

# 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?

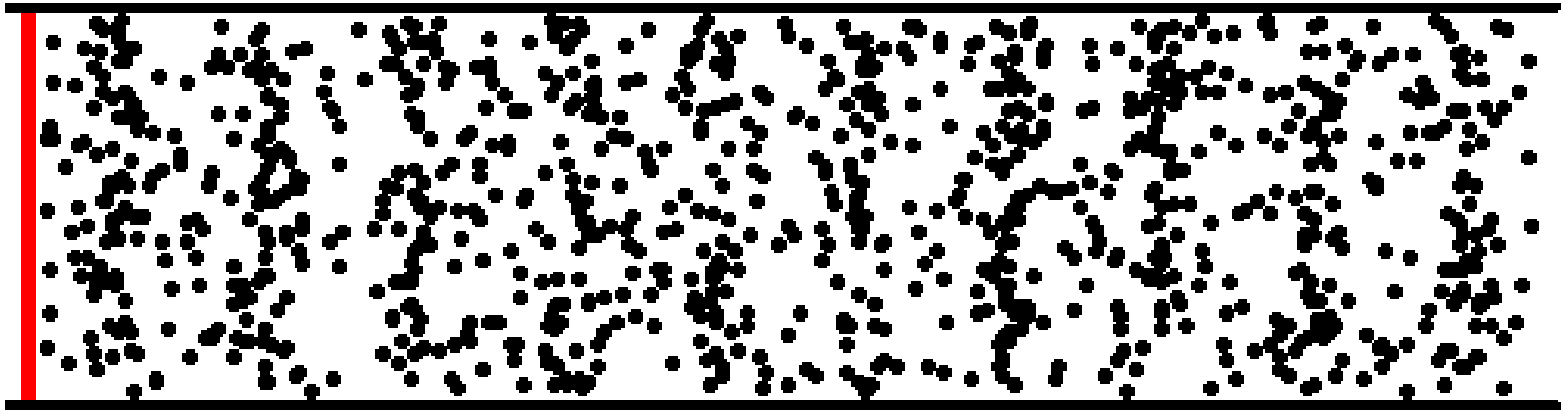
# Characteristics of Ultrasound

- 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.



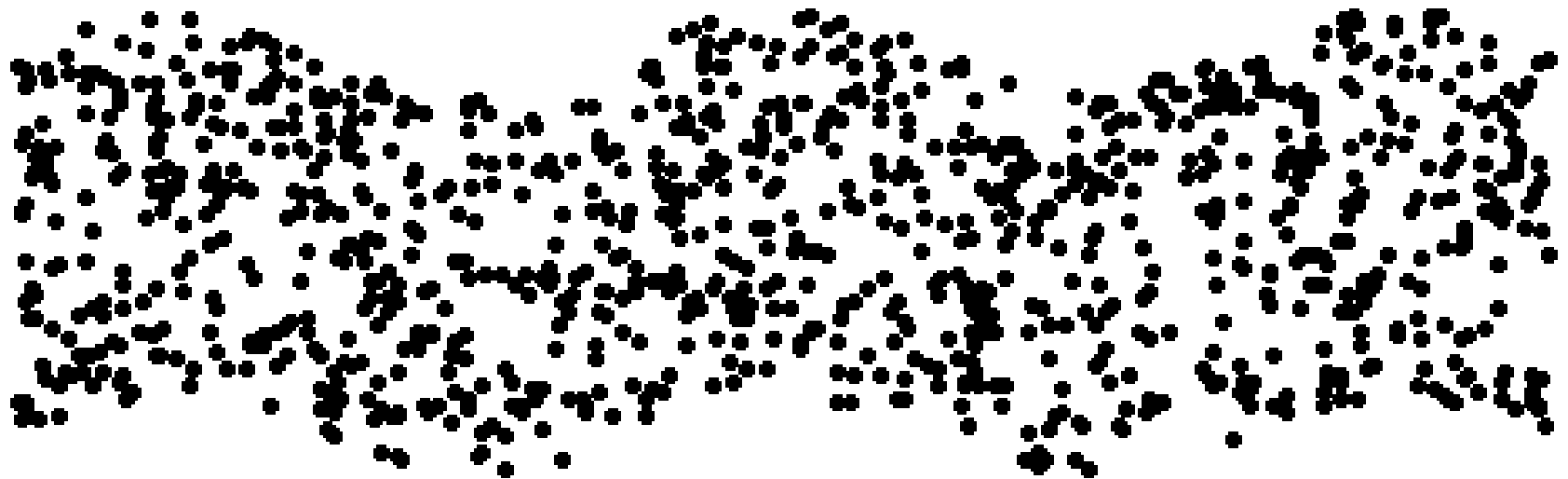
# Basics of Acoustic Waves

- Longitudinal Wave:



# Basics of Acoustic Waves

- Shear Wave:



# 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.

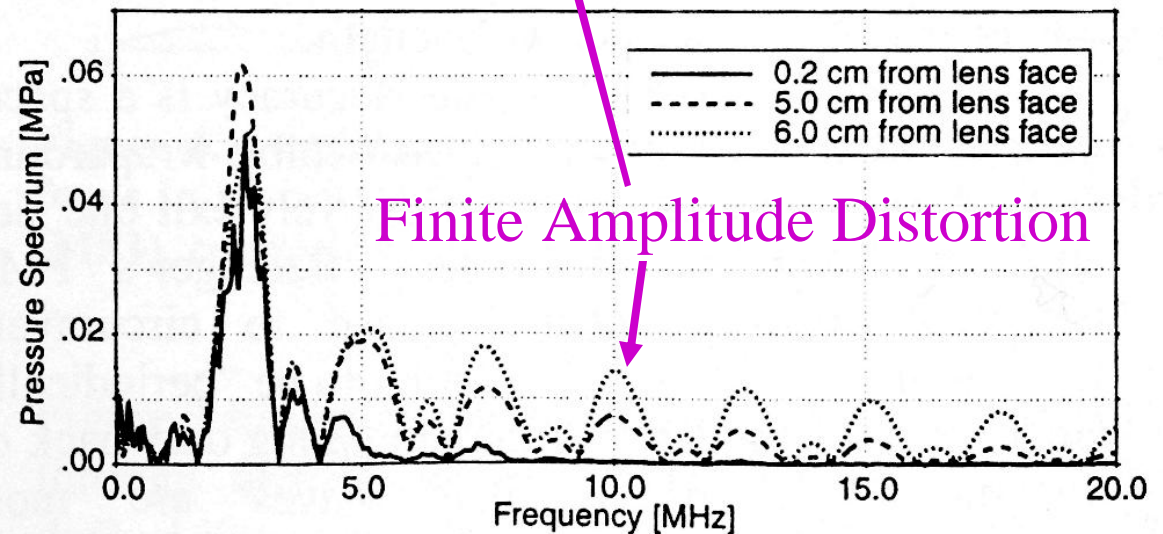
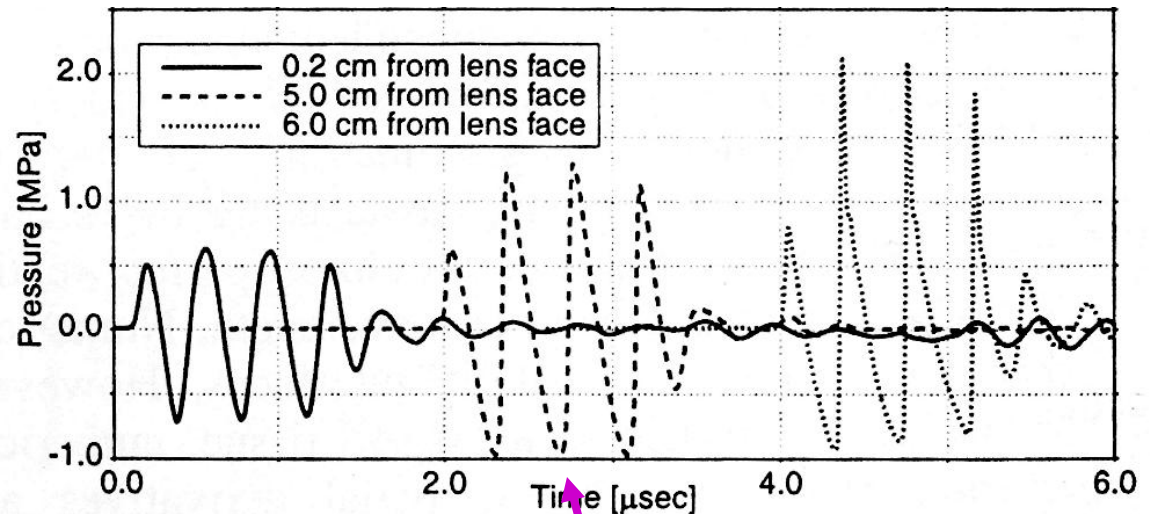
# Sound Velocity and Density Change

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

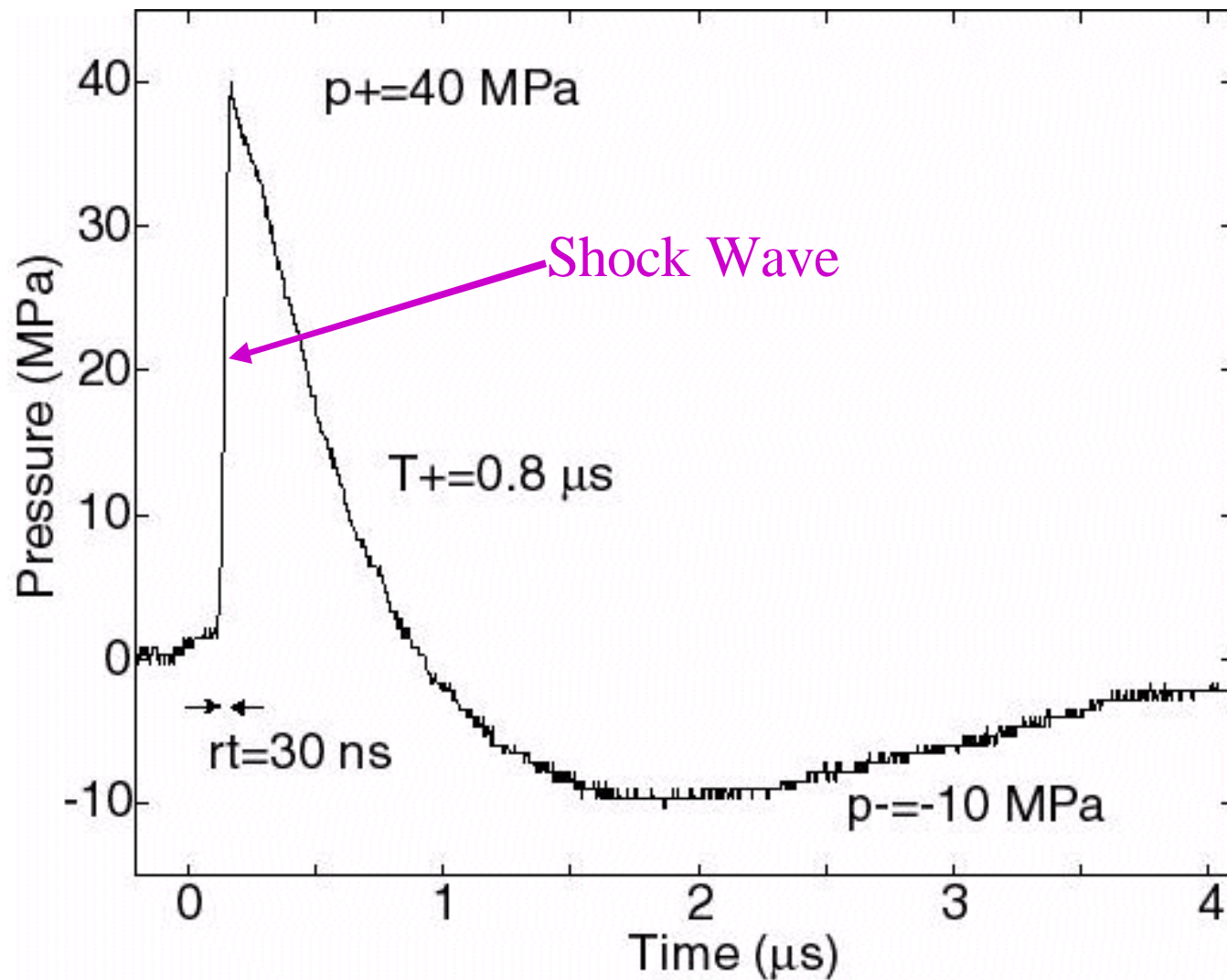
Phase velocity

Nonlinearity

Particle velocity



# When Peak Pressure Is Very High



# 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.

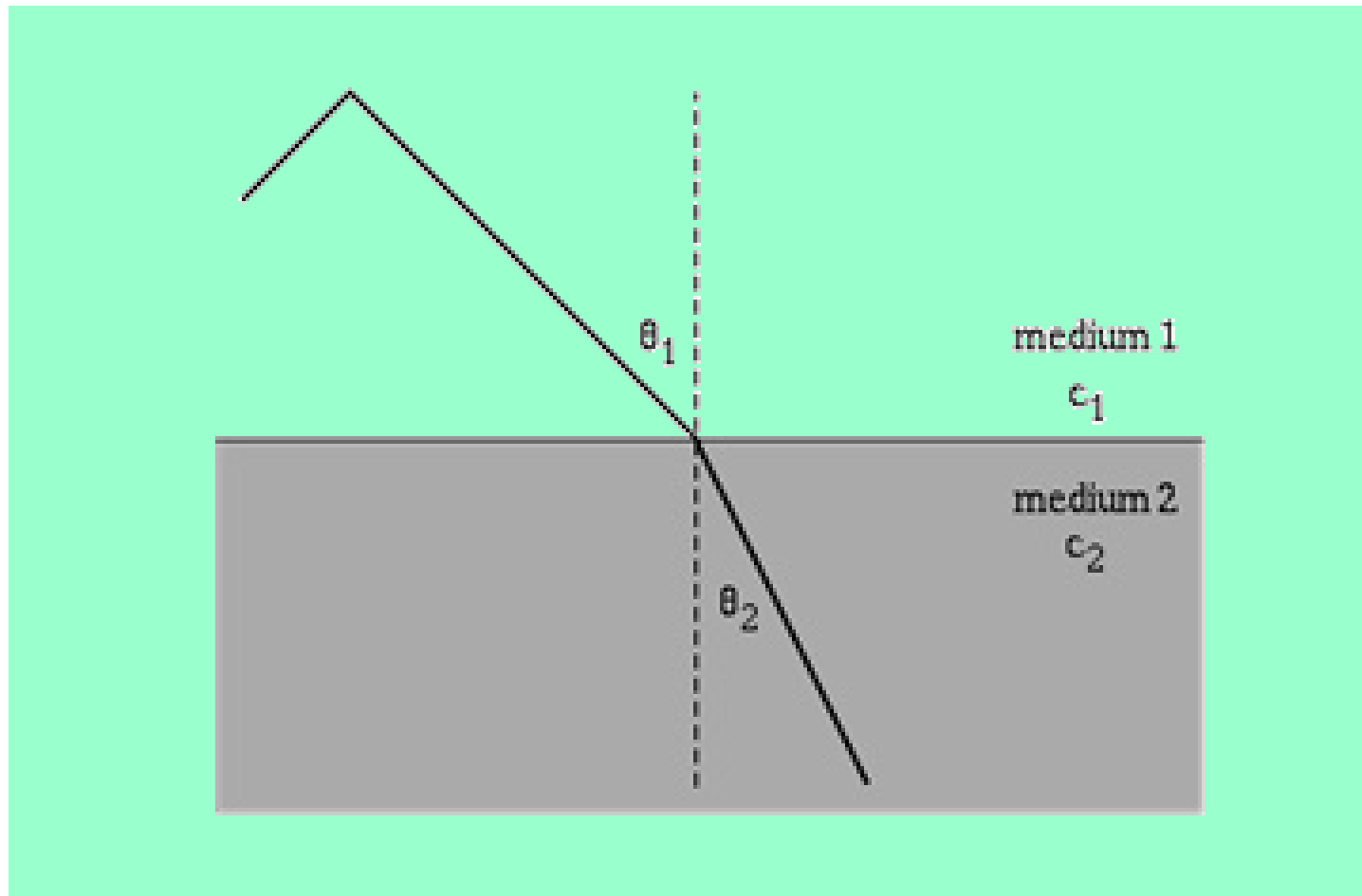
# Reflection

Low Density to High Density

High Density to Low Density

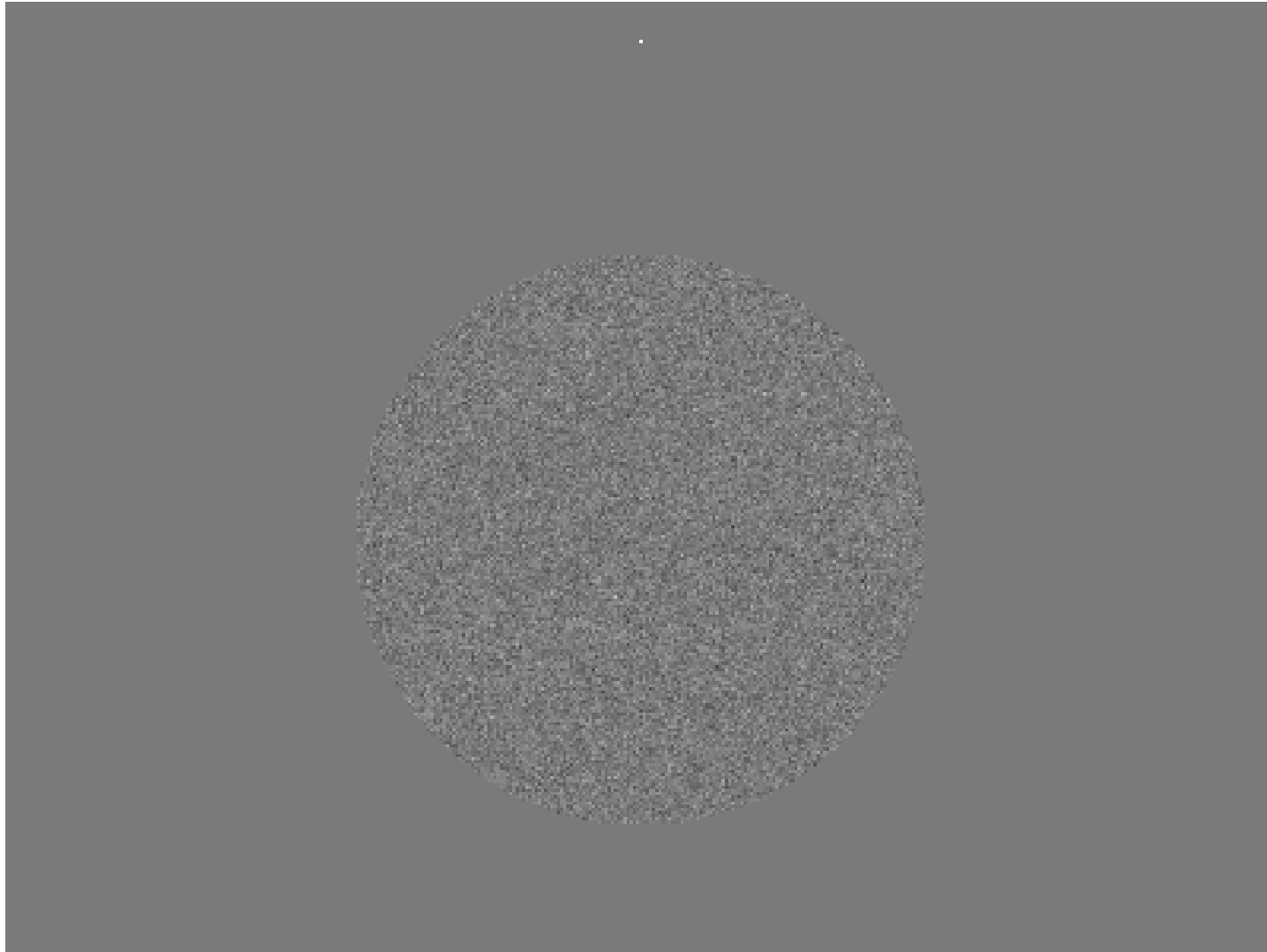


# Refraction

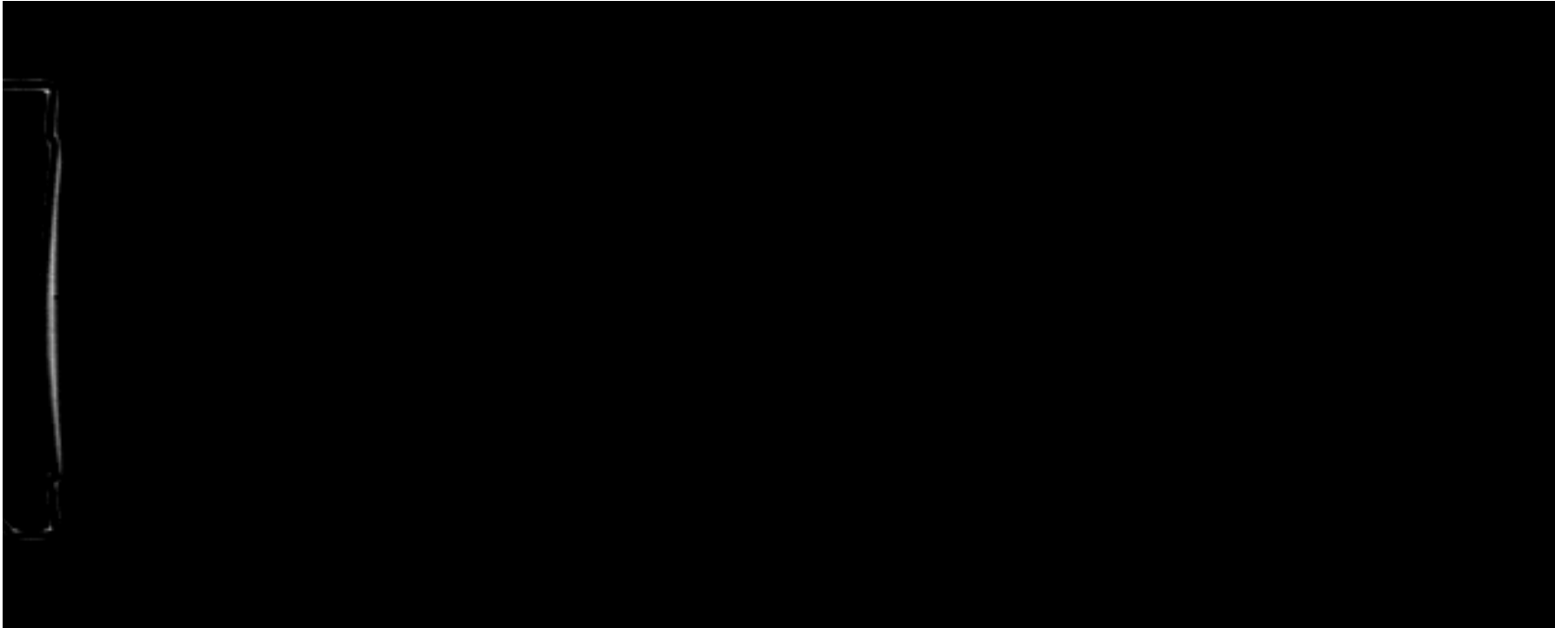




# Acoustic Scattering



# Diffraction



# Characteristics of Ultrasound

- Sound wave with frequencies higher than the audible range ( $>20\text{-}25\text{kHz}$ ):
  - Typical frequency range for biomedical applications:  $0.1\text{-}50\text{MHz}$ .
  - $c = f \cdot \lambda$ .
  - Sound (propagation) speed in soft tissues are around  $1500\text{m/sec}$ . 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 <sup>2</sup> -sec) <sup>a</sup>
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

<sup>a</sup> Rayl is a unit commonly used for acoustic impedance. One rayl = 1 kg/m<sup>2</sup>-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).

