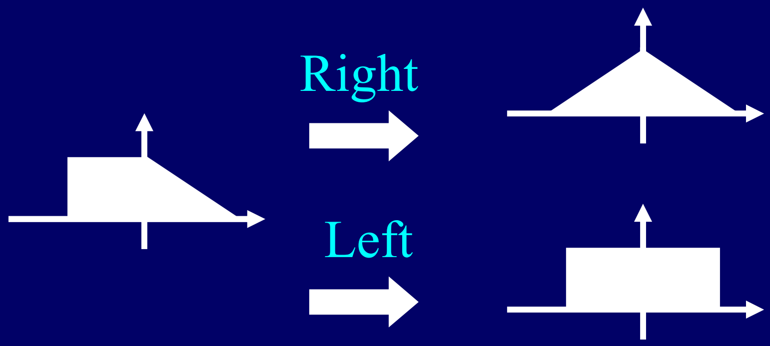


CW Doppler Processing

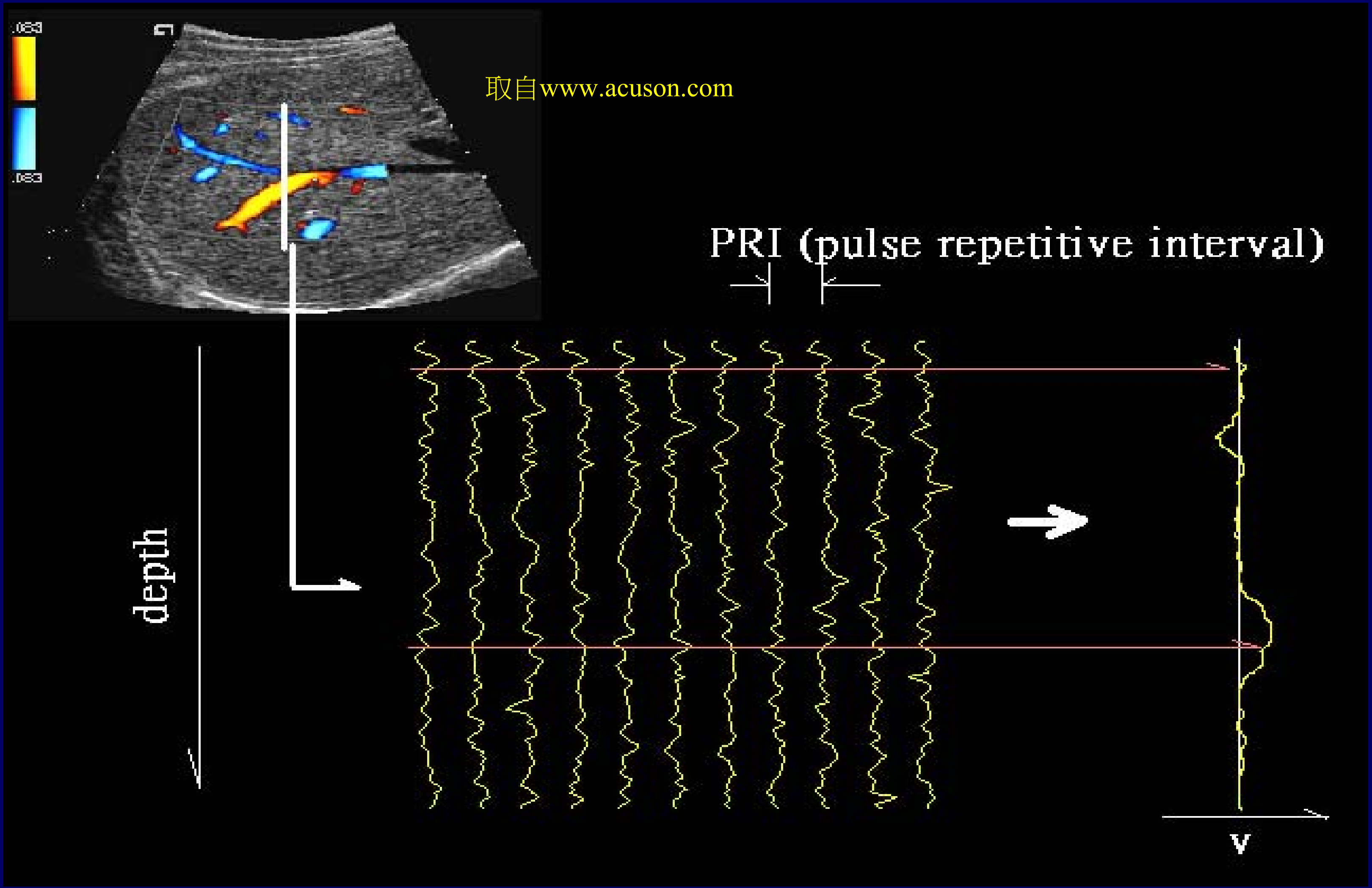
- Time-interval histogram.
- 32-128 ppt FFT.
- Mode-based spectrum estimation (AR), time-frequency analysis.
- Magnitudes are converted in dB and displayed.
- Post-processing similar to B-mode.

Audio Doppler

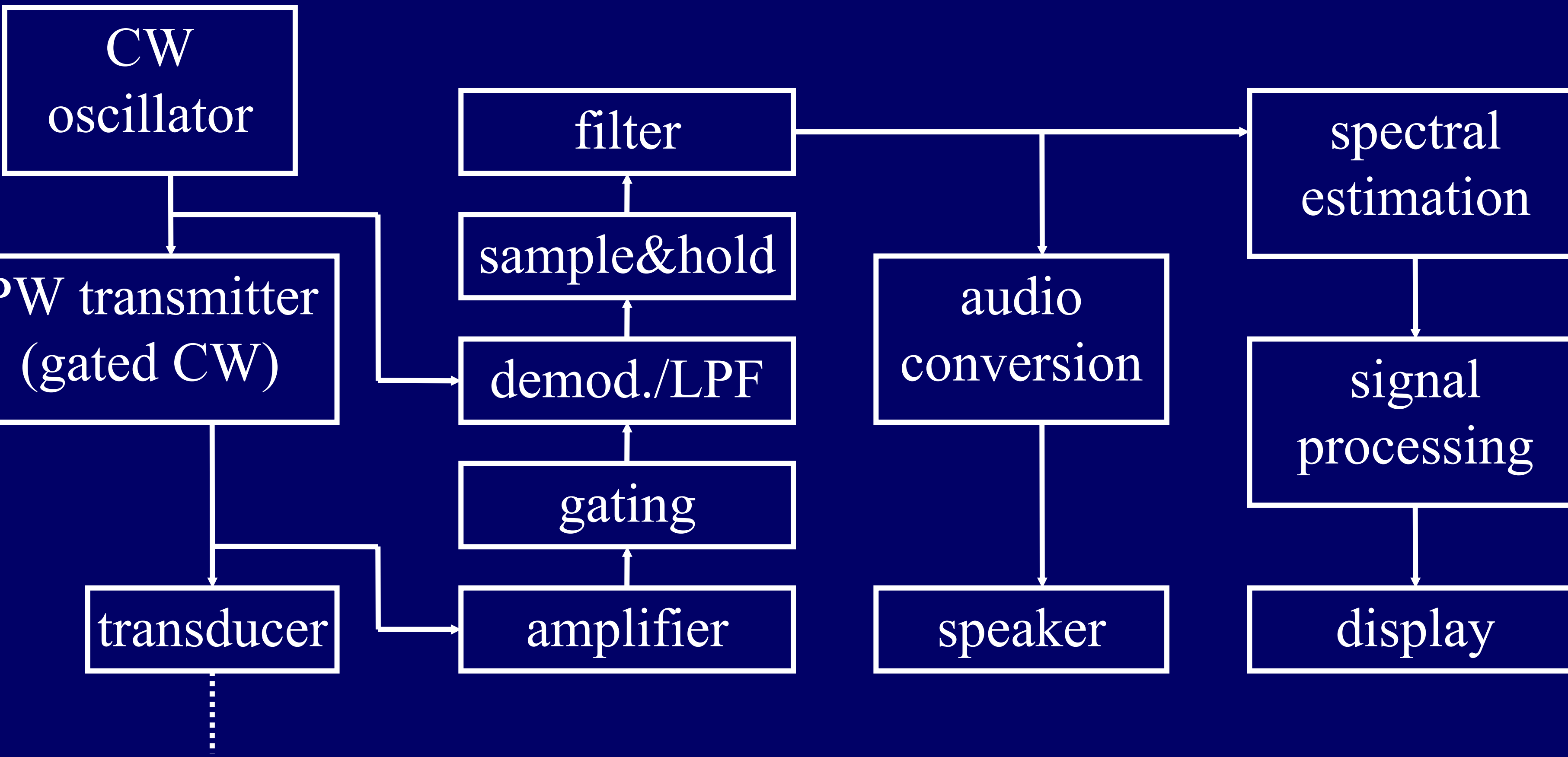
- For typical blood velocities and carrier frequencies, the Doppler shifts from blood happen to be in the human audible range (near DC to 20KHz).
- Positive shifts in one channel and negative ones in the other.
- Hilbert transform.
- Clinically useful.