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

Characteristic impedance :  $Z_0 = \rho c$

**TABLE 9.3**

## REFLECTIVITY OF NORMALLY INCIDENT WAVES

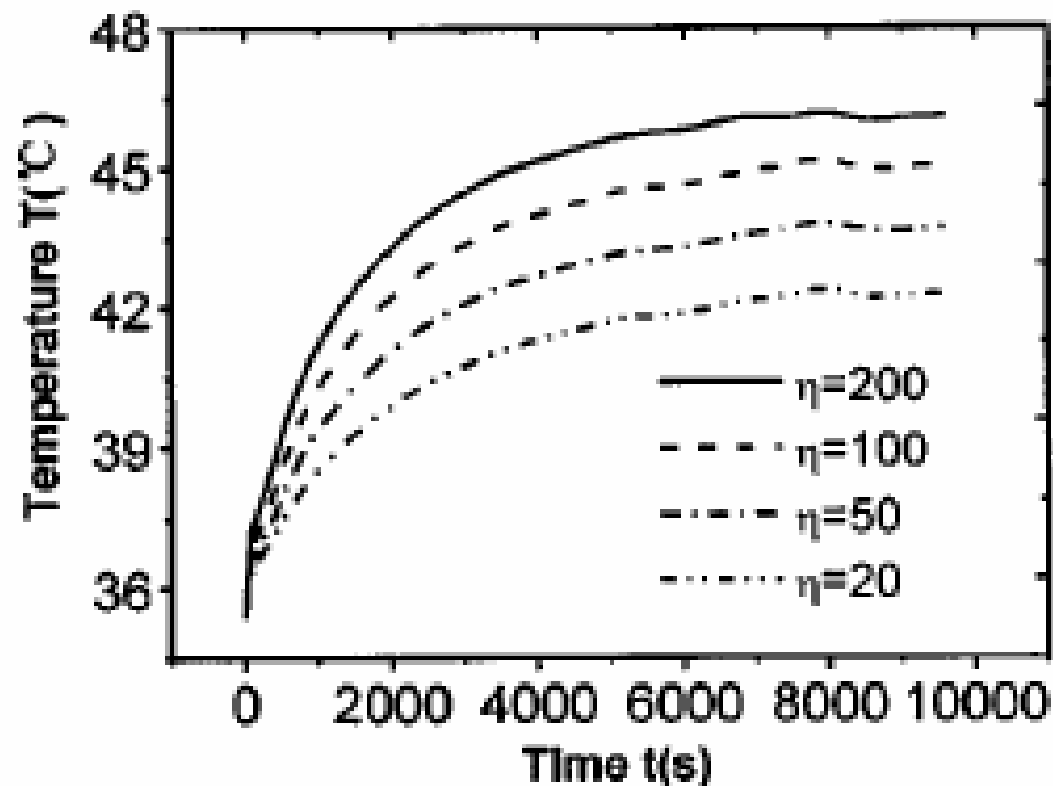
Materials at Interface	Reflectivity
Brain-skull bone	0.66
Fat-bone	0.69
Fat-blood	0.08
Fat-kidney	0.08
Fat-muscle	0.10
Fat-liver	0.09
Lens-aqueous humor	0.10
Lens-vitreous humor	0.09
Muscle-blood	0.03
Muscle-kidney	0.03
Muscle-liver	0.01
Soft tissue (mean value)-water	0.05
Soft tissue-air	0.9995
Soft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

# Bio-Effects

- Heating
- Cavitation

# Ultrasound Heating

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



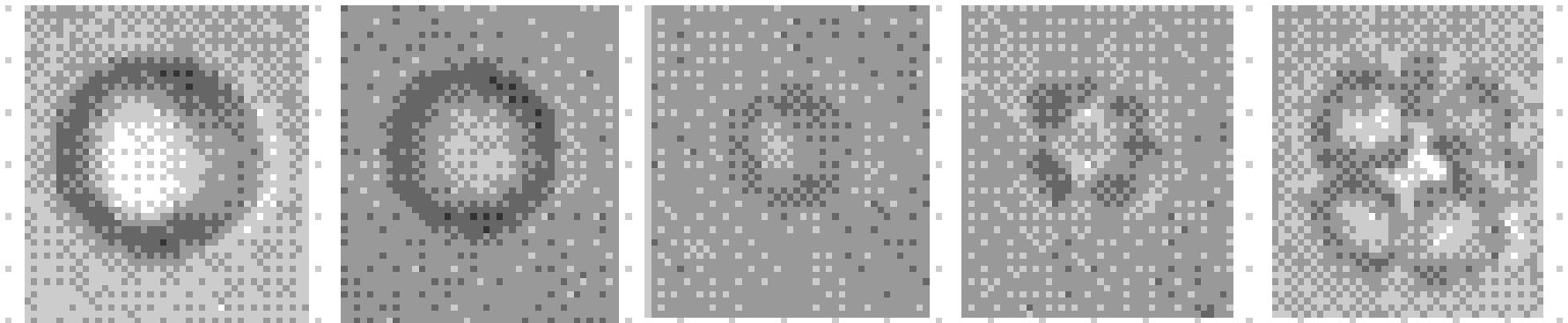


# Bio-Effects

- 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.

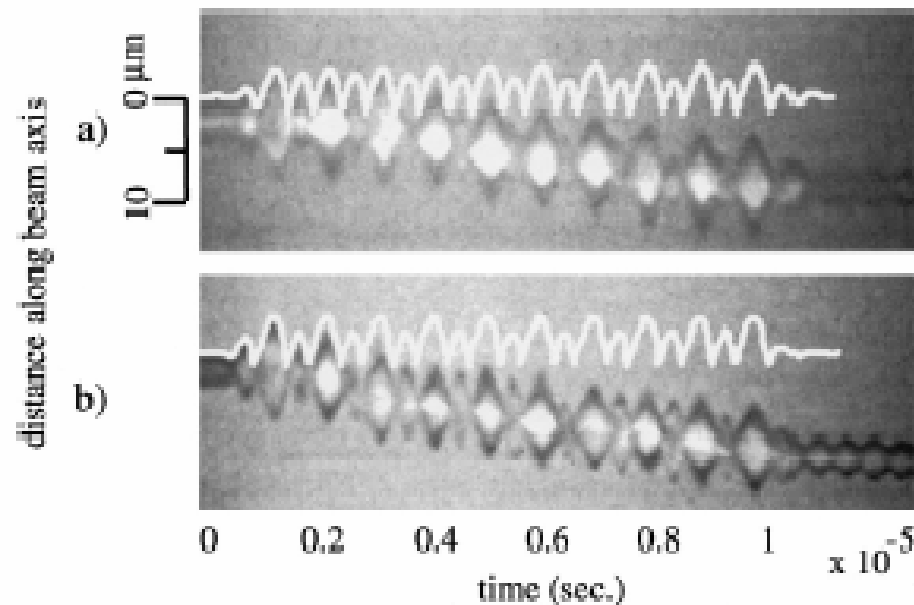


# Other Acoustic Phenomena

- 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.

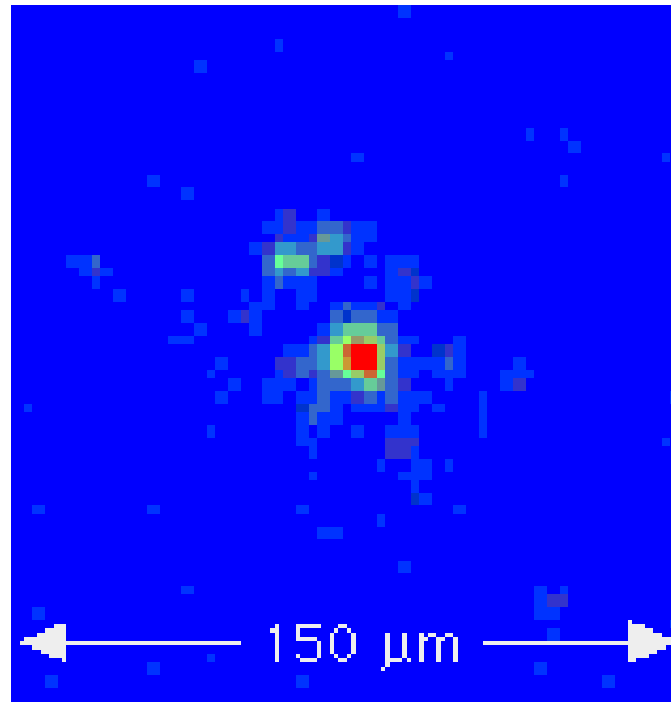


# Other Acoustic Phenomena

- Radiation force.
- Sonoluminescence.
- ...etc.

# Sonoluminescence

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



...,etc.

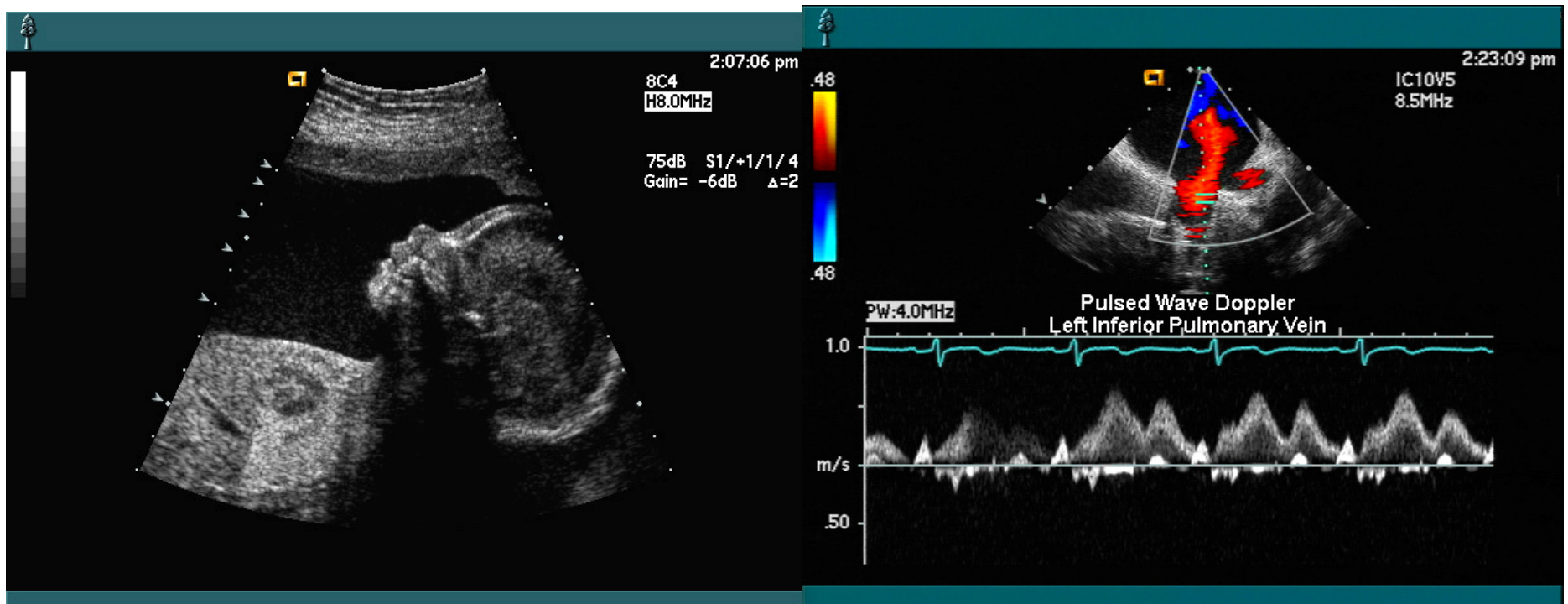
# What can ultrasound do in medicine and biology?



# Ultrasound in Medicine and Biology

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

# Ultrasonic Imaging



# Ultrasound in Medicine and Biology

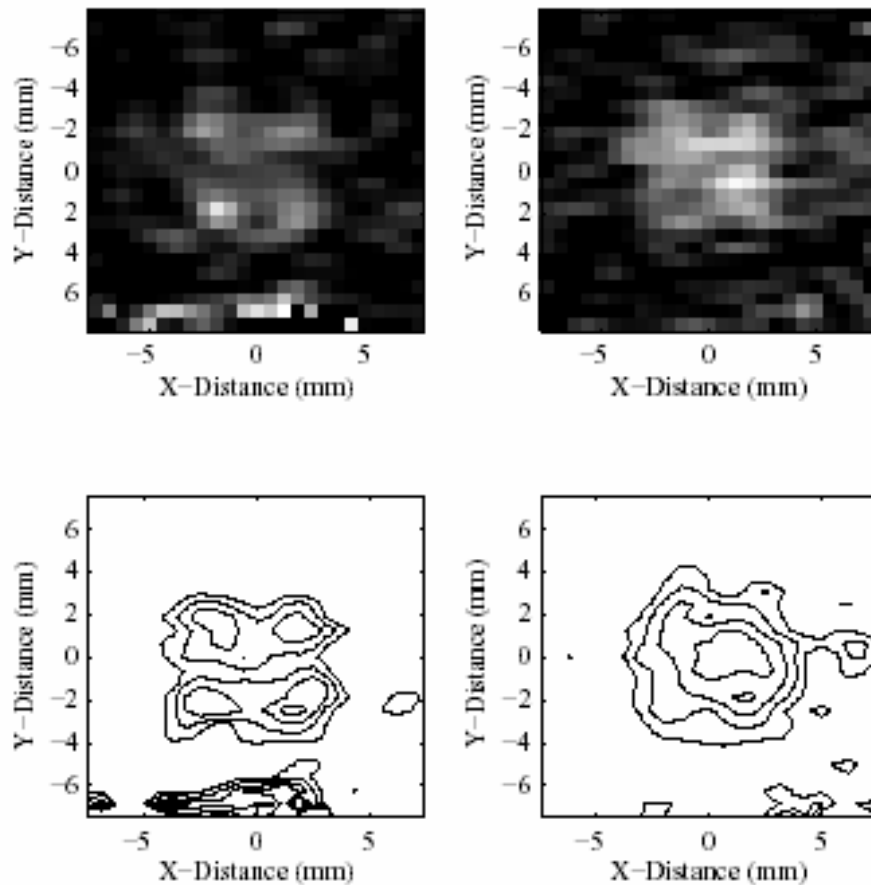
- Therapeutics:
  - Heat generation:
    - Hyperthermia.
    - HIFU.
  - Shock wave
    - Lithotripsy.
  - ...etc.

# Hyperthermia

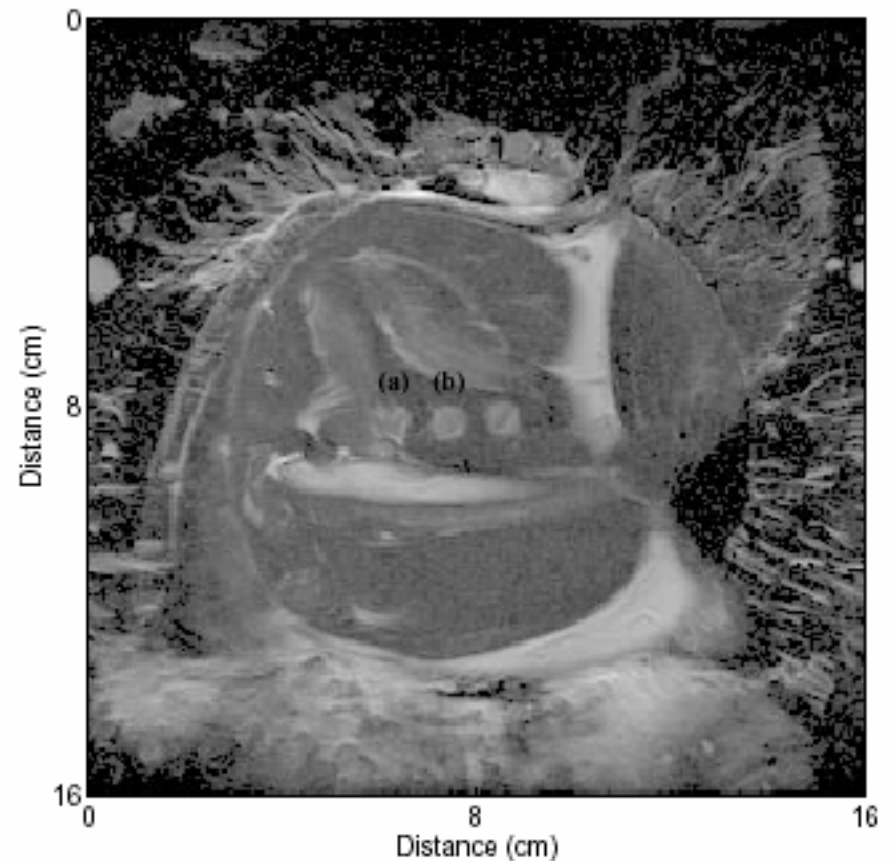
- Hyperthermia is a method of treating cancerous tissue by elevating the tissue temperature to 42.5 °C or above, and maintaining this for 30-60 minutes.



# Hyperthermia



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

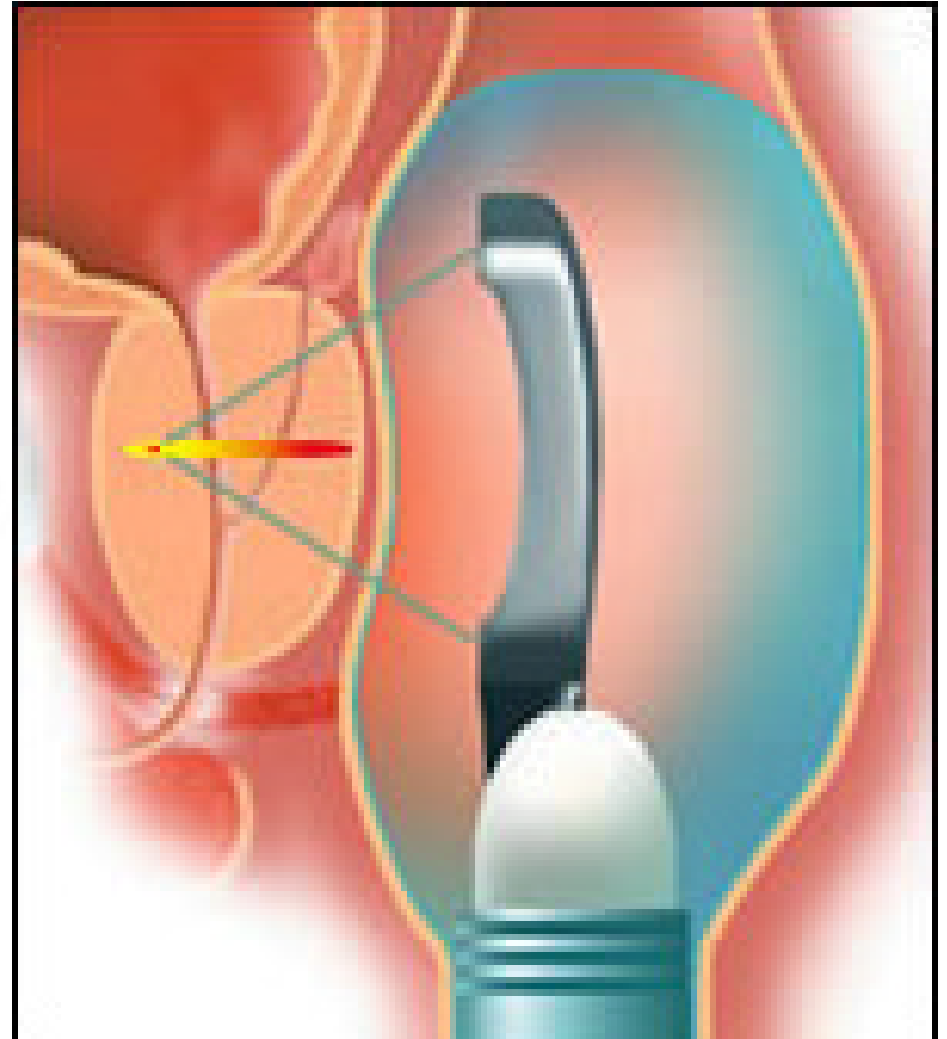


**Figure 4: T2 weighted image of thermal necrosis caused by (a) single four focus pattern and (b) switched focus pattern across axis.**

# 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



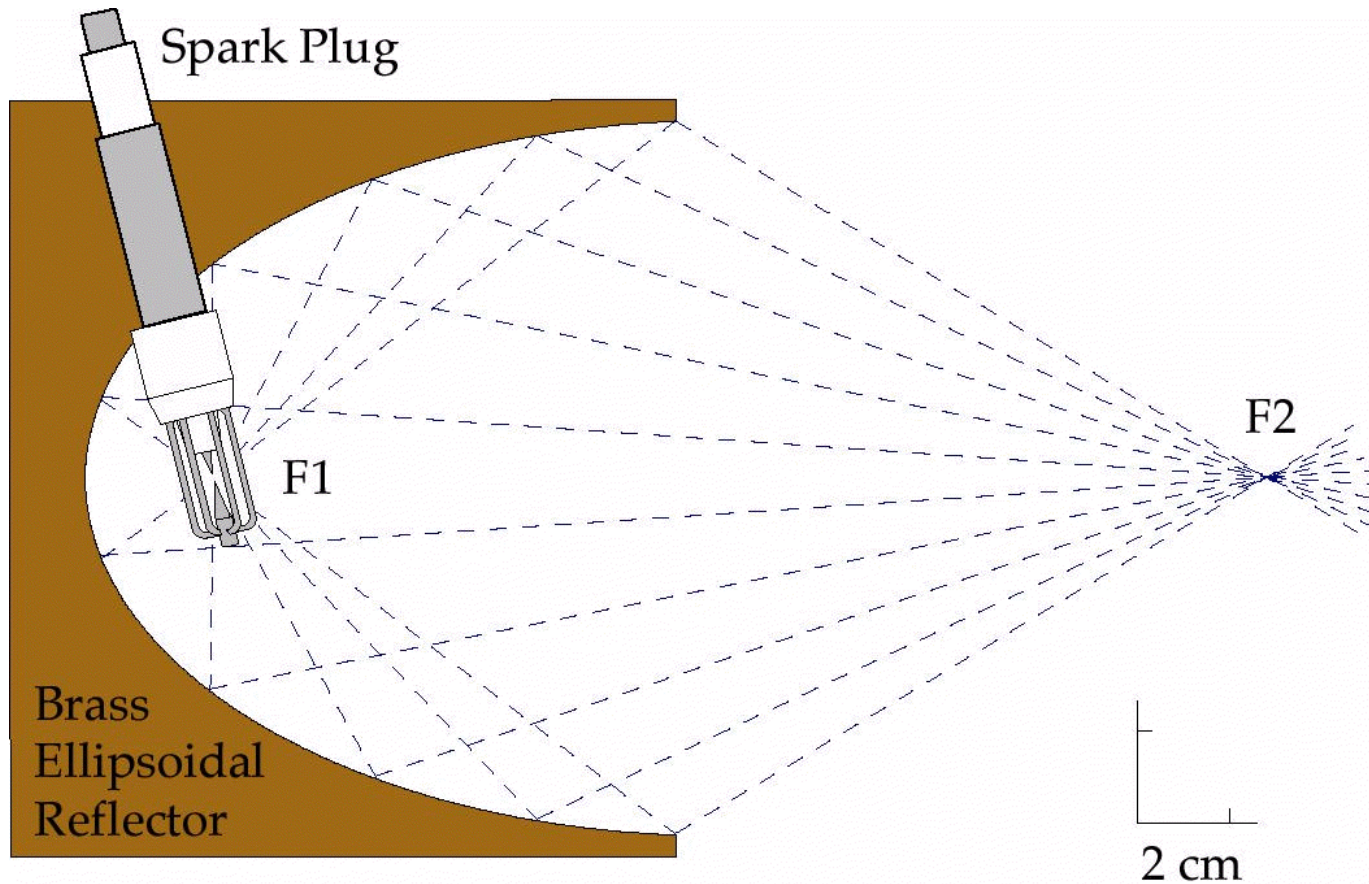


# Ultrasound in Medicine and Biology

- 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 characteristics.

# Bio-Effects

- Temperature rise and cell damage (cavitation).
- FDA Track I: Pre-amendments.
  - $I_{SPTA}$  (720 mW/cm<sup>2</sup>) and  $I_{SPPA}$  (190 W/cm<sup>2</sup>).
- FDA Track III:
- ALARA (as low as reasonably achievable).

# Bio-Effects

- Thermal index (TI):
  - TIS, TIB, TIC.
  - Analytical.
- Mechanical Index (MI):
  - Experimental.
  - Destruction of bubble with different sizes at various frequencies.



# Imaging and Focusing



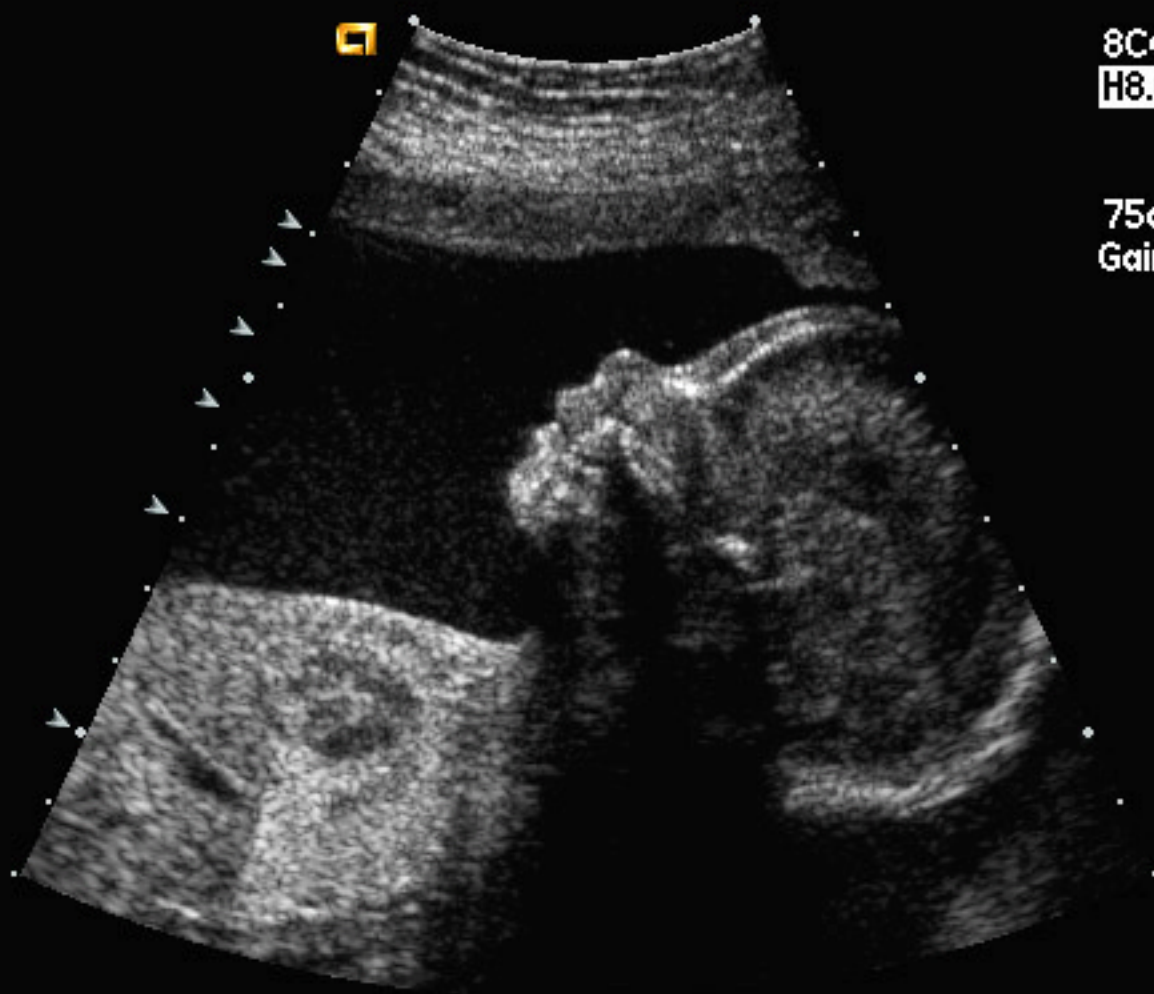
2:07:06 pm

8C4

H8.0MHz

75dB S1/+1/1/4

Gain= -6dB  $\Delta=2$





11:31:12 am

8V5

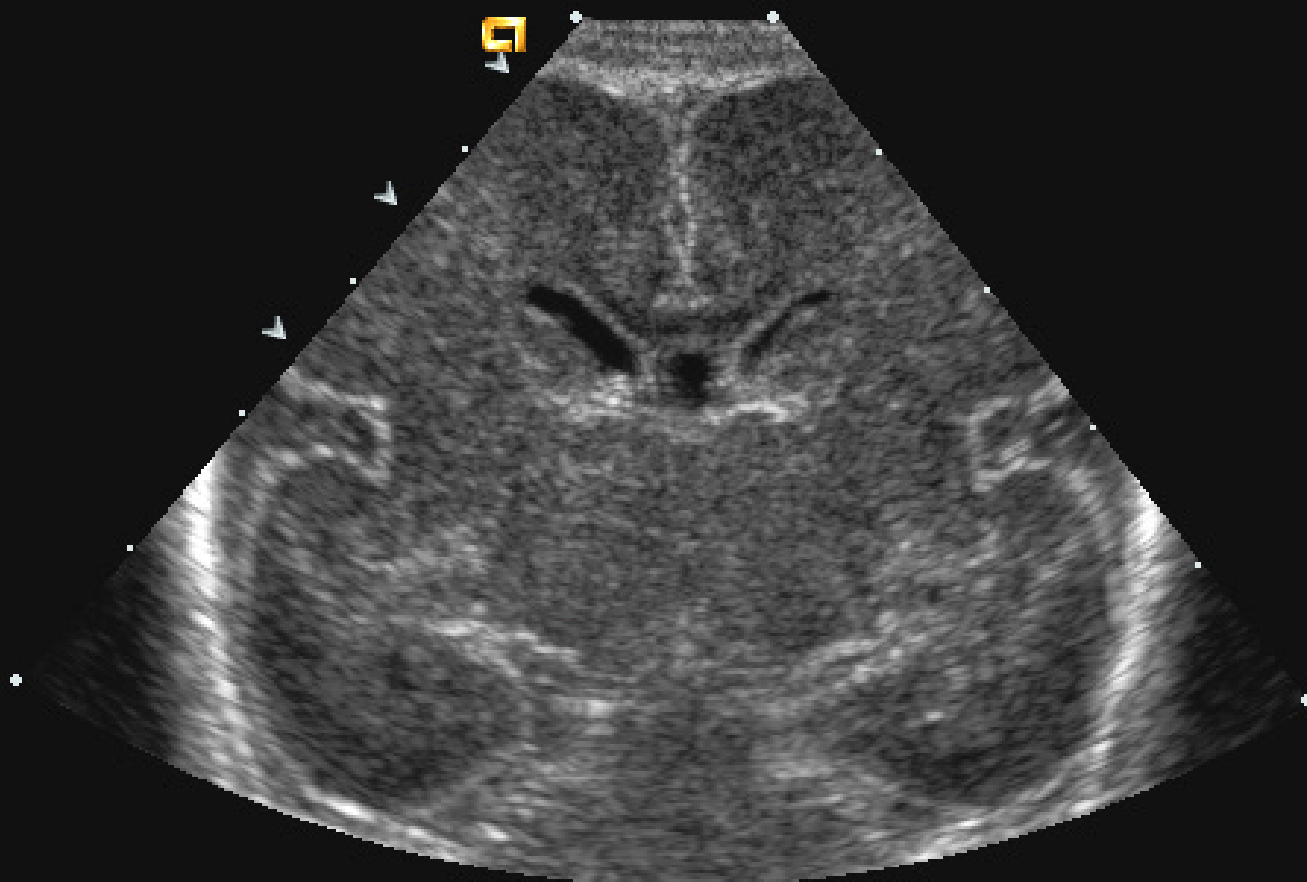
8.5MHz

20mm

NeoHead

85dB S1/+1/3/2

Gain= 0dB  $\Delta=2$





10:37:54 am

15L8w

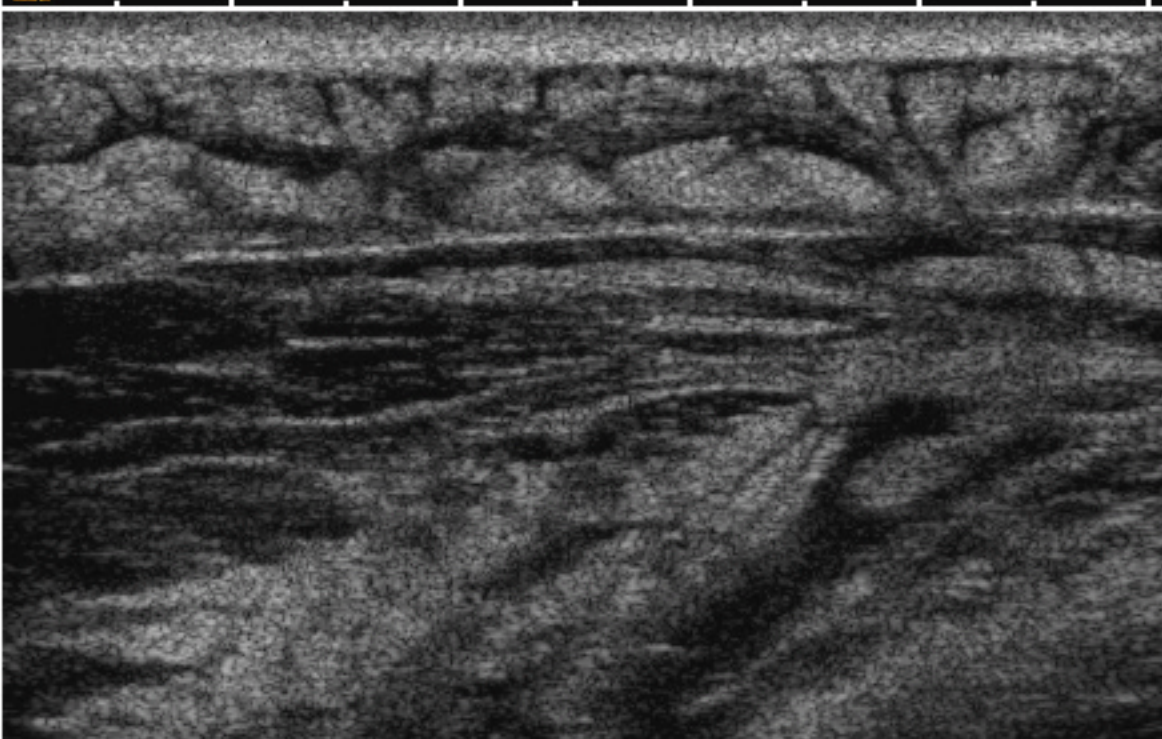
13.0MHz

30mm

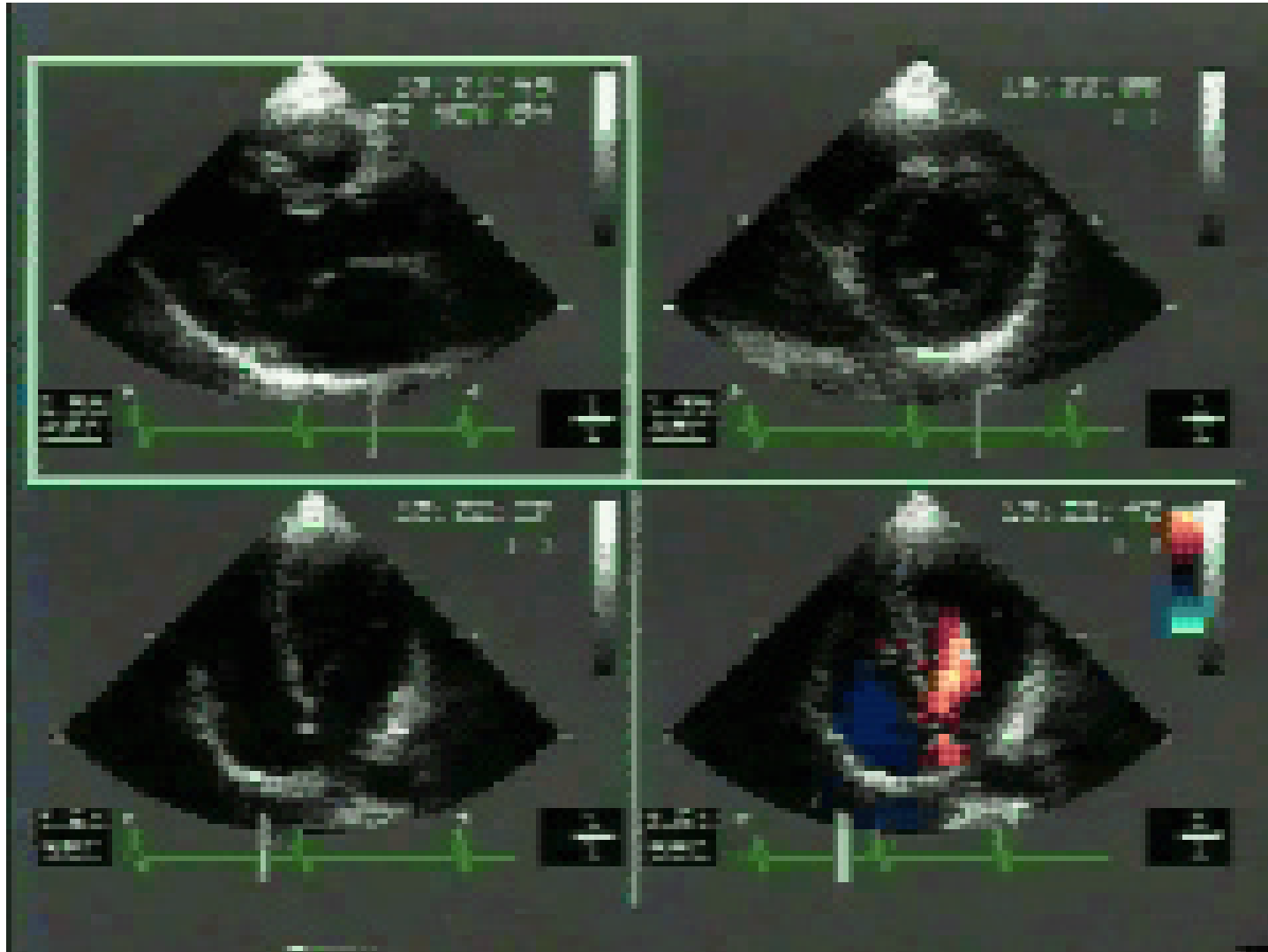
ABD

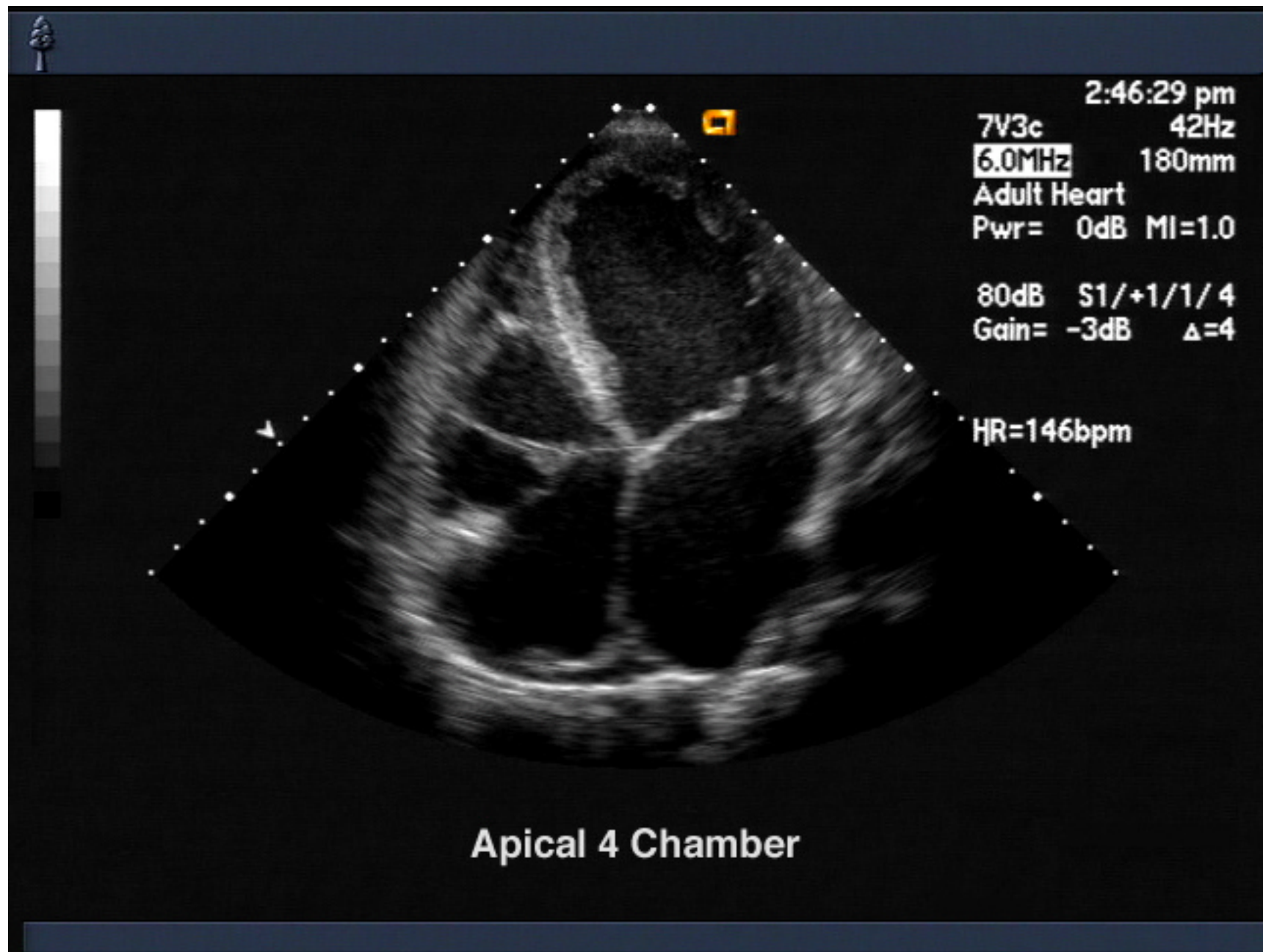
85dB S1/+2/2/4

Gain= -5dB  $\Delta=2$

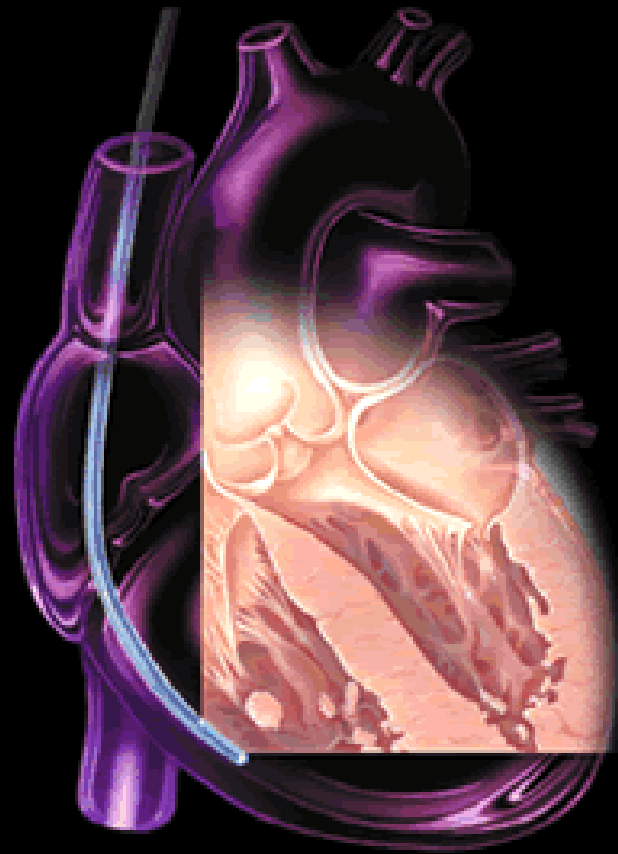
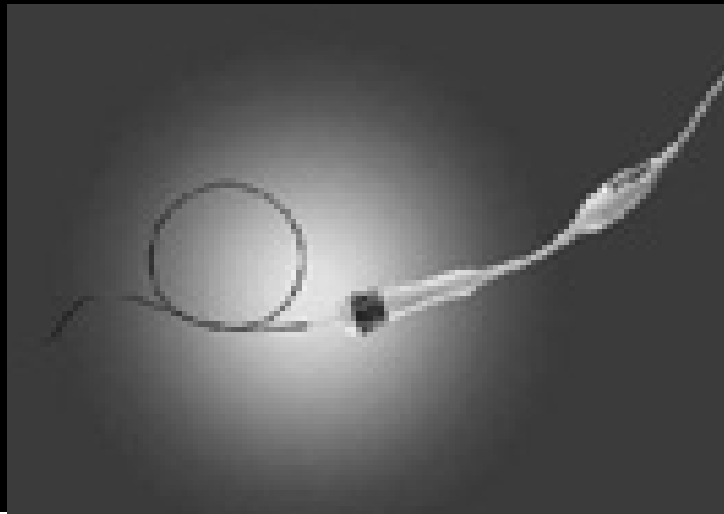