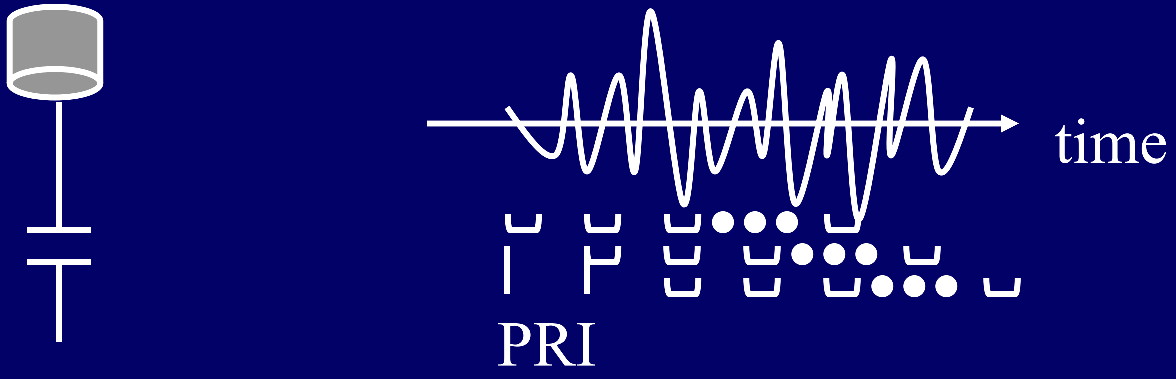
PW Blood Flow Measurements

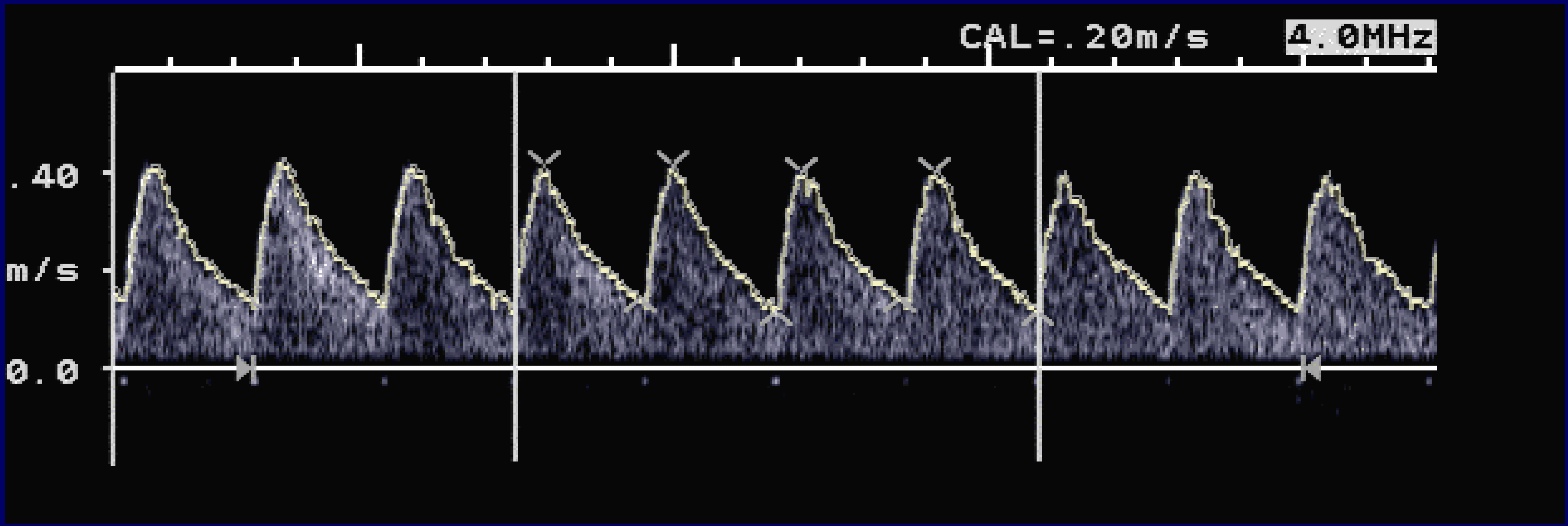


PW System Diagram



Pulsed Wave (PW) Doppler





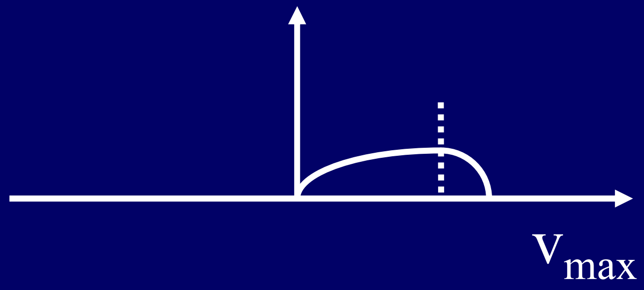
Velocity Ambiguity

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

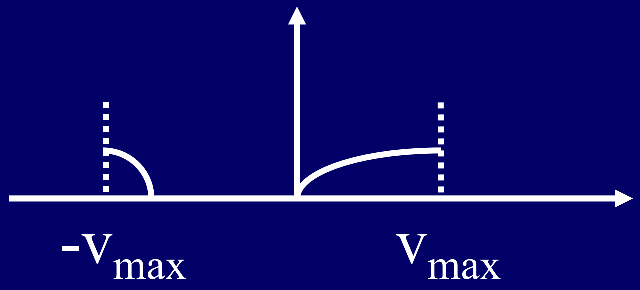
$$2f_{\max} = \frac{4v_{\max} f_s}{c} \le \frac{1}{PRI}$$

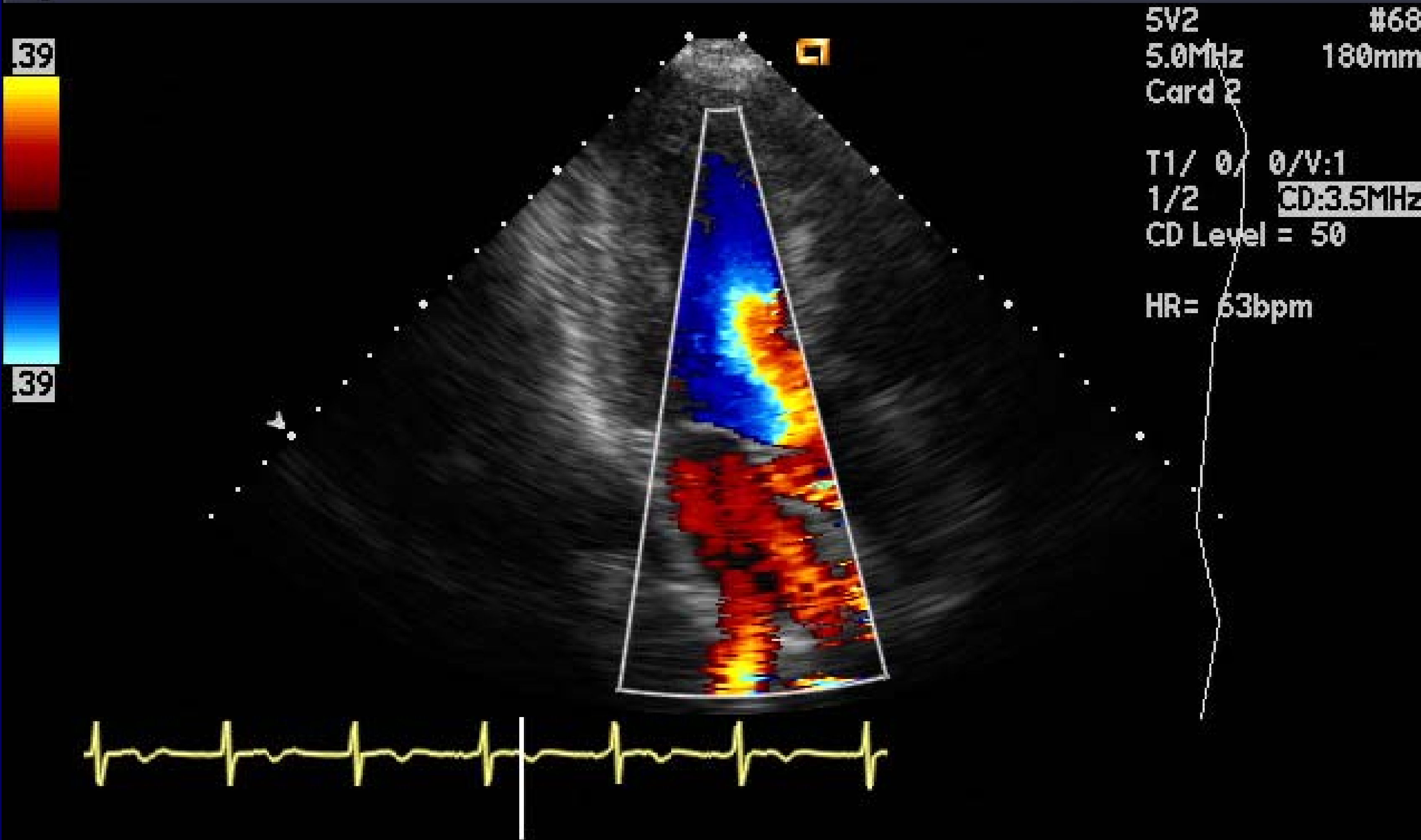
$$v_{\max} \le \frac{\lambda}{4 \cdot PRI}$$