# Real-Time Imaging

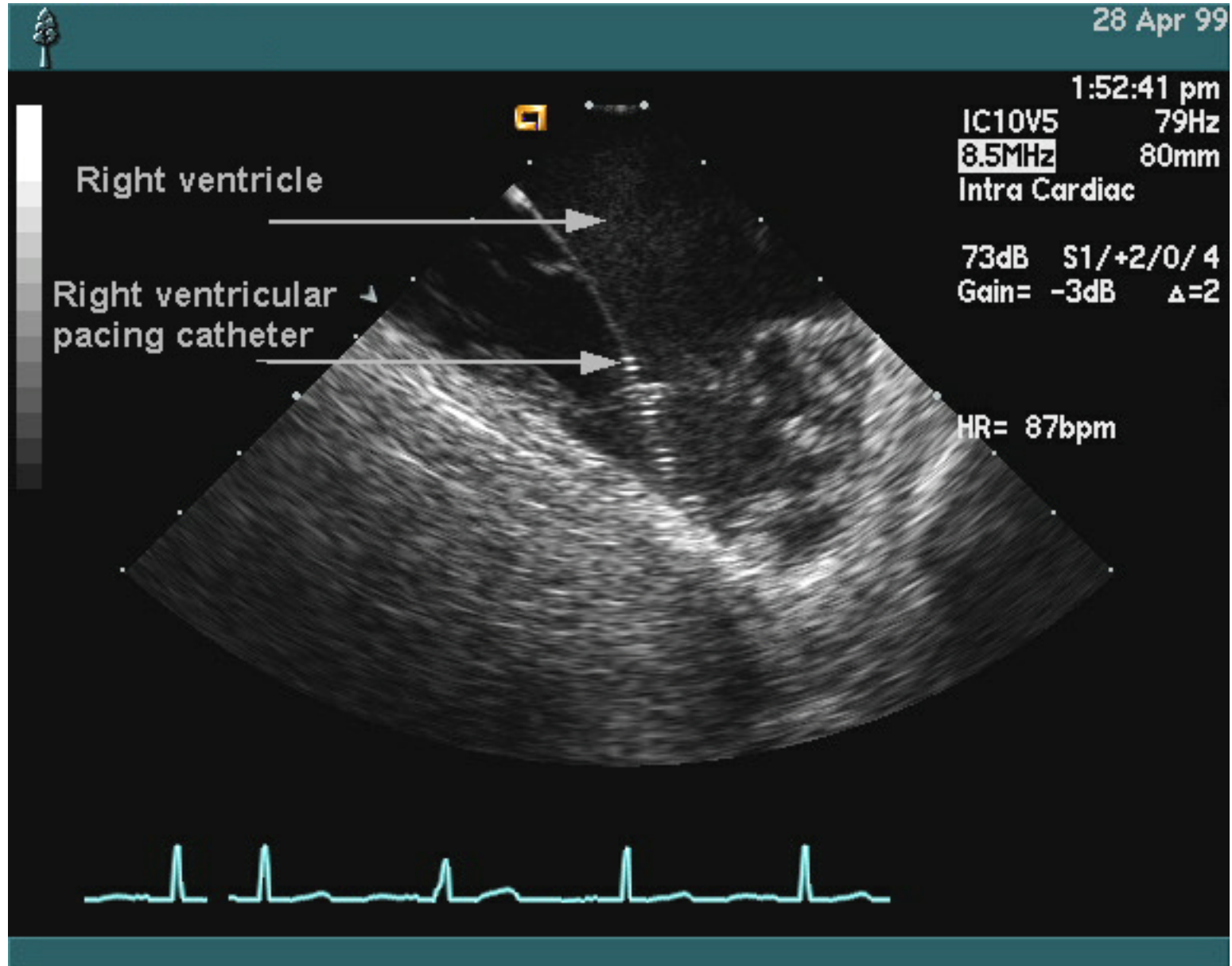




# The **AcuNav** Diagnostic Ultrasound Catheter

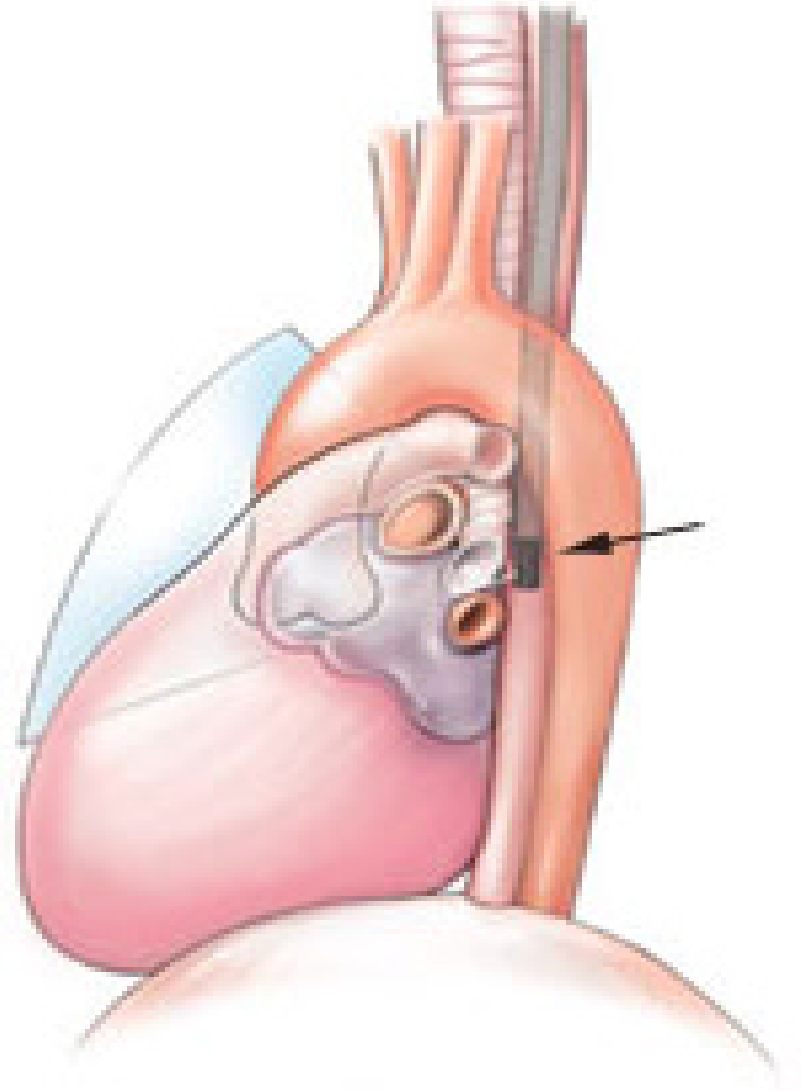
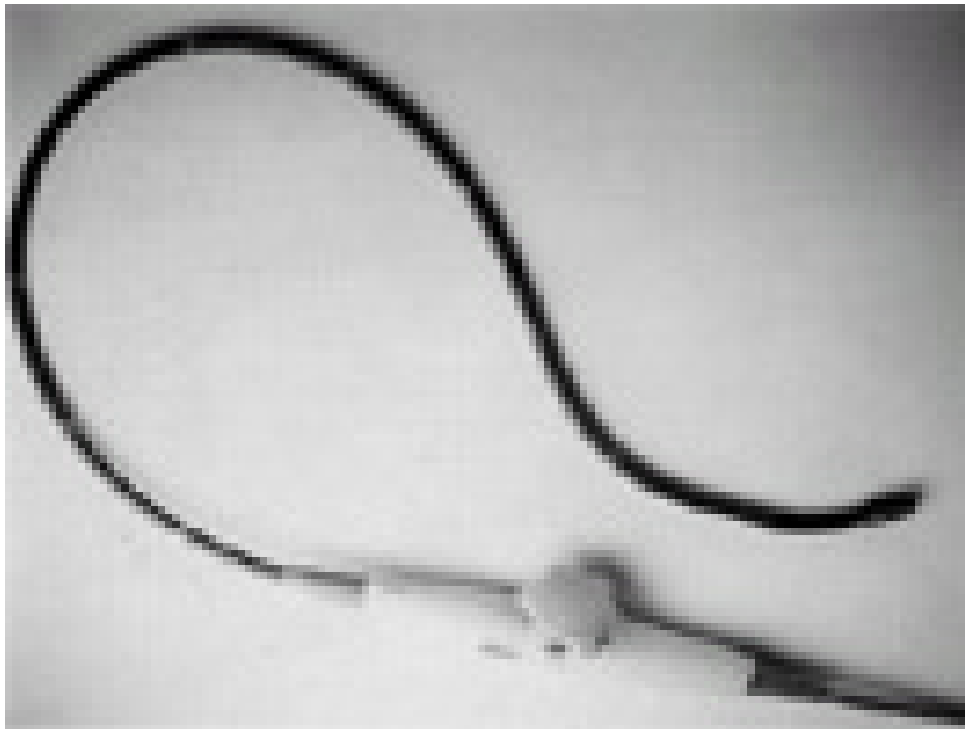


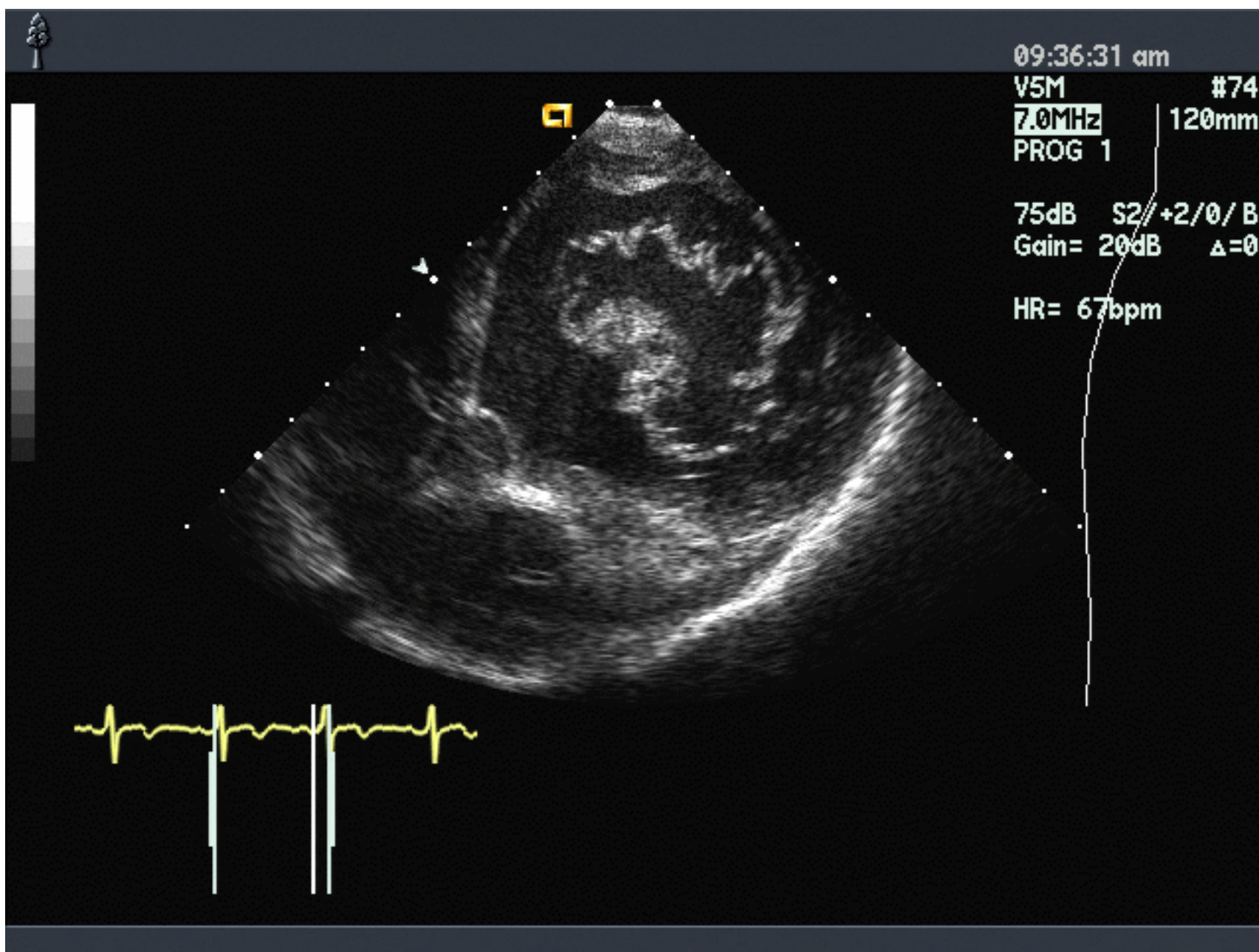




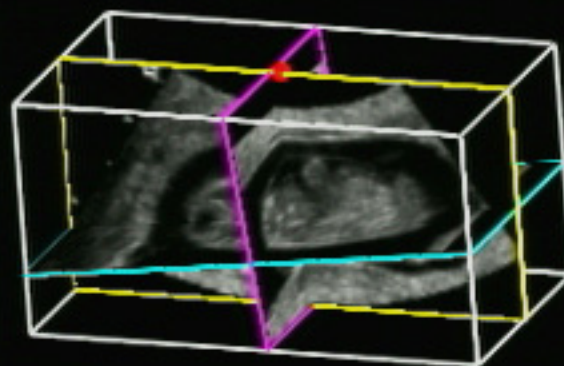
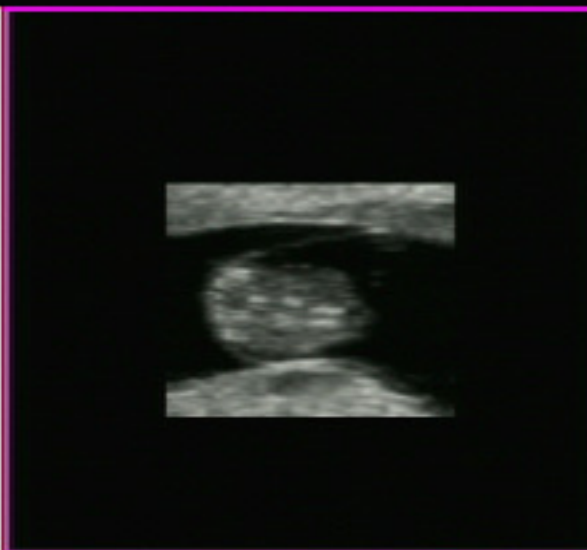


# TransEsophageal Echocardiogram (TEE)









Set ROI



View 3D

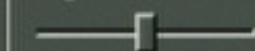


View Planes

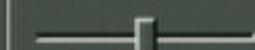
R



Brightness



Contrast



Slice Thickness



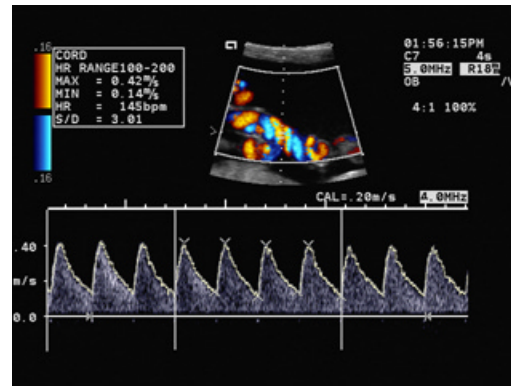
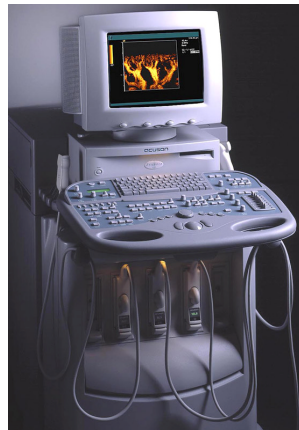
☒ Link Planes

☐ Show Overlays

8 Week Fetus

Works-in-Progress

# Clinical Applications



(From [www.acuson.com](http://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.

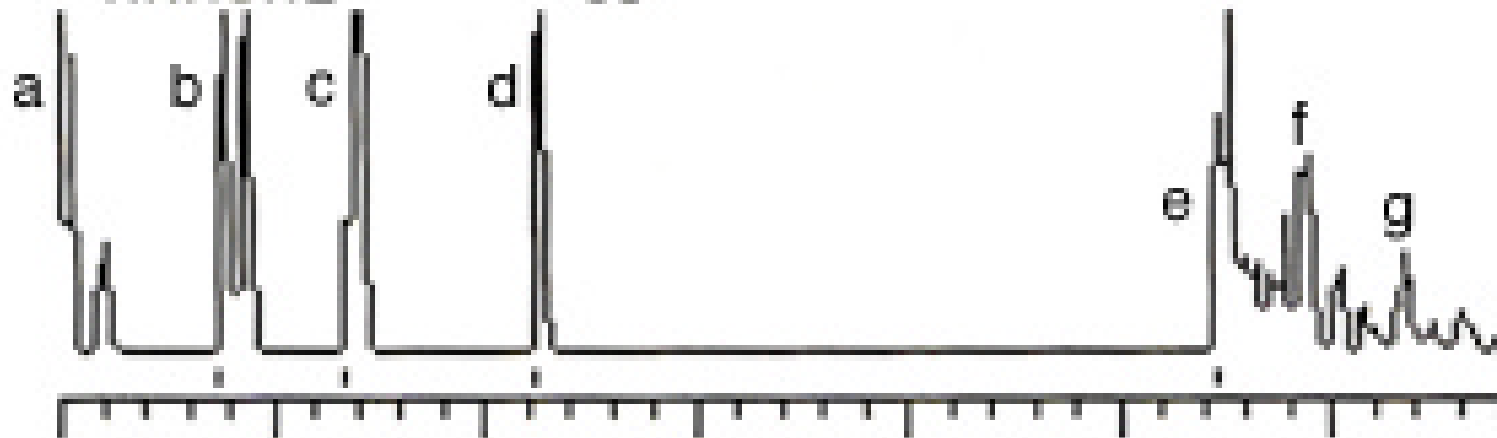
# Function Modes

- 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)

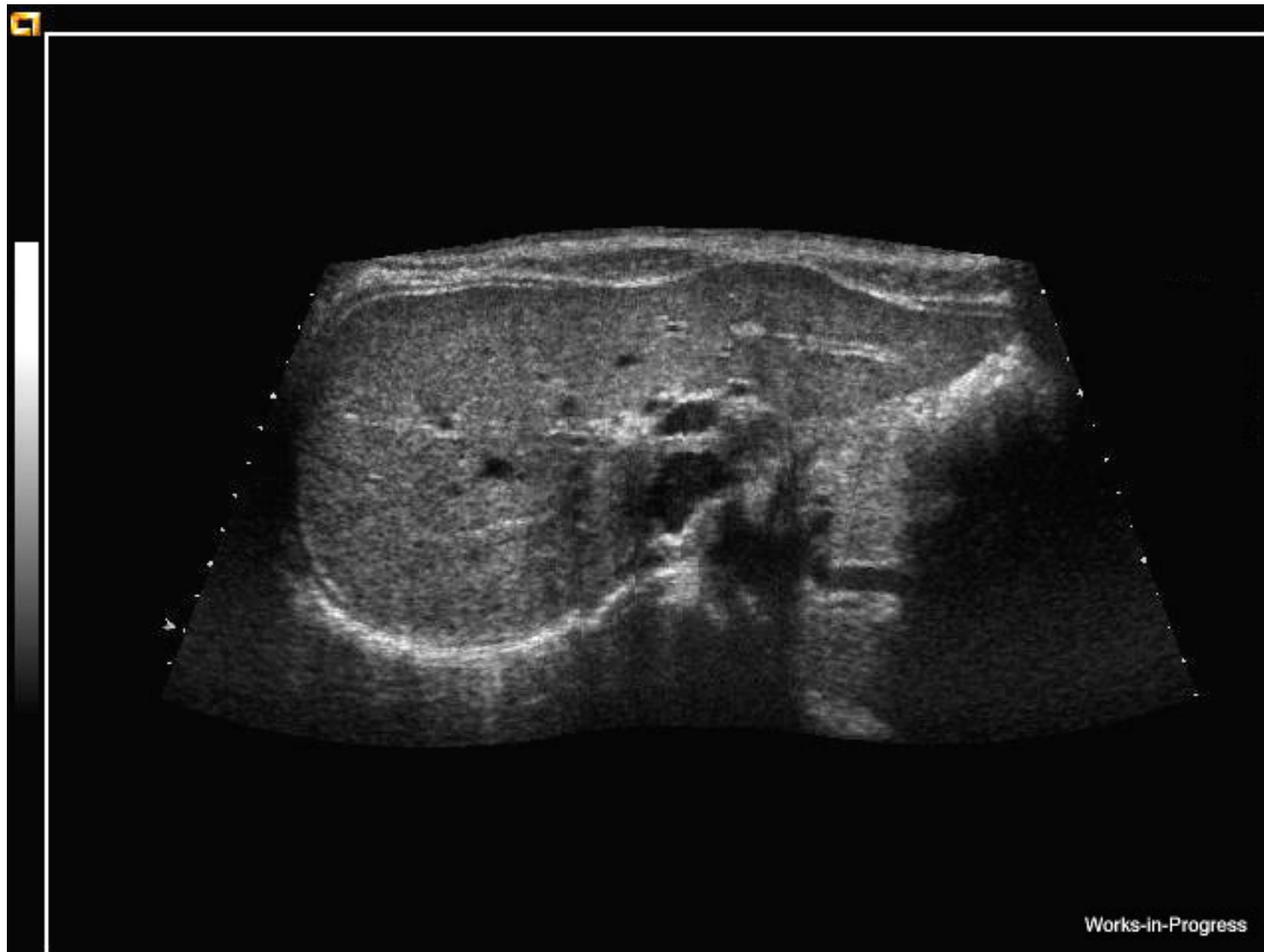
B I O M E T R Y   M O D E  
09:56 AM                      06-07-00  
PATIENT:  
U: A 1532 L 1641 P 1532

LT     4.92                      70%  
ACD   3.06     AL 2 3.3 1       GAIN  
CUSTOM VELOCITY               RECORD 01  
MANUAL                      OD



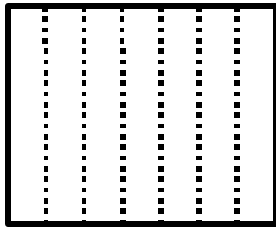


# B-Scan (Brightness, 2D)



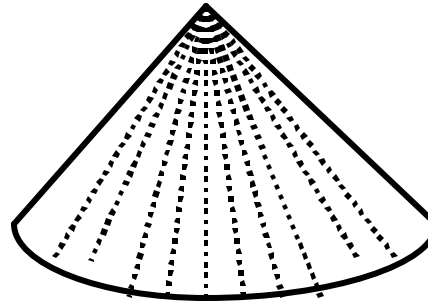
# 2D Scan Formats

linear



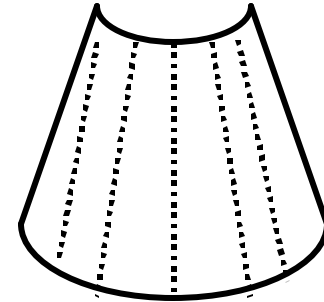
easy access  
limited view

sector



limited access  
wide view

curved linear

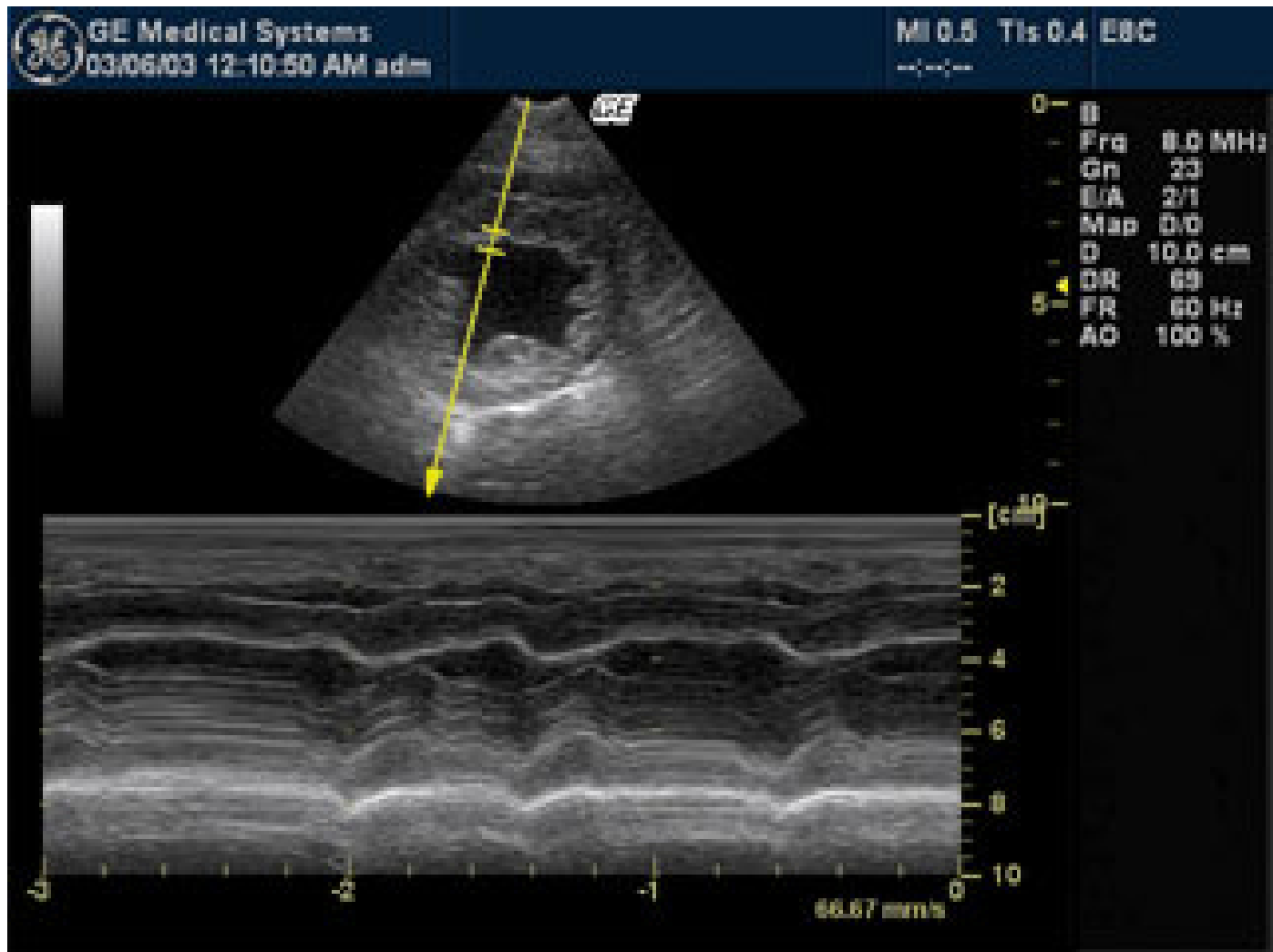


easy access  
wide view

# 3D Ultrasound



# M-Mode (Motion)

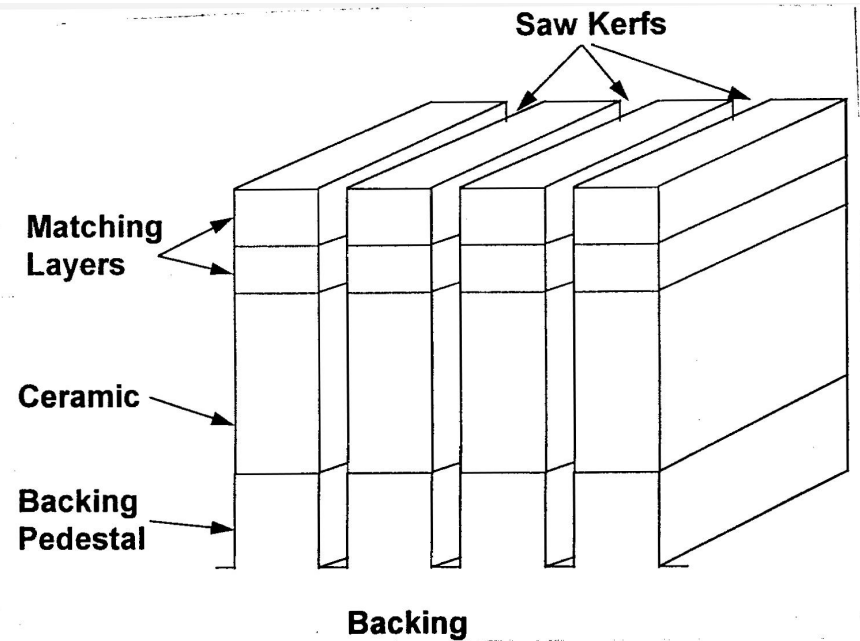


# Transducers: Generation and Detection of Sound Waves

# Ultrasonic Array Transducers



(From [www.acuson.com](http://www.acuson.com))