no aliasing



aliasing

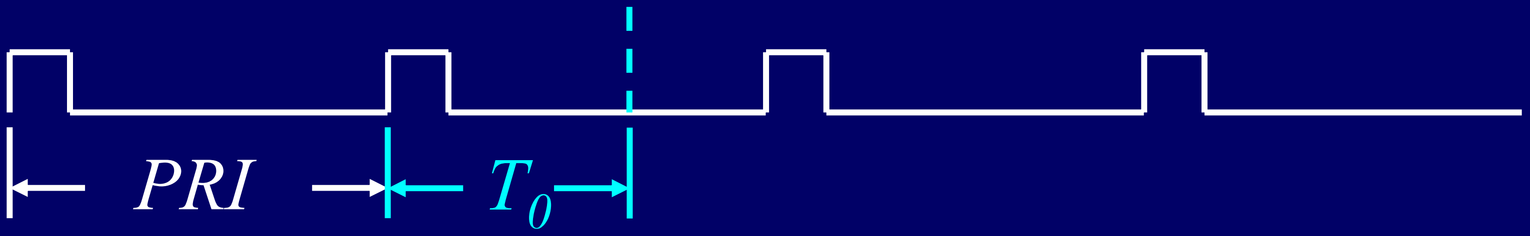




Pulmonary Vein Inflow

Range Ambiguity

$c \cdot PRI / 2$

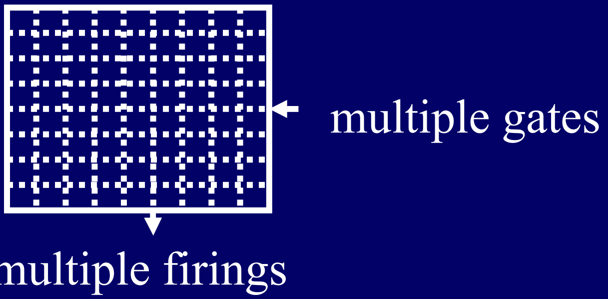


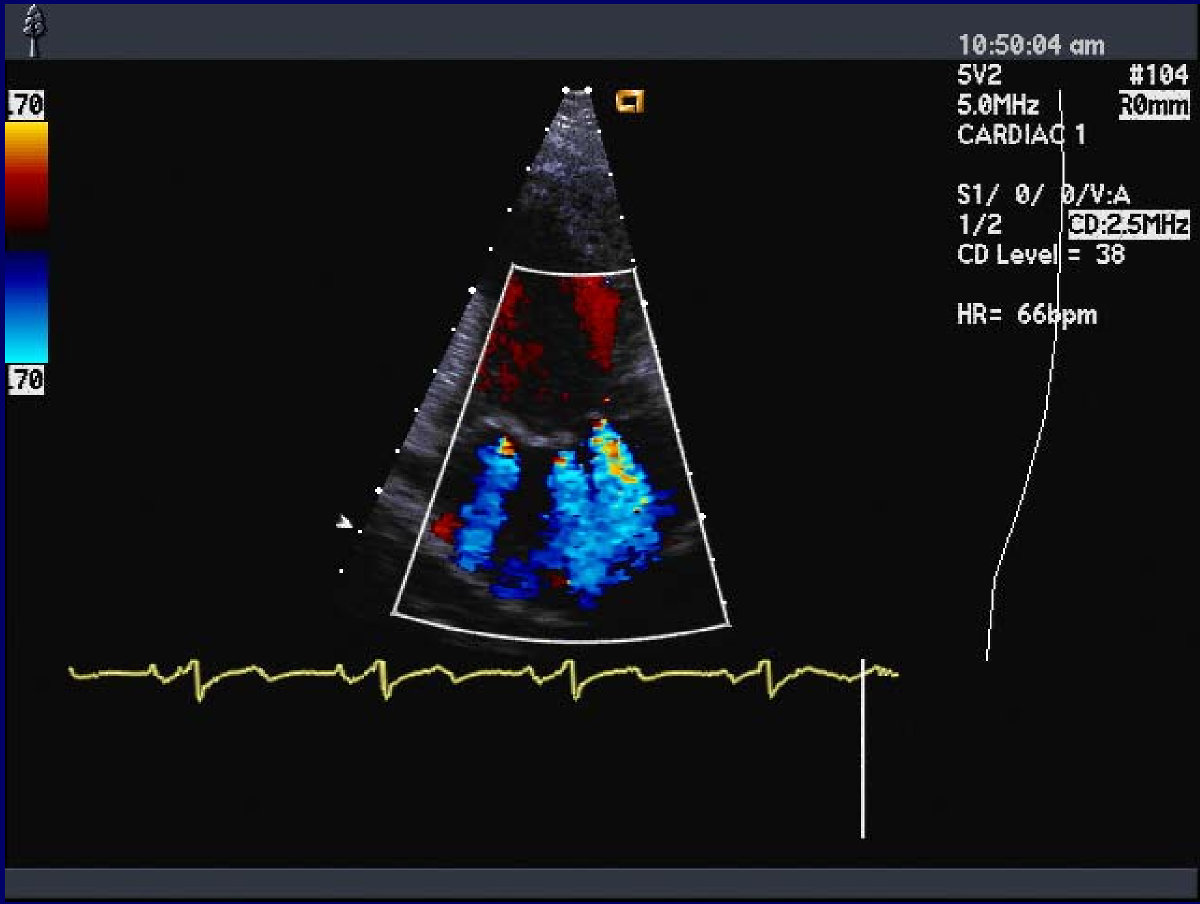
$c \cdot T_0 / 2$ OR $c \cdot (PRI + T_0) / 2$?