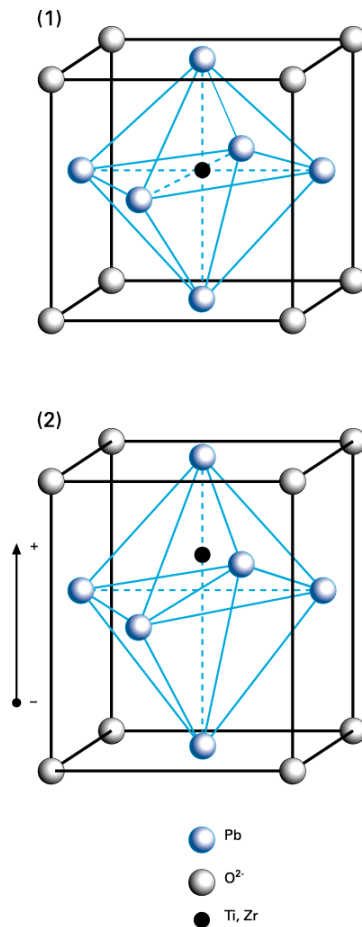


# Transducer

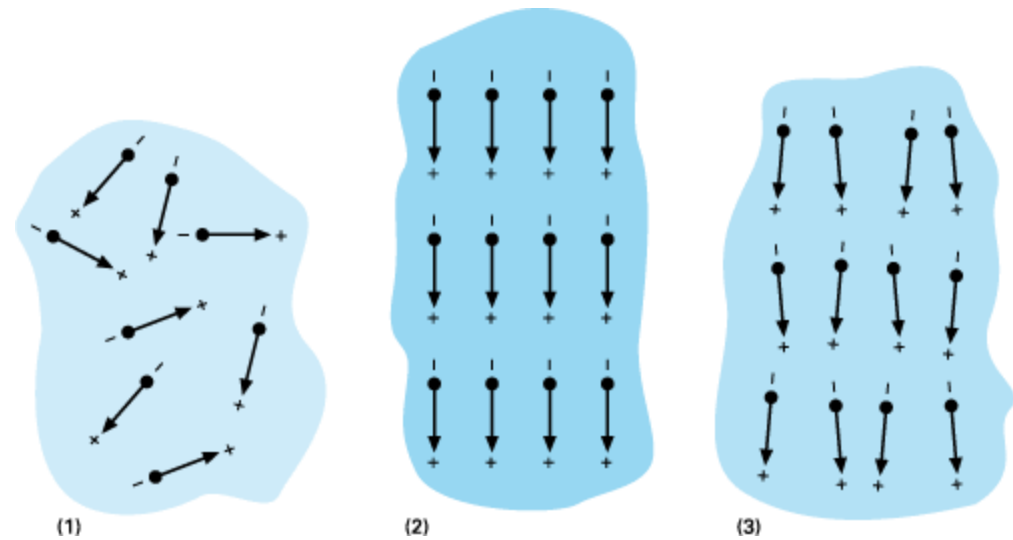
- Energy conversion: electrical ? mechanical.
- Generation and detection (speaker and microphone).
- Medical ultrasound: same device in MHz range.
- Piezoelectricity: electrical polarization ? mechanical strain.
- PZT, PVDF and composite materials are commonly used.

# Piezoelectricity

## Anisotropy



## Poling



Curie temperature: 320<sup>0</sup> – 370<sup>0</sup>C.

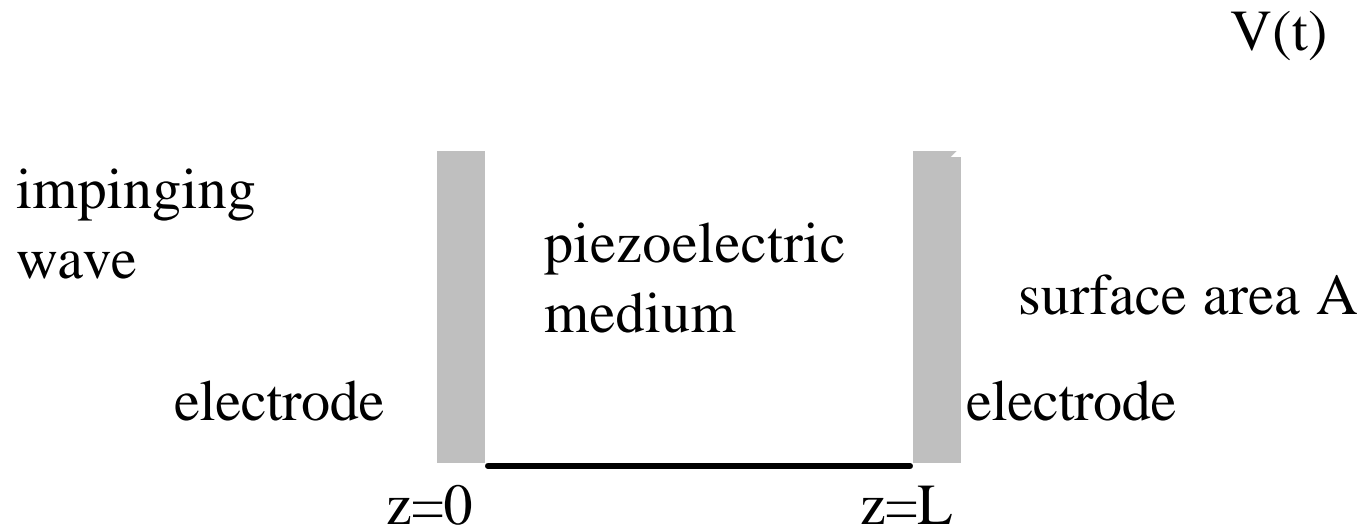


# Piezoelectricity

$e$ : Piezoelectric  
stress constant

# Detection of Ultrasound

- Reciprocal to generation.



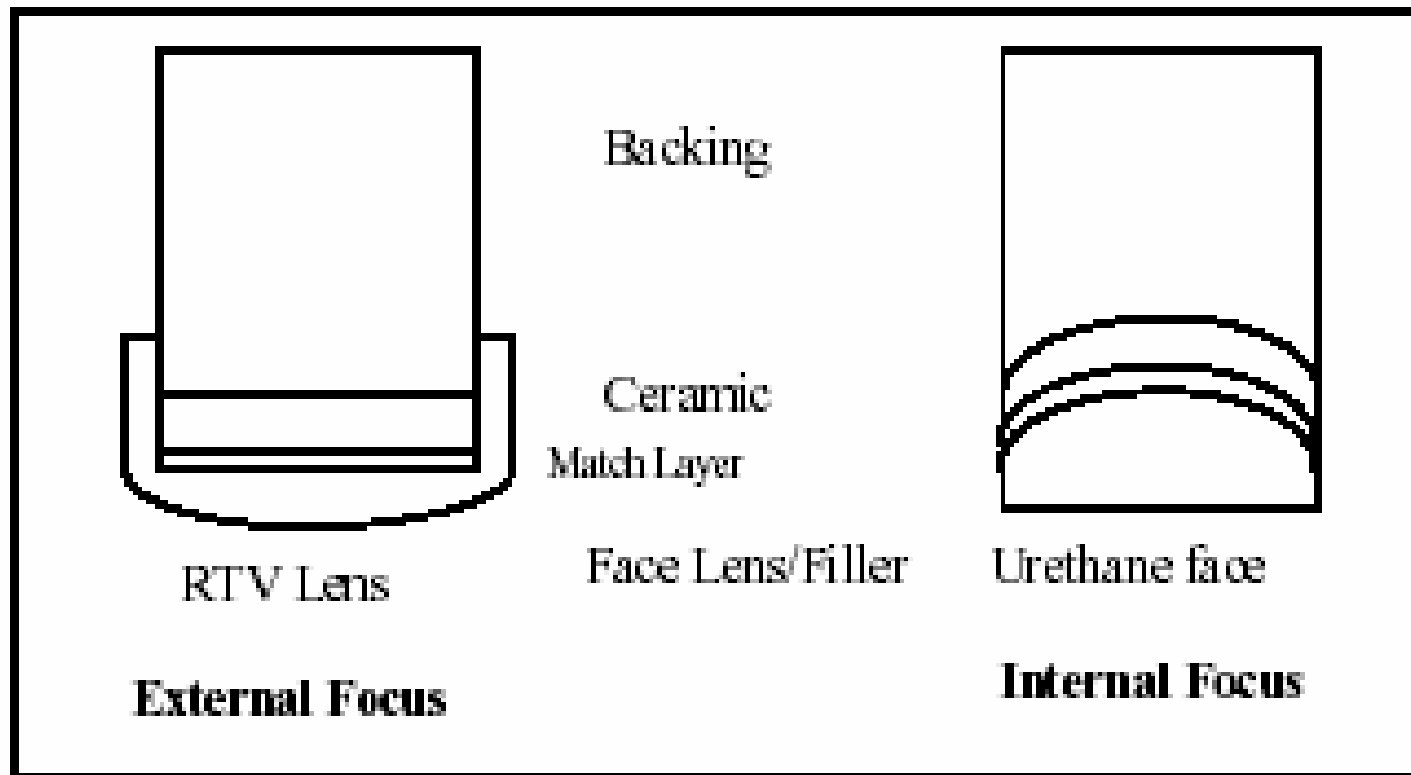
# Design Considerations

- Bandwidth and sensitivity.

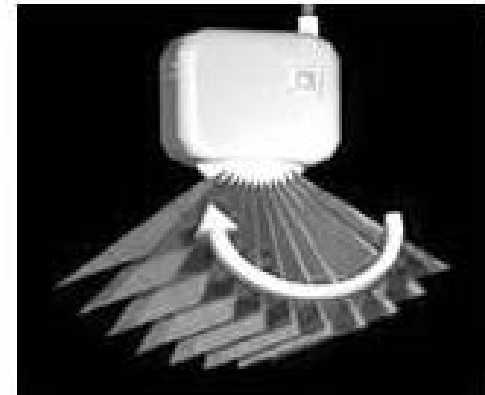
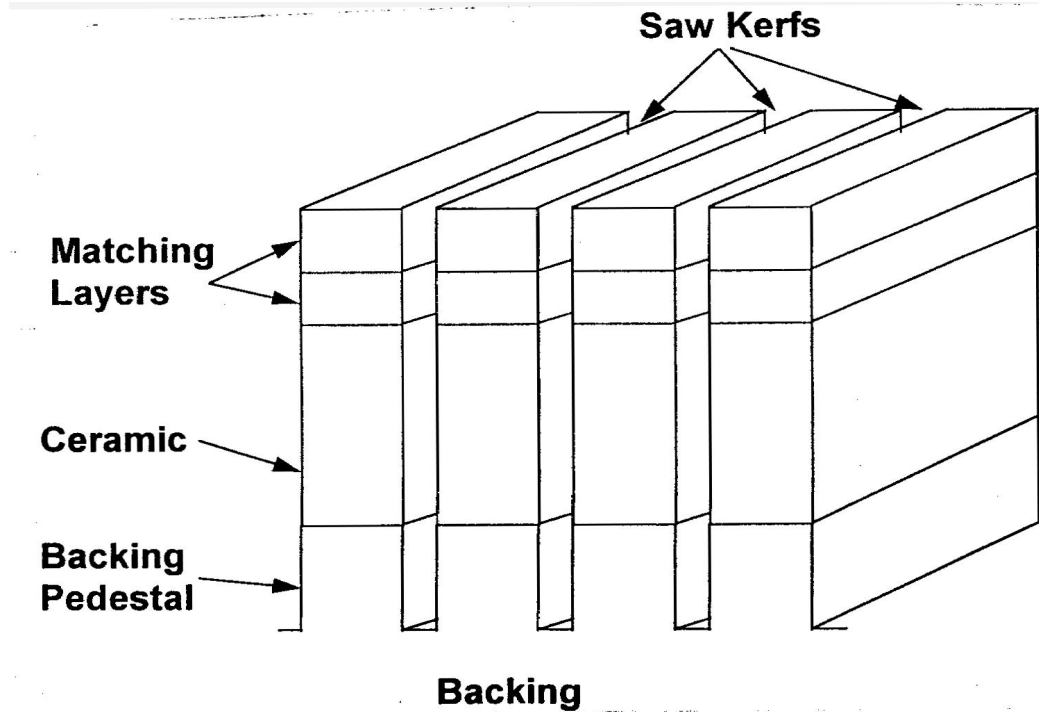
Ring down

# Acoustic Lens

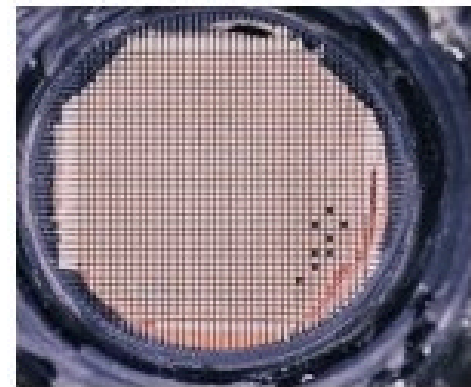
- Fixed geometric elevational focusing.



# 1-D and 2-D Arrays



Hand-held 3-D probe from Kretztechnik

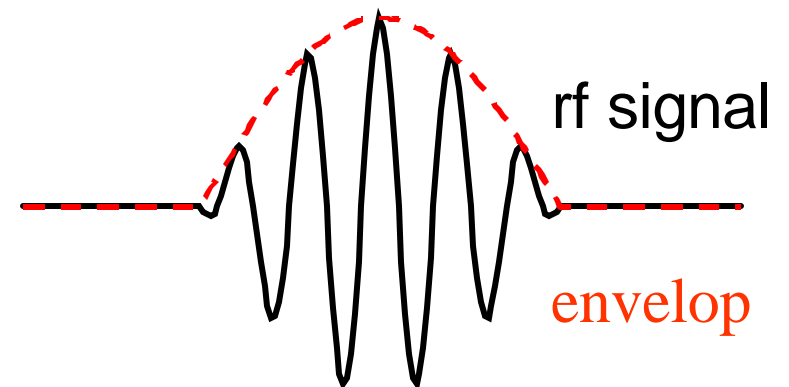
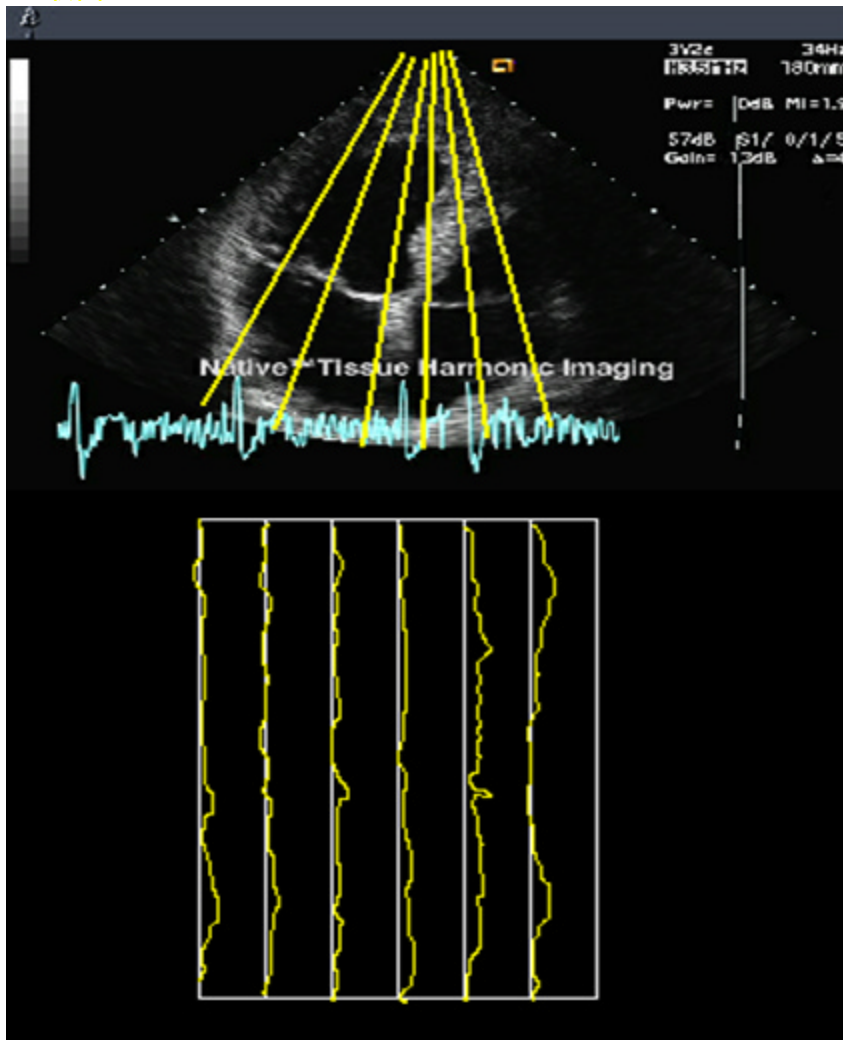


2-D matrix-array at Duke

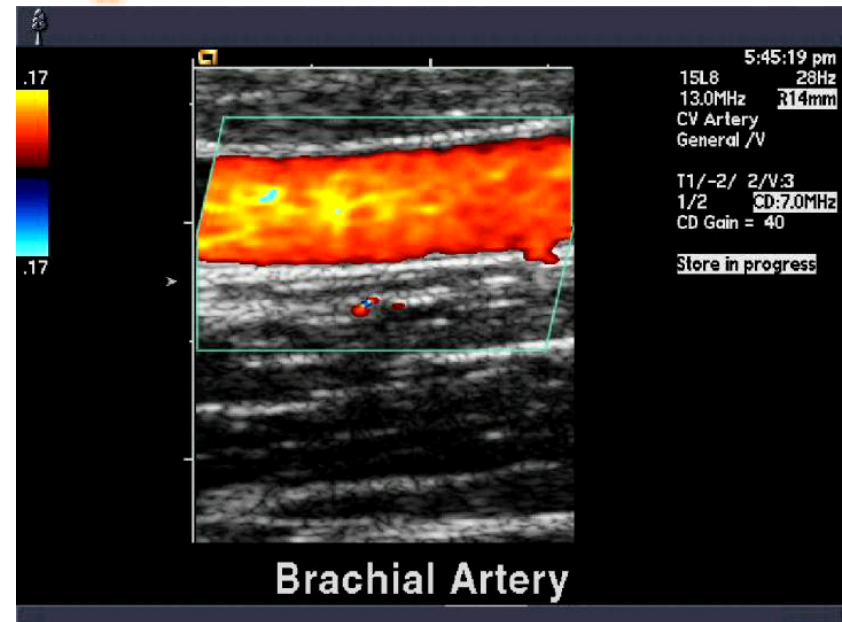
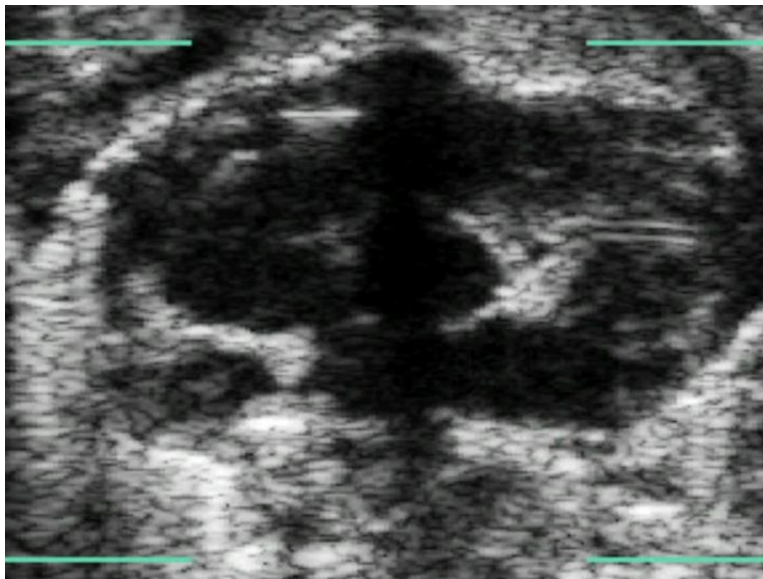
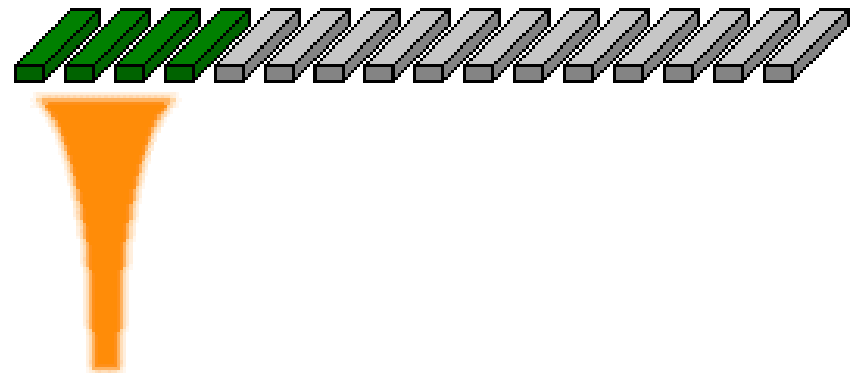
# Focusing and Diffraction

# B-mode Imaging

取自 [www.acuson.com](http://www.acuson.com)



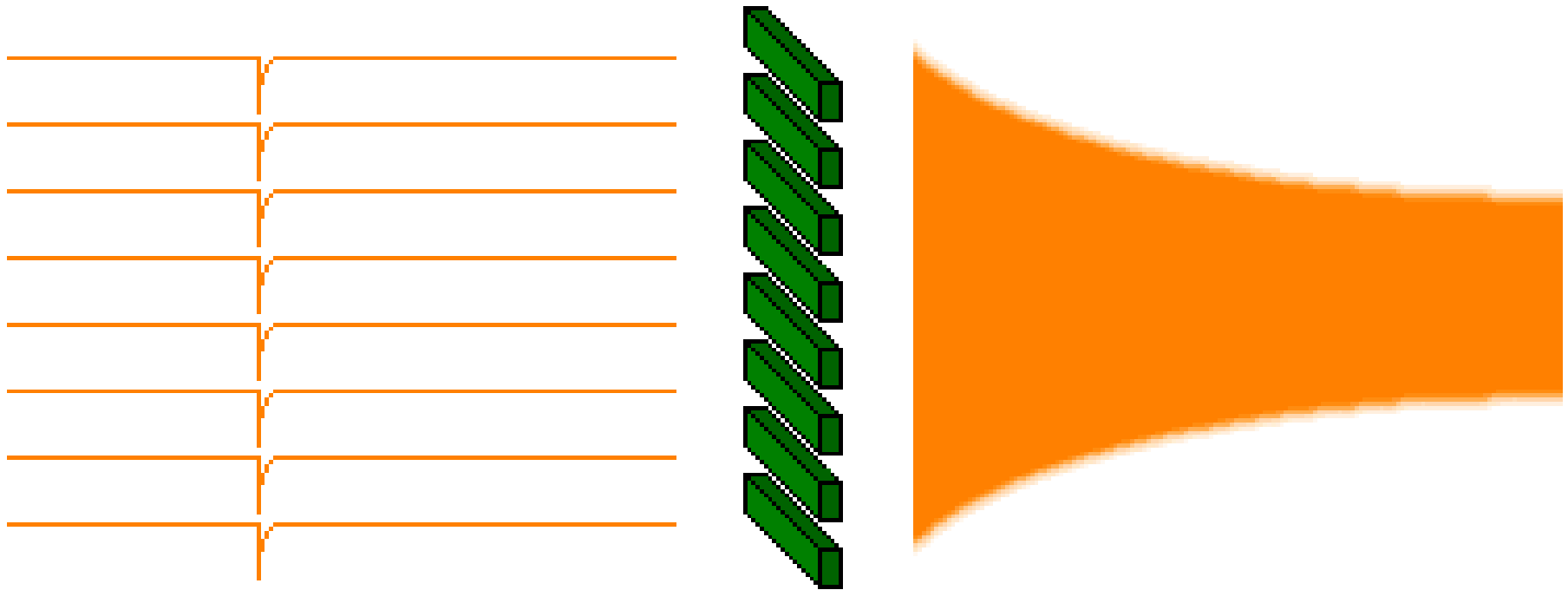
# Linear Scanning



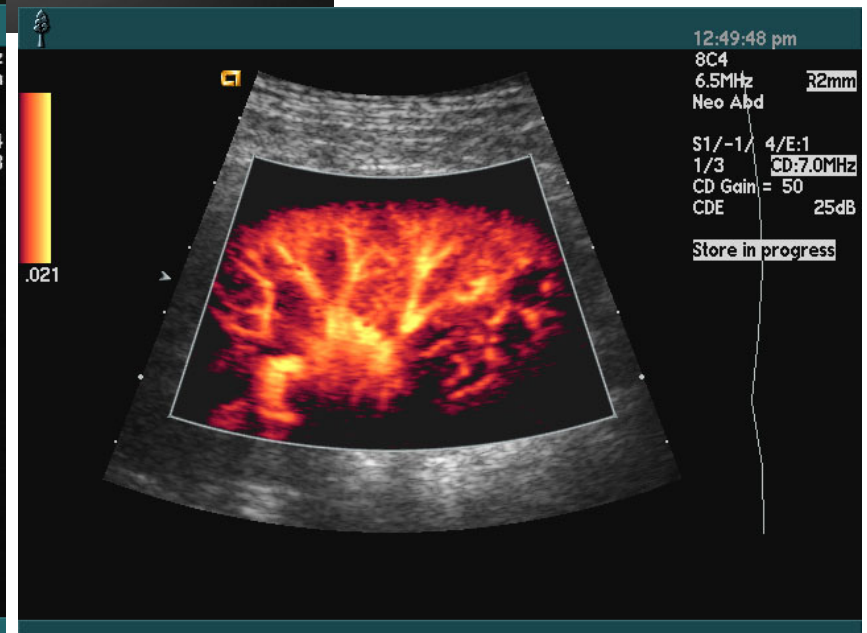


# Beam Formation Using Arrays

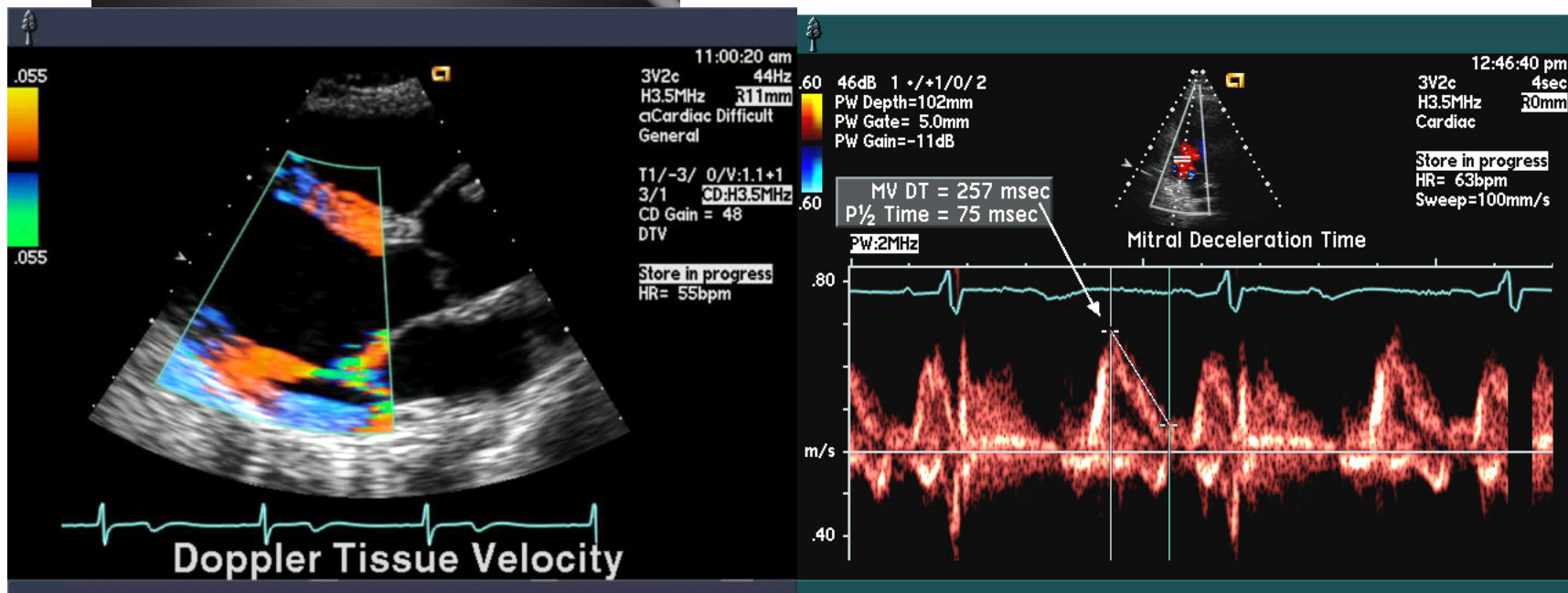
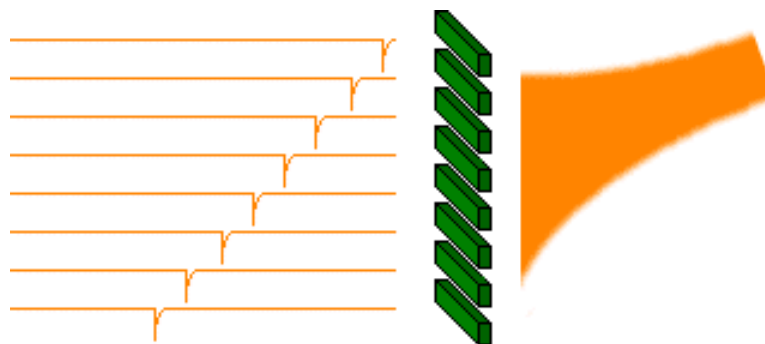
Focusing:



# Curved Linear Scanning

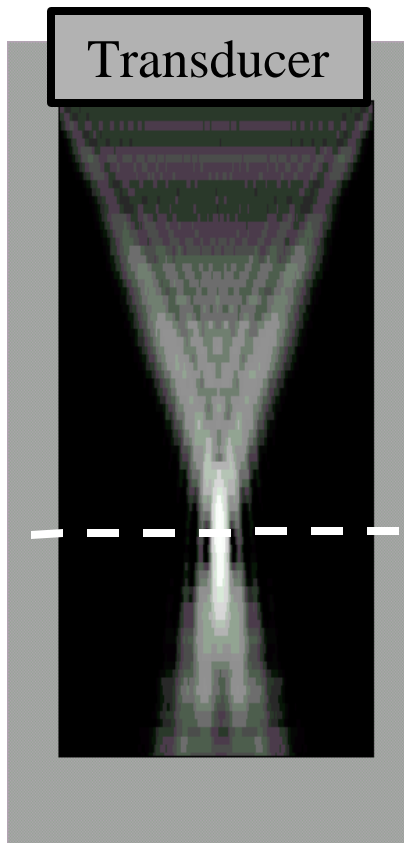


# Sector Steering

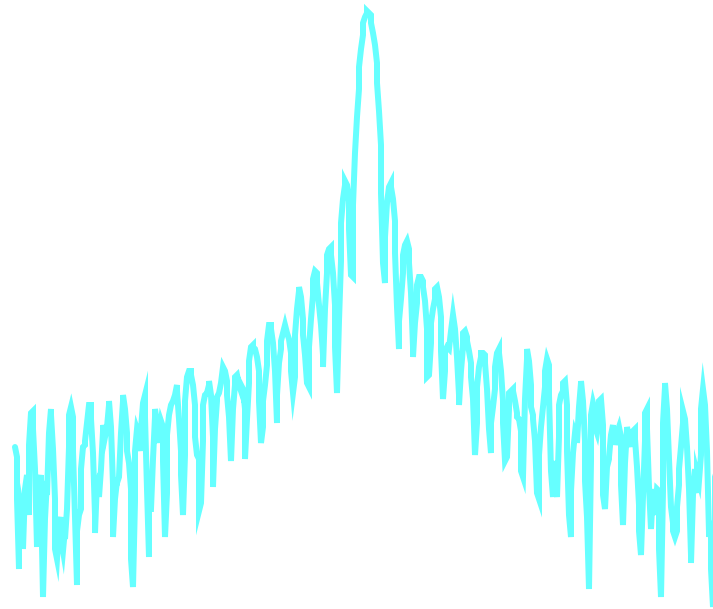


How is the resolution determined?

# Focusing $\leftrightarrow$ Beam Formation

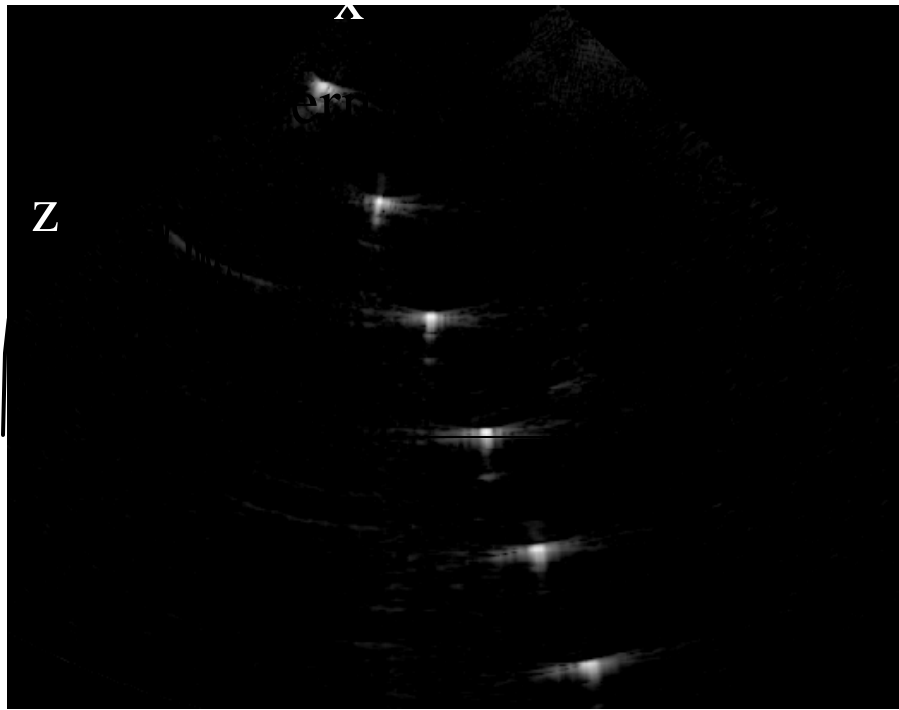


- To form a beam of sound wave such that only the objects along the beam direction are illuminated and possibly detected.

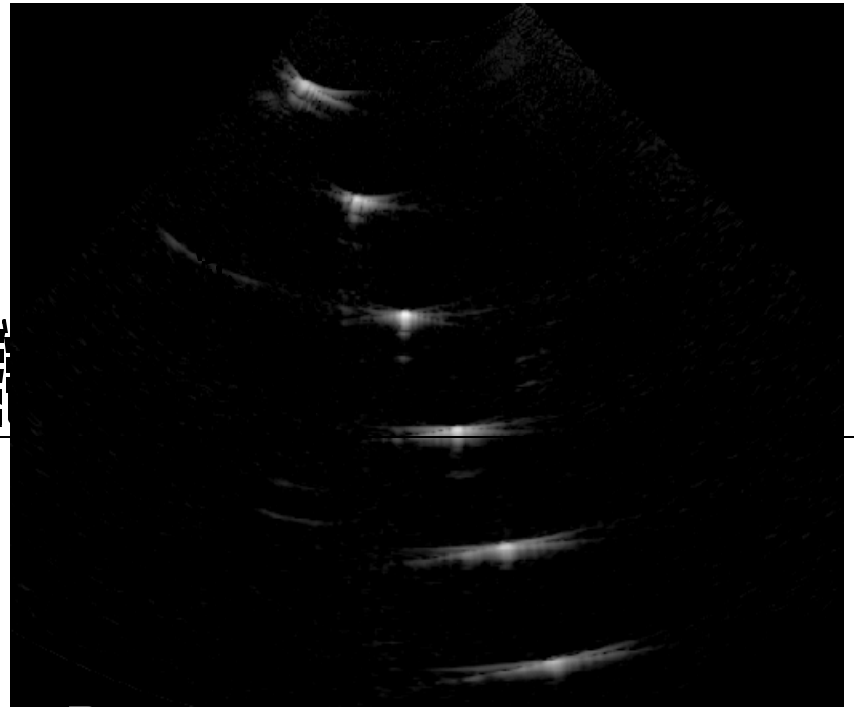


# Nomenclature

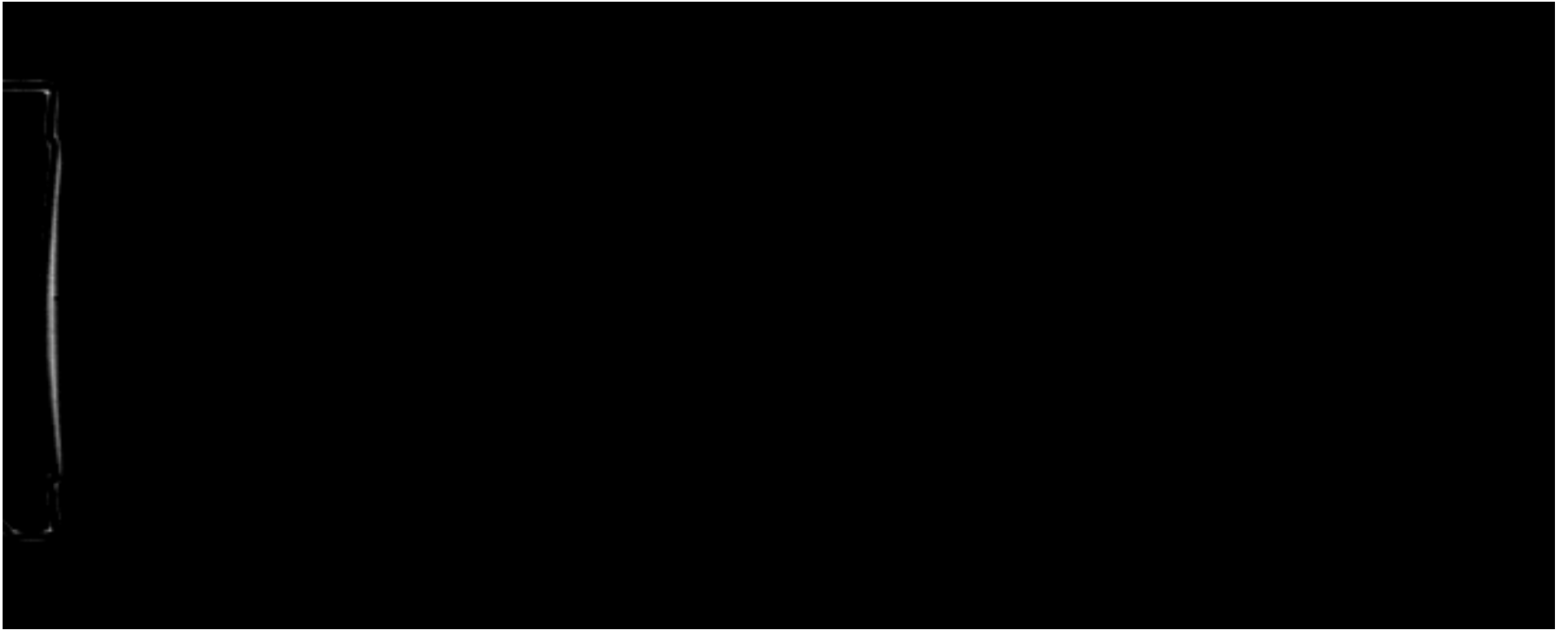
Good Focusing



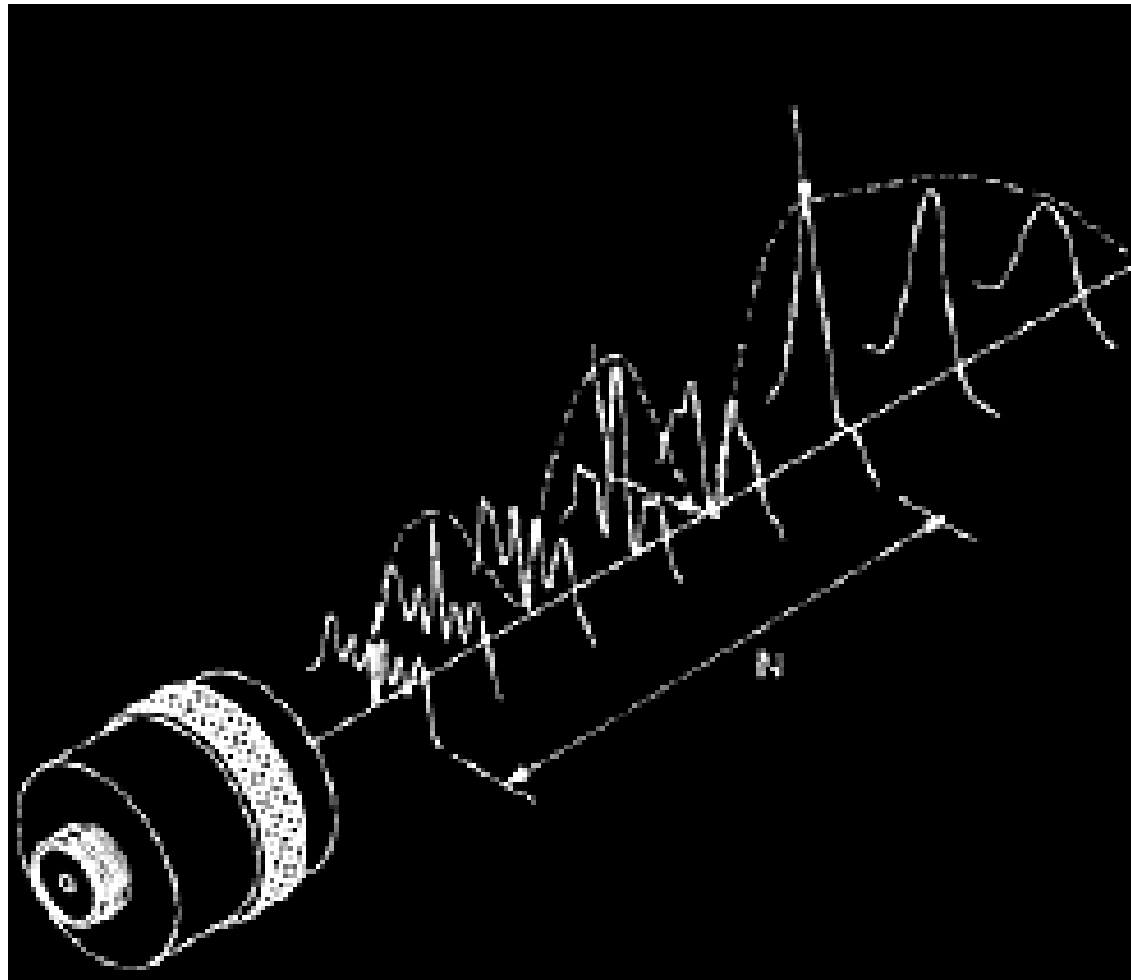
Poor Focusing



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



# Radiation Pattern



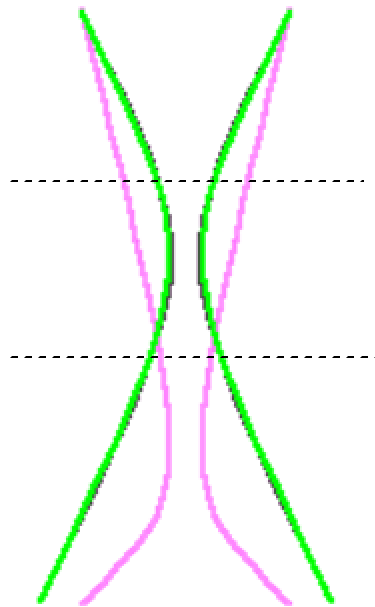


How to focus?