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.

Color Doppler

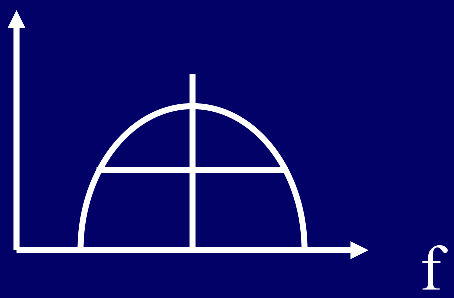




Color Doppler

- 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



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

Color Doppler: Mean Velocity

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

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

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

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

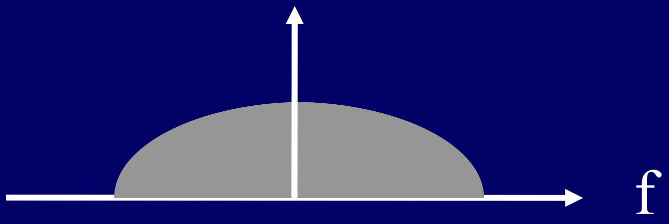
Color Doppler: Variance

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

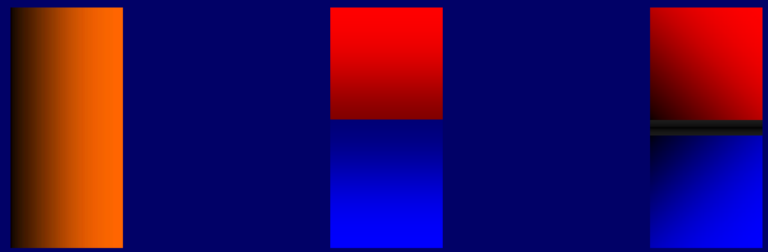
$$\sigma^2 \approx \frac{2}{T^2}\left(1 - \frac{A(T)}{A(0)}\right) = \frac{2}{T^2}\left(1 - \frac{|R(T)|}{R(0)}\right)$$

Color Doppler: Energy

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

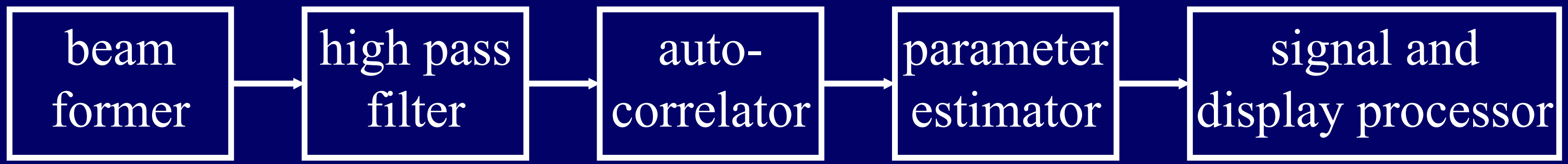


Color Doppler



- 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.

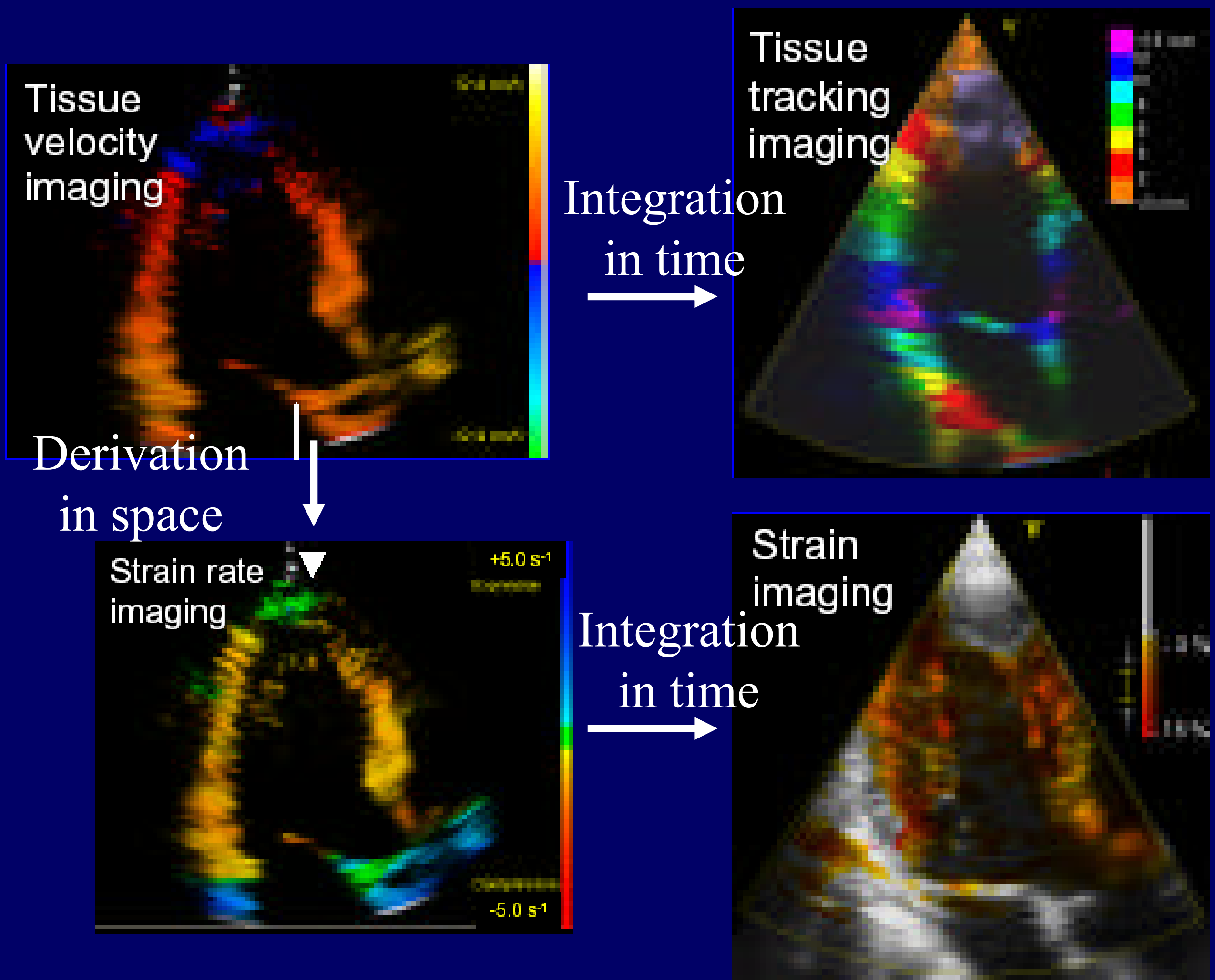
Doppler: Tissue Motion Imaging

- Doppler principles can be used to visualize cardiac motion.
- Higher signal levels allow simpler wall filters and less number of firing.
- Suitable for cardiac applications.

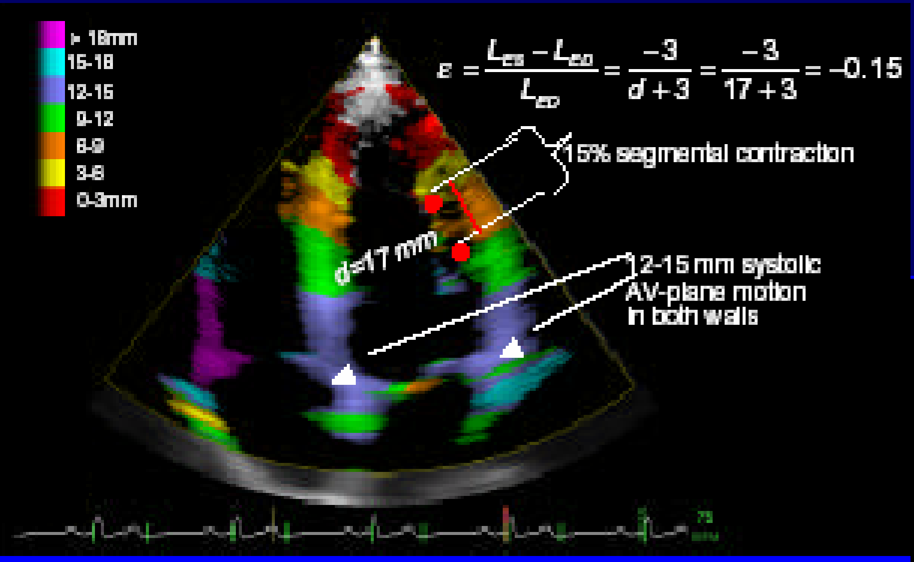
Doppler Tissue Imaging

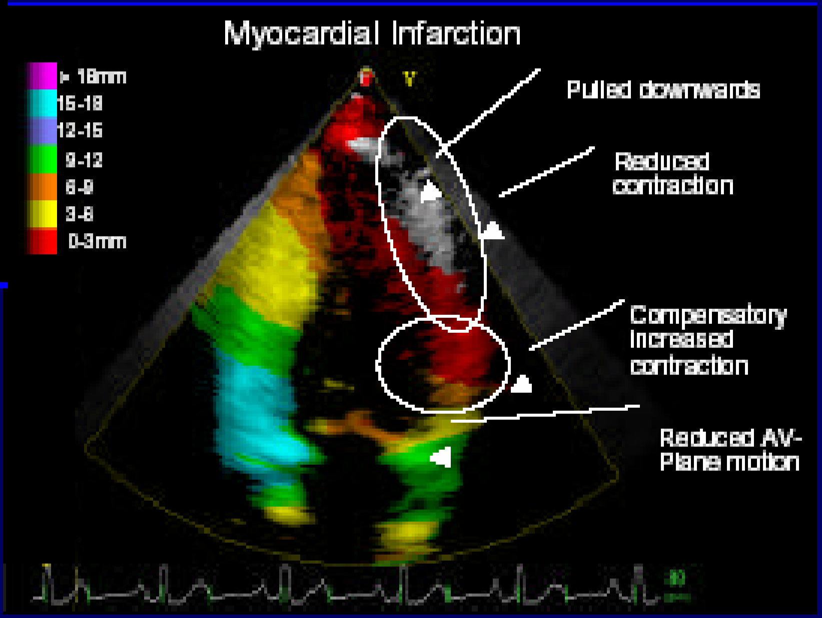
- Heart motion parameters:
  - Velocity: $v=dw/dt$.
  - Displacement w: temporal integration of v.
  - Strain rate: $r=dv/dz$.
  - Strain s: temporal integration of r.