# 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

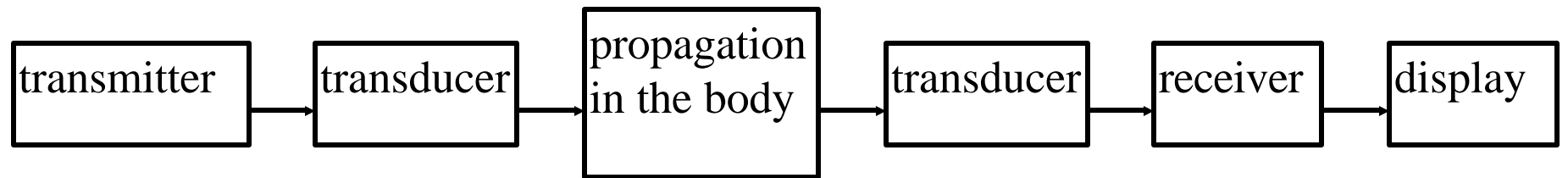


Single Zone Focusing

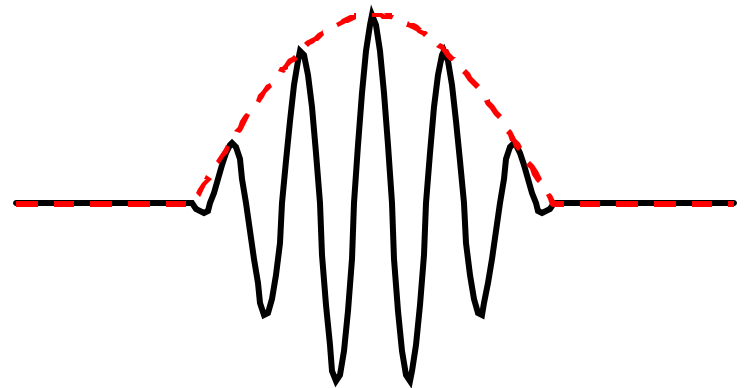
Multi-Zone Focusing

Dynamic Focusing

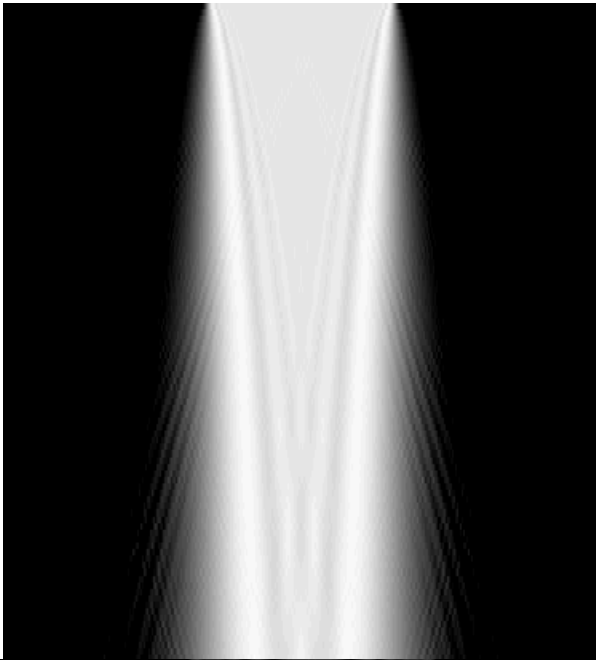
# Imaging Model



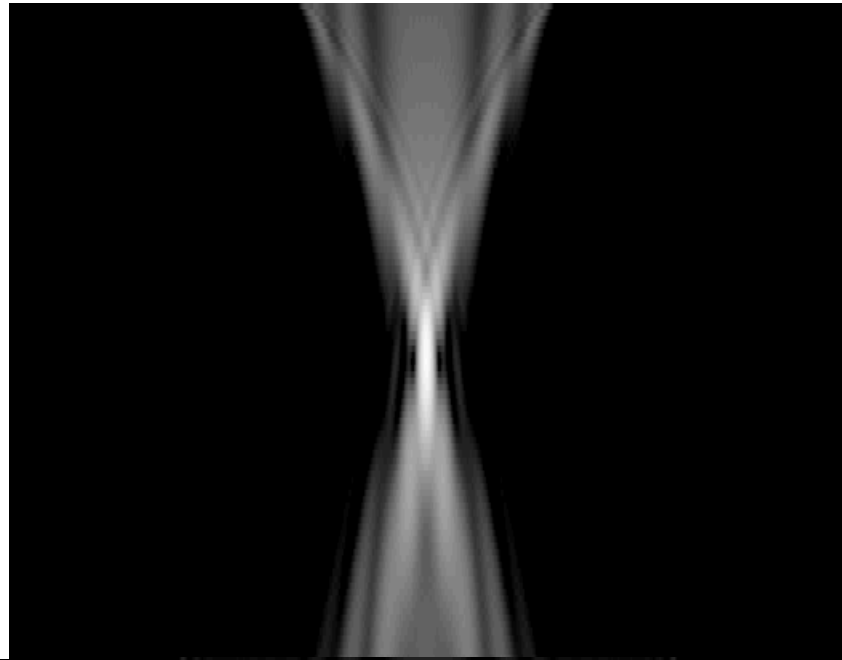
# Imaging Model



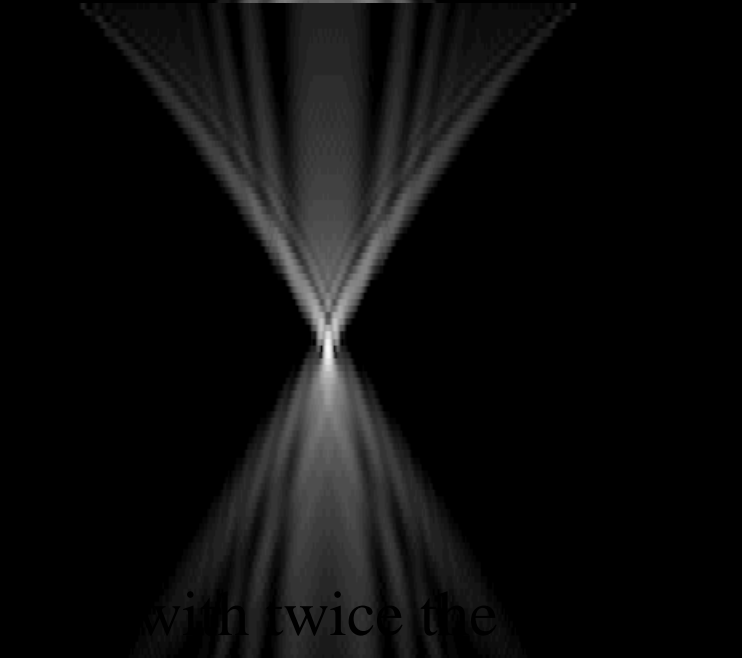
Unfocused



Focused



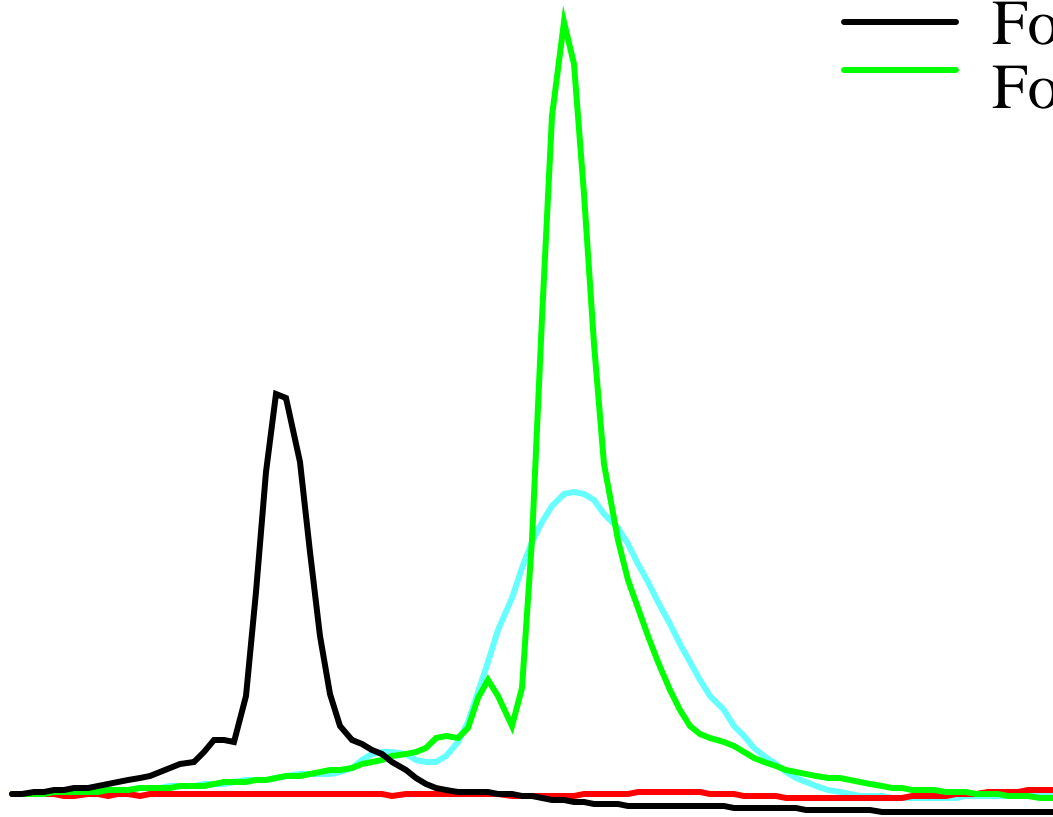
focused at  $\frac{1}{2}$  the distance



focused with twice the distance

# Axial Intensity

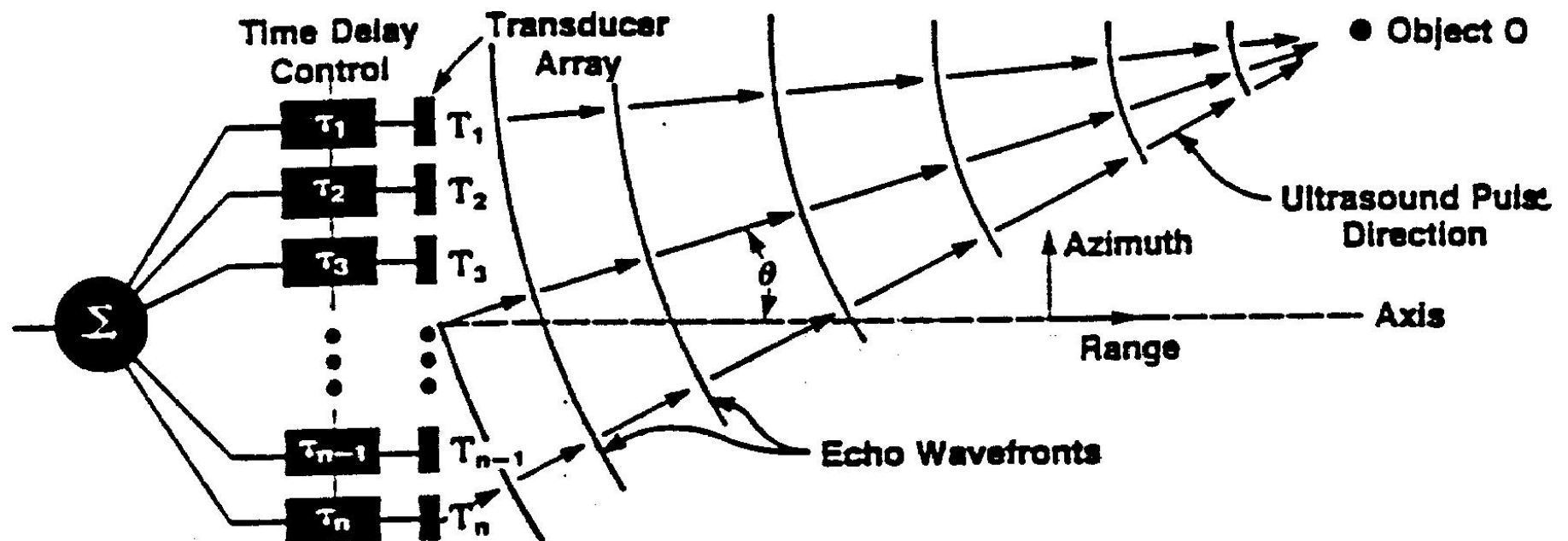
- Unfocused
- Focused
- Focused at  $\frac{1}{2}$  range
- Focused with 2X aperture