Doppler Tissue Imaging



Doppler Tissue Imaging





<u>Ultrasonic Nonlinear Imaging-</u>
<u>*Tissue Harmonic Imaging*</u>

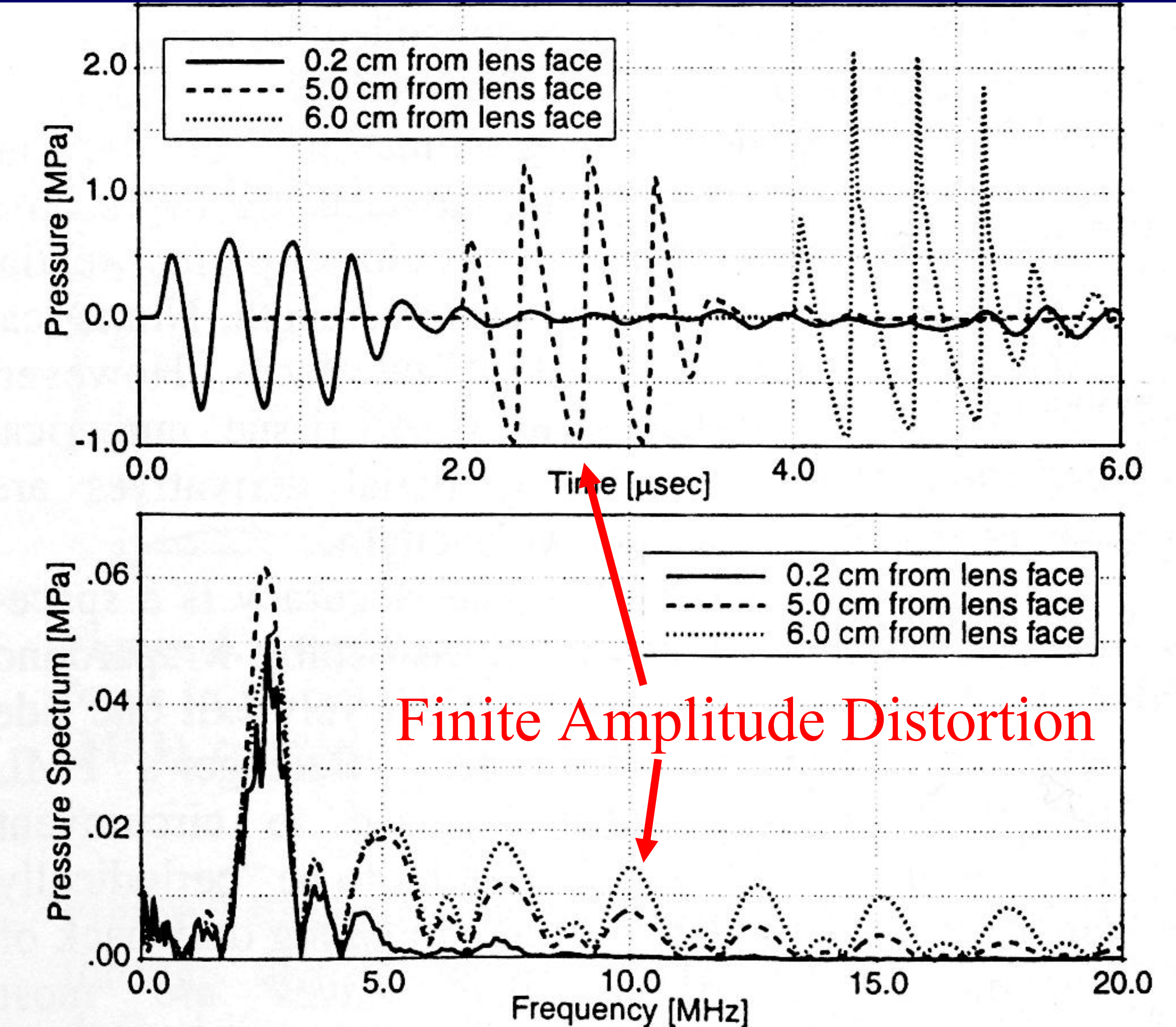
Sound Velocity and Density Change

$$v(x) = c_0 + (1 + \frac{B}{2A})u(x)$$

Phase velocity

Nonlinearity

Particle velocity



Non-linear Parameter B/A

$$P = P_0 + \left(\frac{\partial P}{\partial \rho}\right)_{s;\rho=\rho_0} (\rho - \rho_0) + \frac{1}{2}\left(\frac{\partial^2 P}{\partial \rho^2}\right)_{s;\rho=\rho_0} (\rho - \rho_0)^2 + \cdots$$

$$P - P_0 = A\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{B}{2}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2$$

- B/A defines non-linearity of the medium. The larger the B/A, the higher the non-linear response.

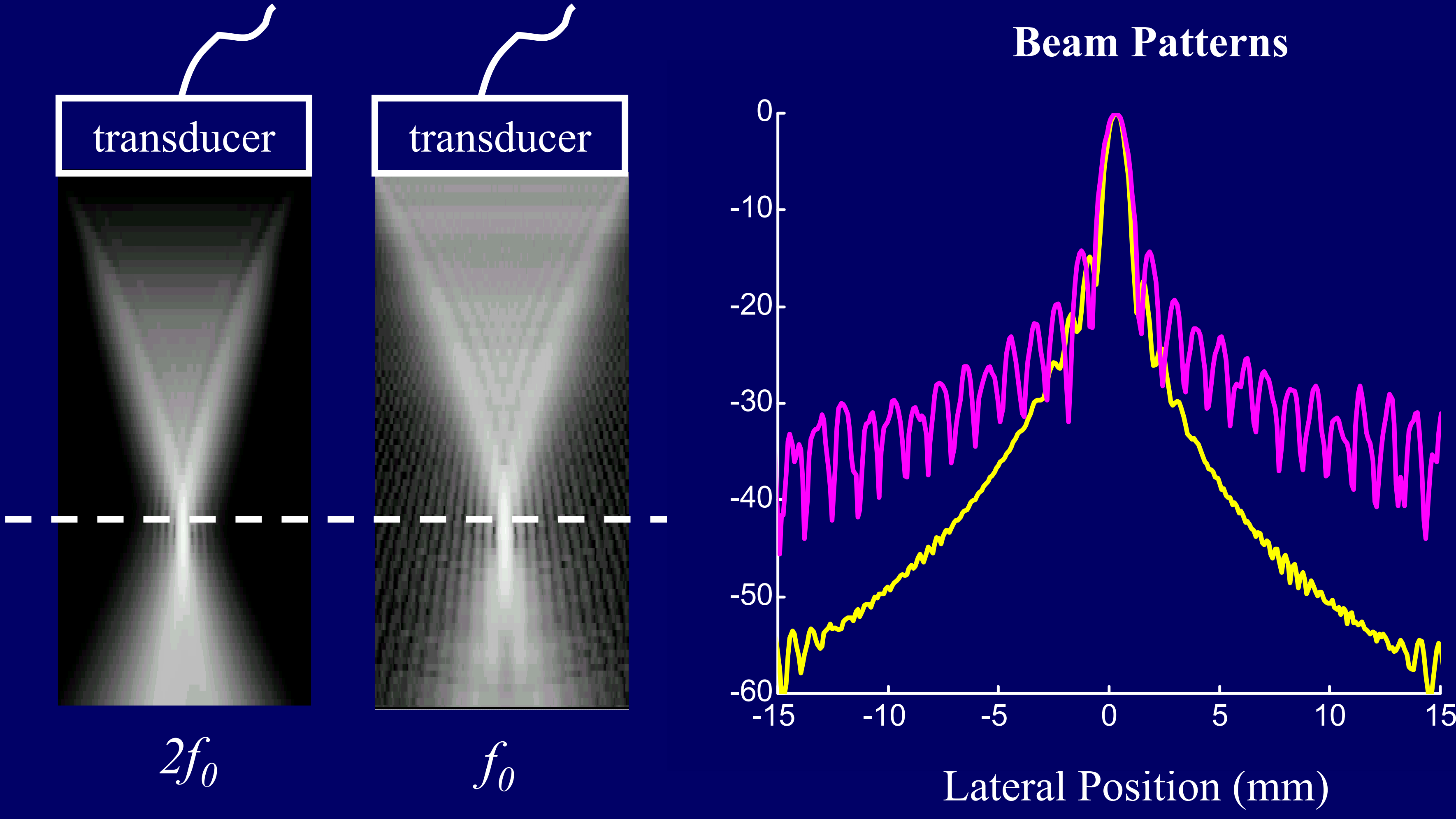
B/A Parameters: Typical Values

- Typical values:
  - Water:5.5+/-0.3.
  - Liver: 7.23.
  - Fat: 10.9.
  - Muscle: 7.5.
- B/A imaging may be used for tissue characterization.

Tissue Non-linearity

- Tissue harmonics are virtually zero at the probe face.The intensity continues to increase until attenuation dominates.
- The higher the intensity is, the more tissue harmonics are generated.
- Such a mechanism automatically increase the difference between signal and acoustic noise.

Comparison of Radiation Patterns



What If We Use the Second Harmonic Signal for Imaging?

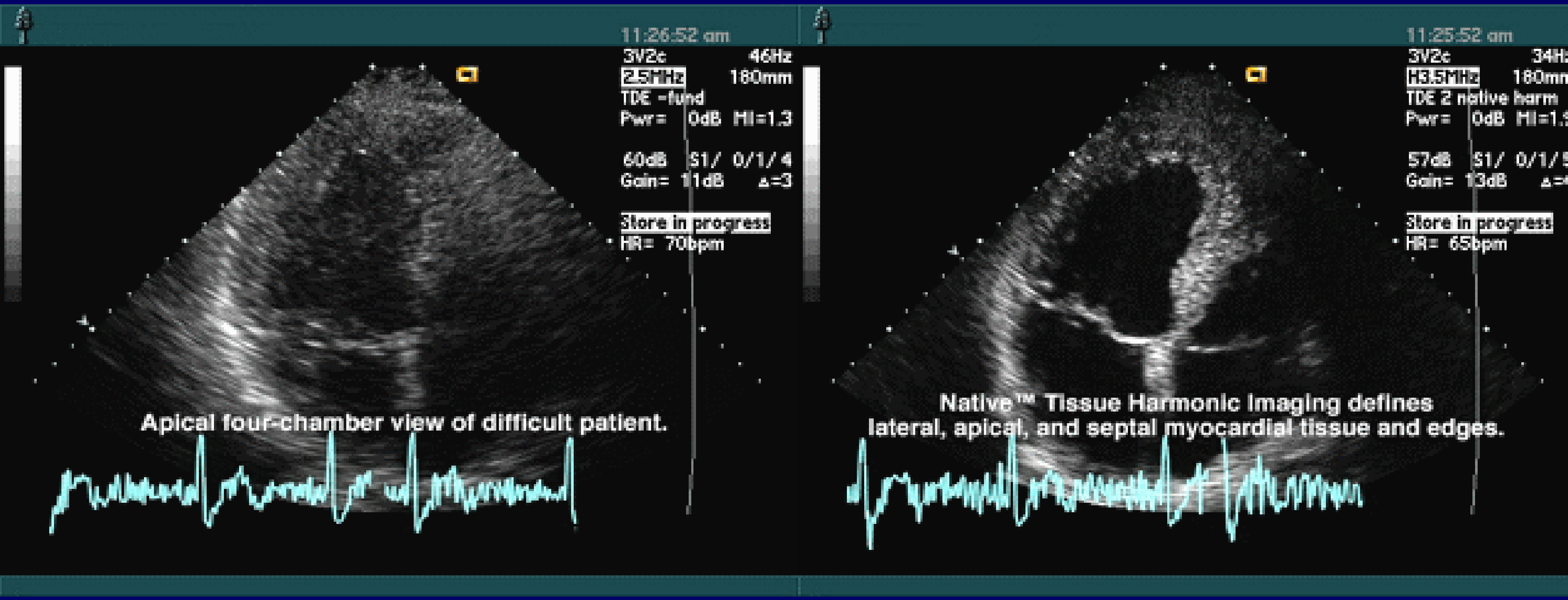
Advantages of Tissue Harmonic Imaging

- Low sidelobes.
- Better spatial resolution compared to fundamental imaging at the original frequency.
- Less affected by tissue inhomogeneities – better performance on technically difficult bodies.

Tissue Harmonic Imaging

- Performance of ultrasound has been sub-optimal on technically difficult bodies.
- Most recent new developments have bigger impact on technically satisfactory bodies.
- Poor image quality leads to uncertainty in diagnosis and costly repeat examinations.
- Tissue harmonic imaging has been successful on difficult bodies.

Reduction of Imaging Artifacts



Reduction of Imaging Artifacts