# Implementation of Focusing Using Arrays



# Beam Formation Using Arrays

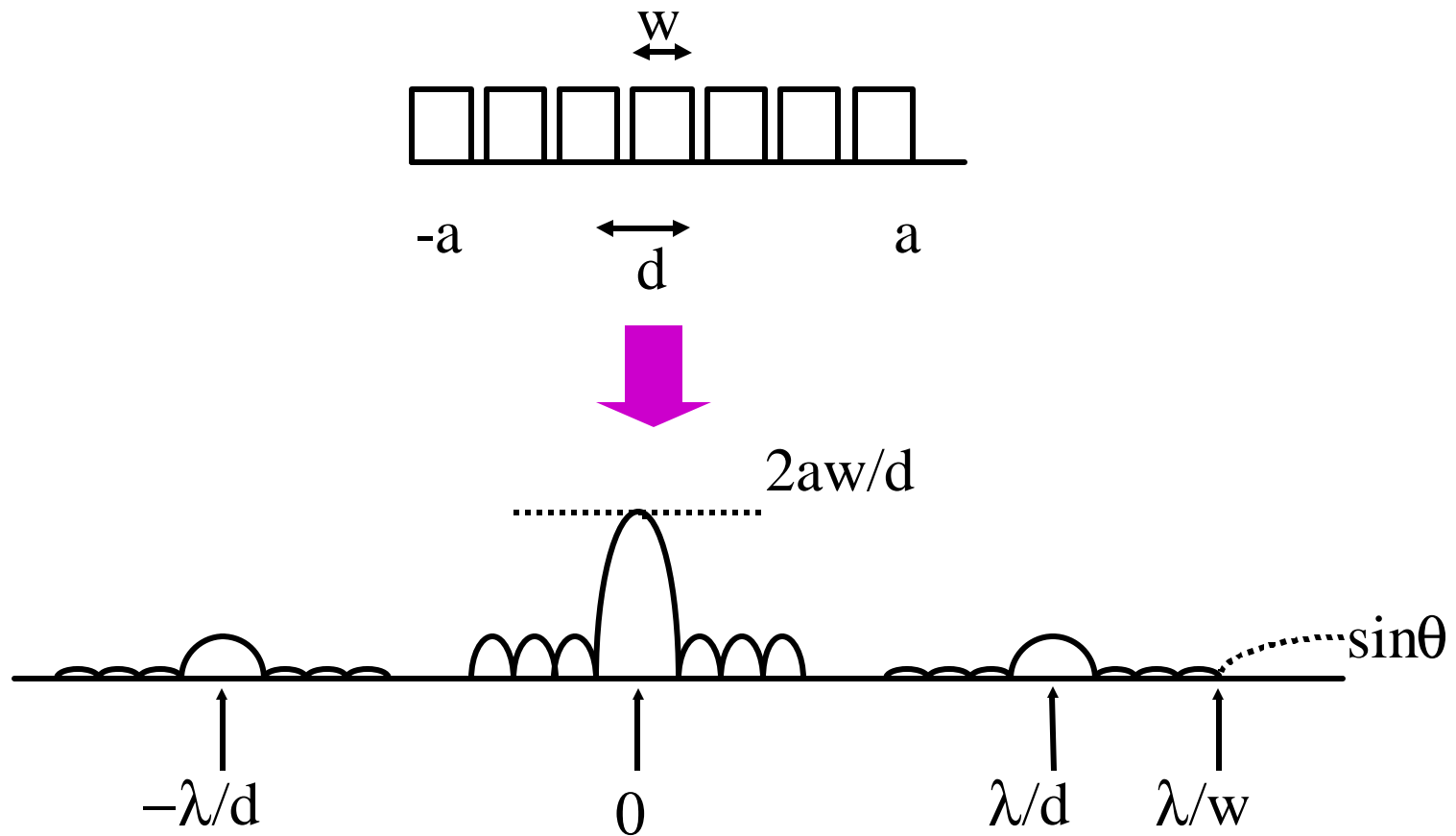


← Delay and Sum

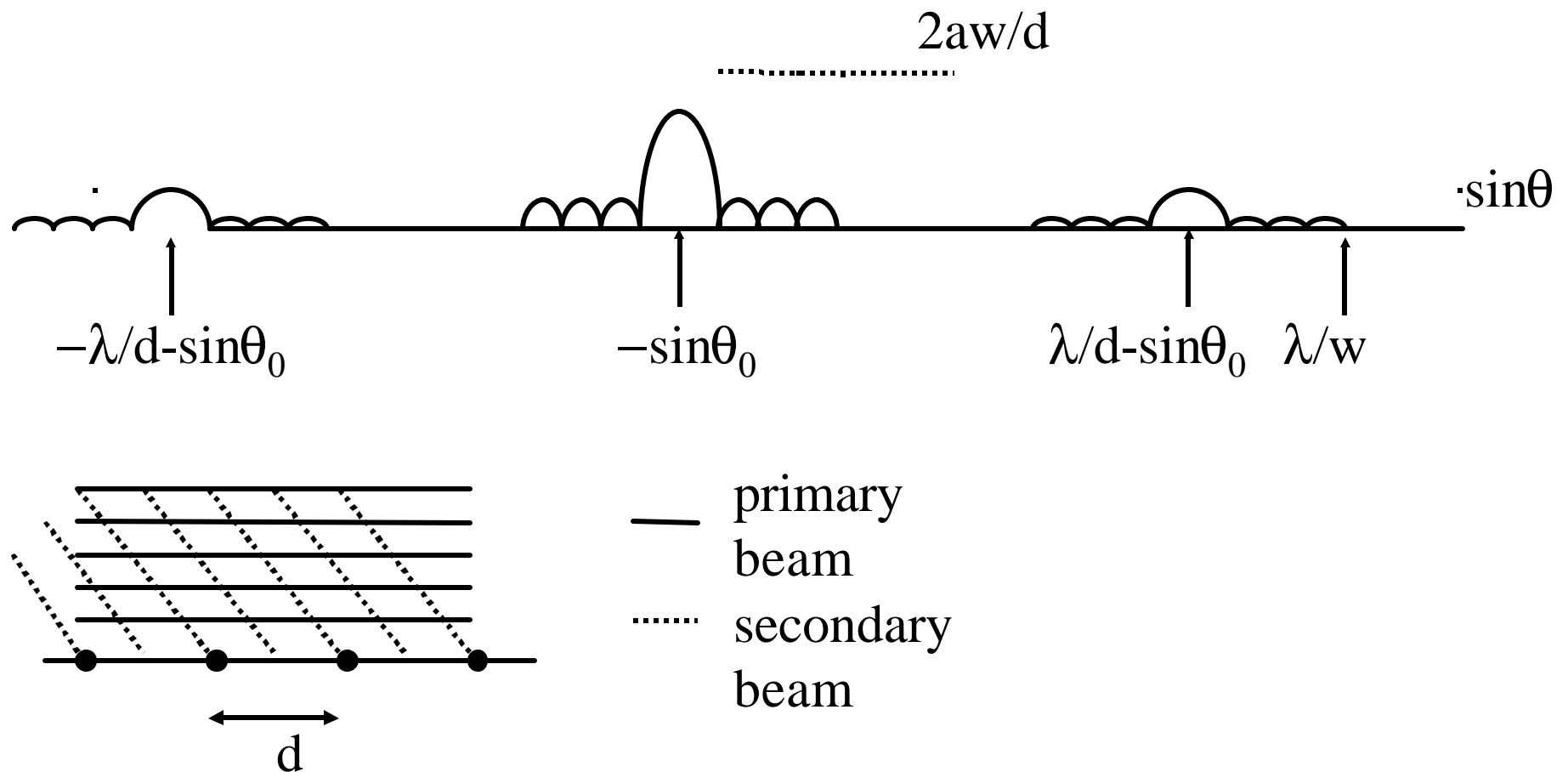
# Propagating Delays

# Propagating Delays

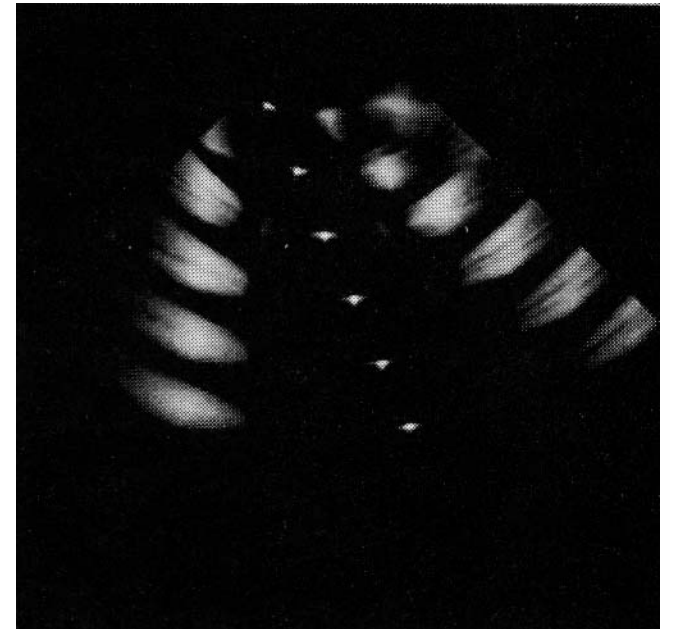
# Array $\rightarrow$ Sampled Aperture



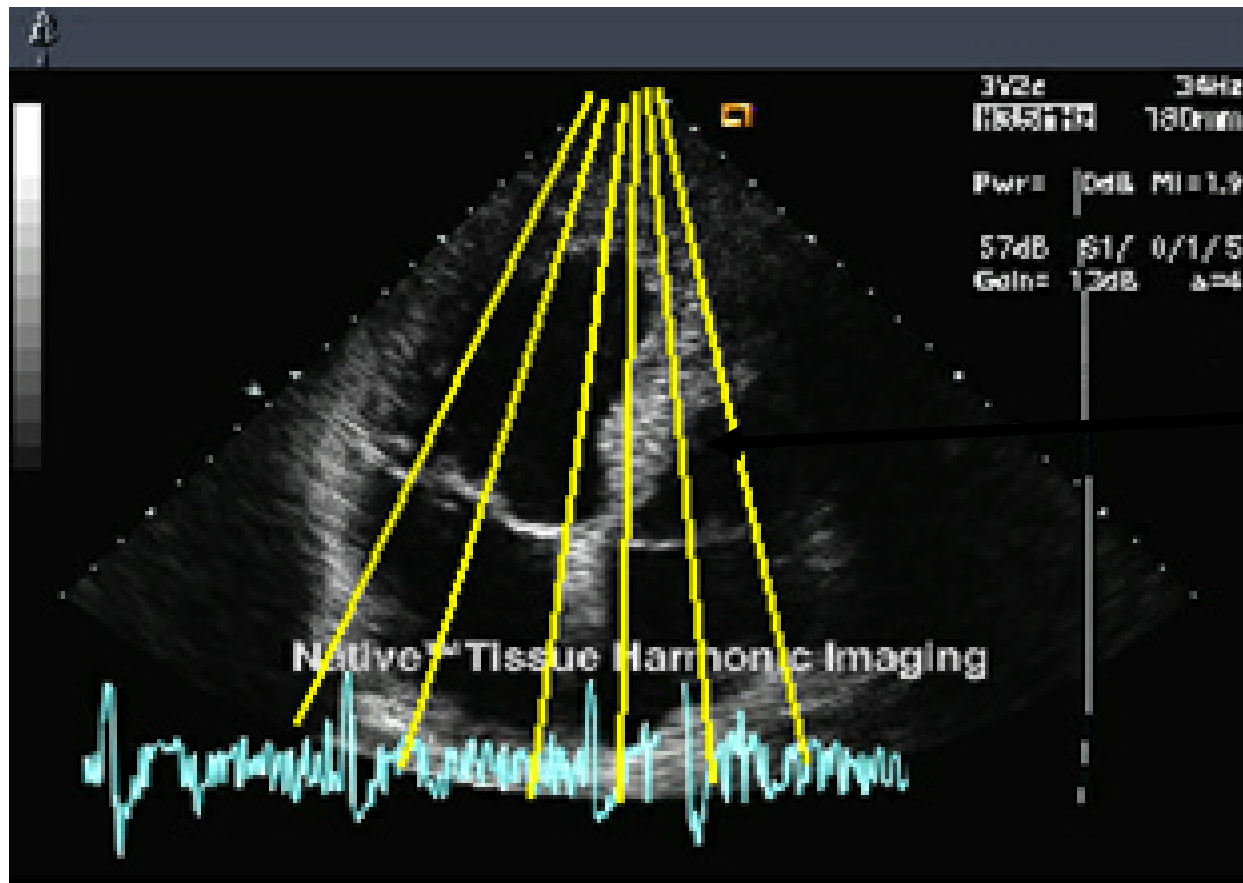
# Array Steering and Grating Lobes



# Grating Lobes



# Beam Sampling

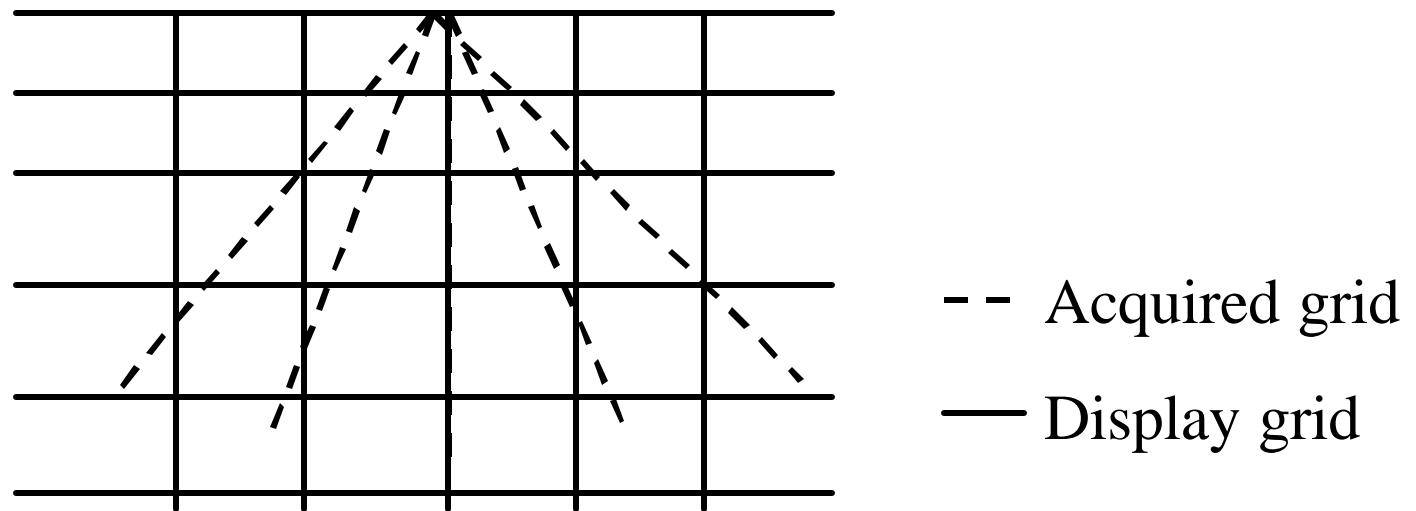


# Real-Time Image Formation

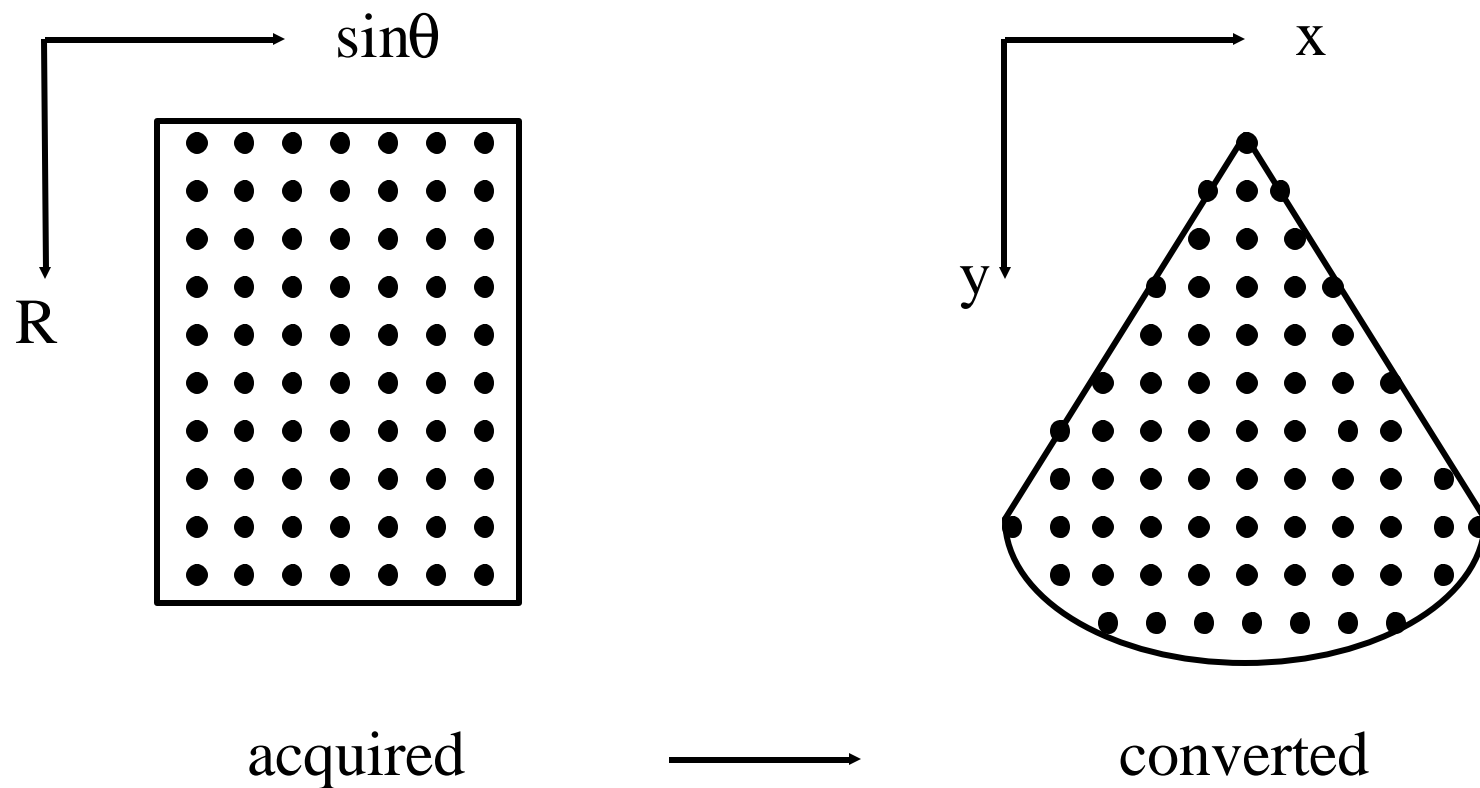


# Scan Conversion

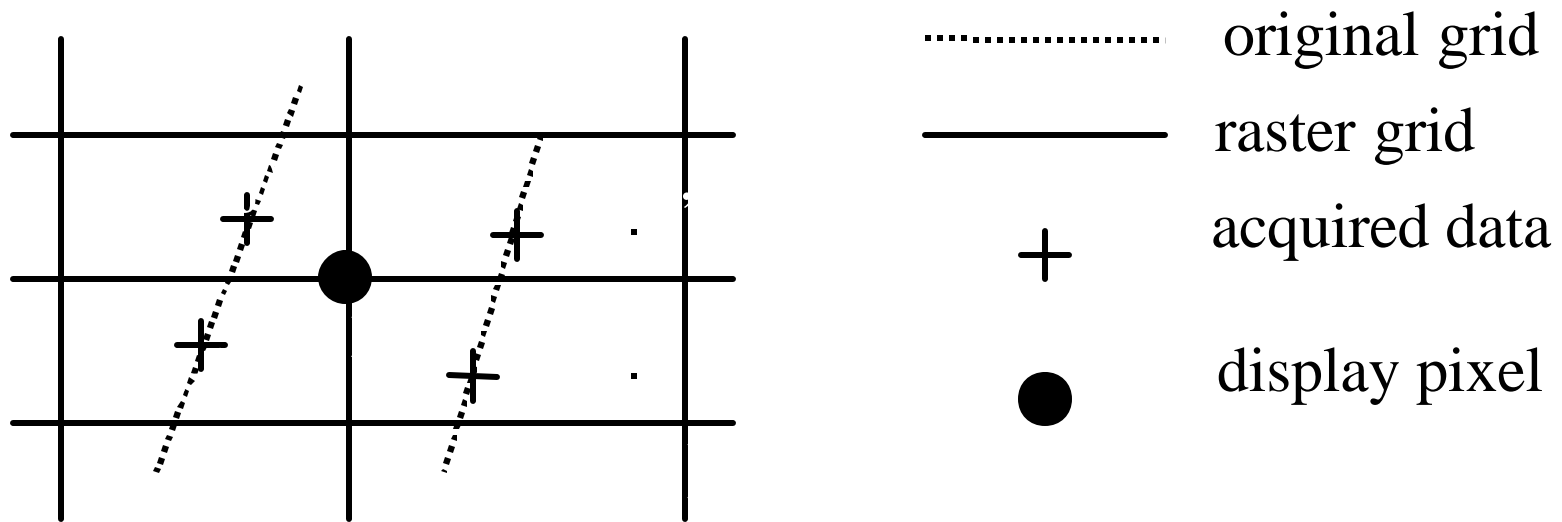
- Acquired data may not be on the display grid.



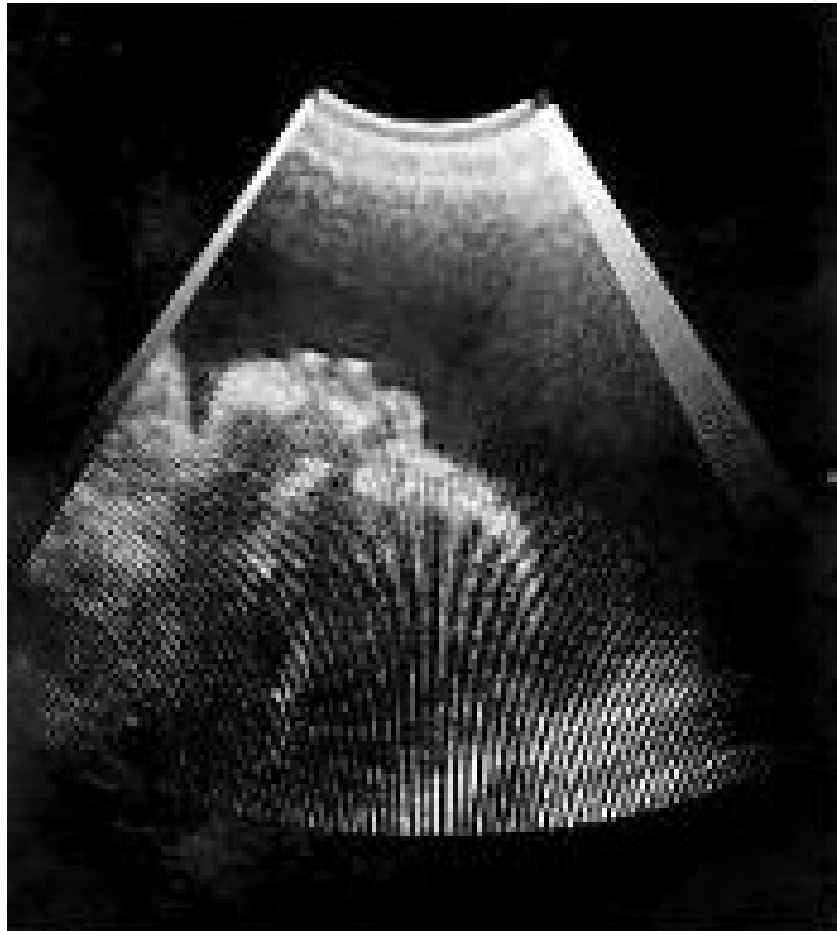
# Scan Conversion



# Scan Conversion



# Moiré Pattern



# Temporal Resolution (Frame Rate)

- Frame rate= $1/\text{Frame time}$ .
- Frame time=number of lines \* line time.
- Line time= $(2 * \text{maximum depth})/\text{sound velocity}$ .
- 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.

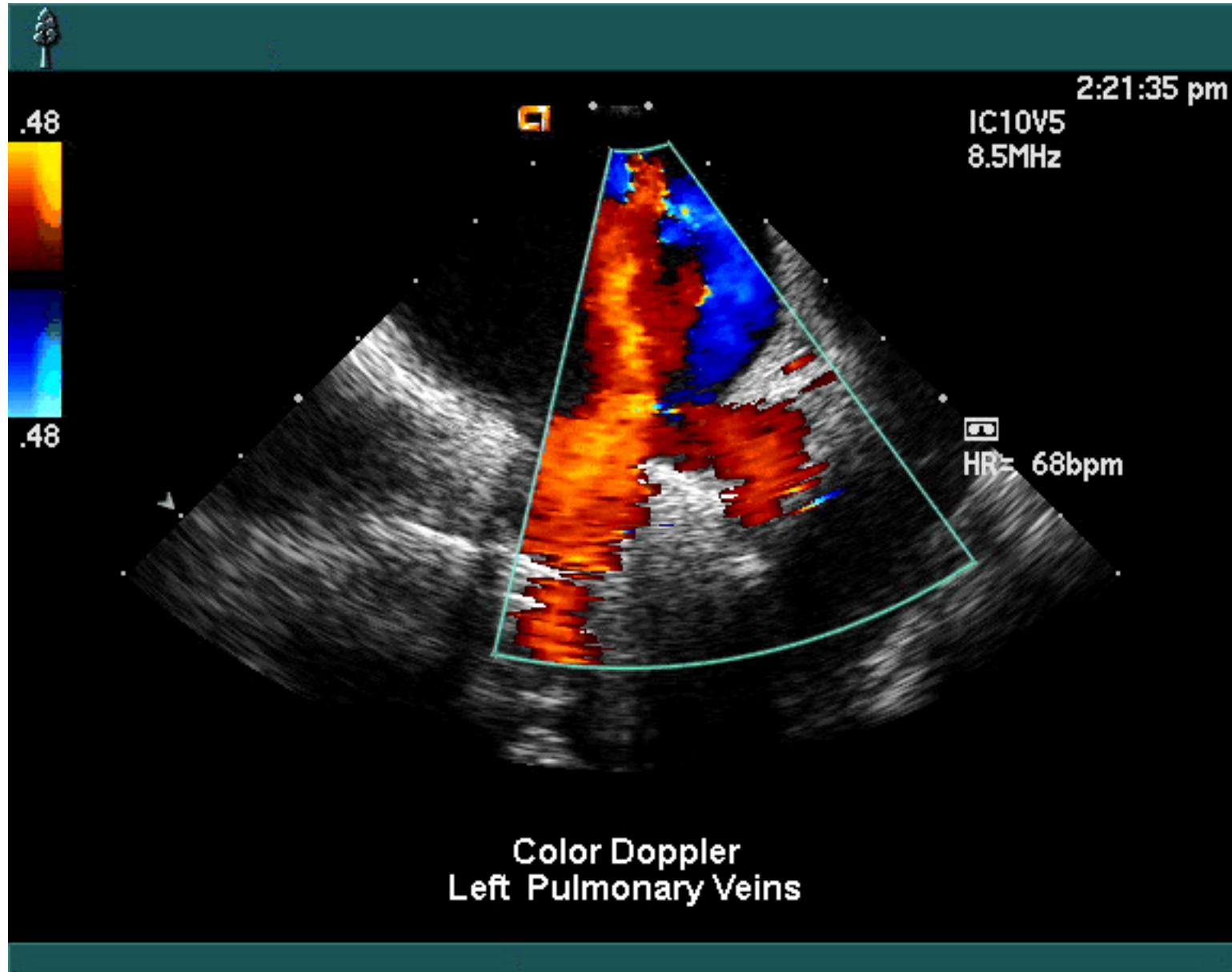
# Temporal Resolution

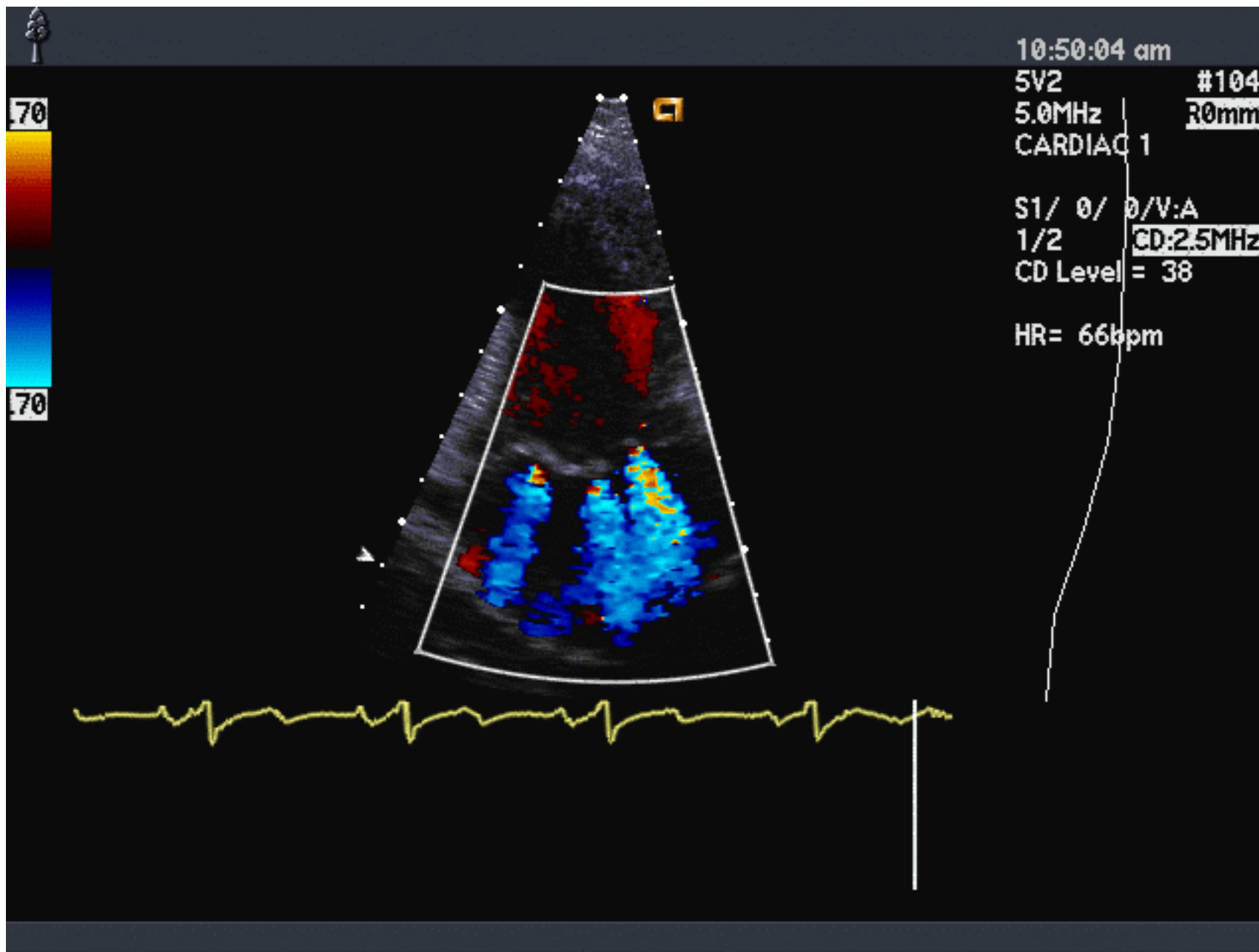
- For an actual frame rate lower than 30 Hz, interpolation is used.
- For an actual frame rate higher than 30 Hz, information can be displayed during playback.
- Even at 30 Hz, it is still possibly undersampling.

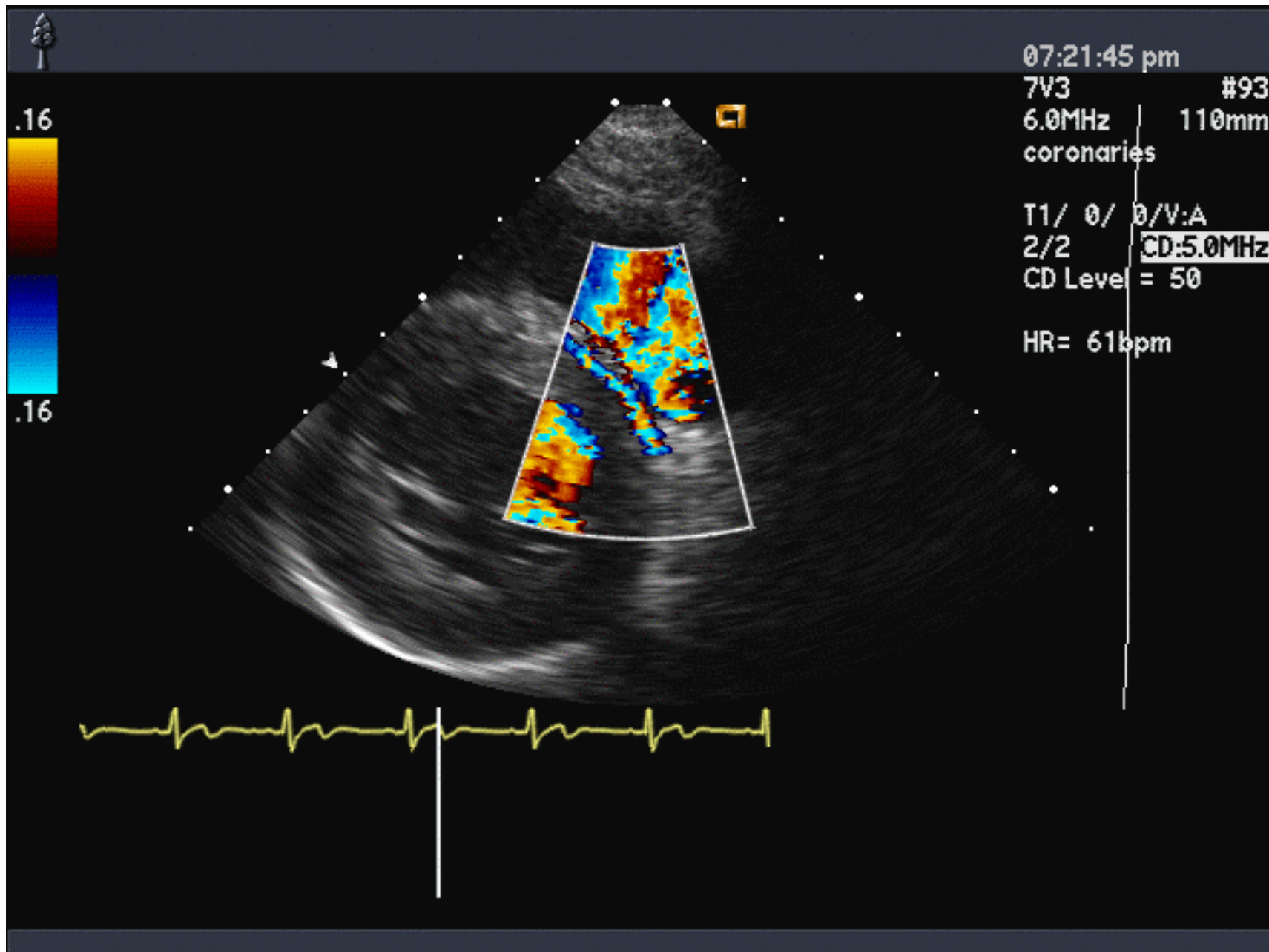
# Doppler Techniques for Motion Estimation



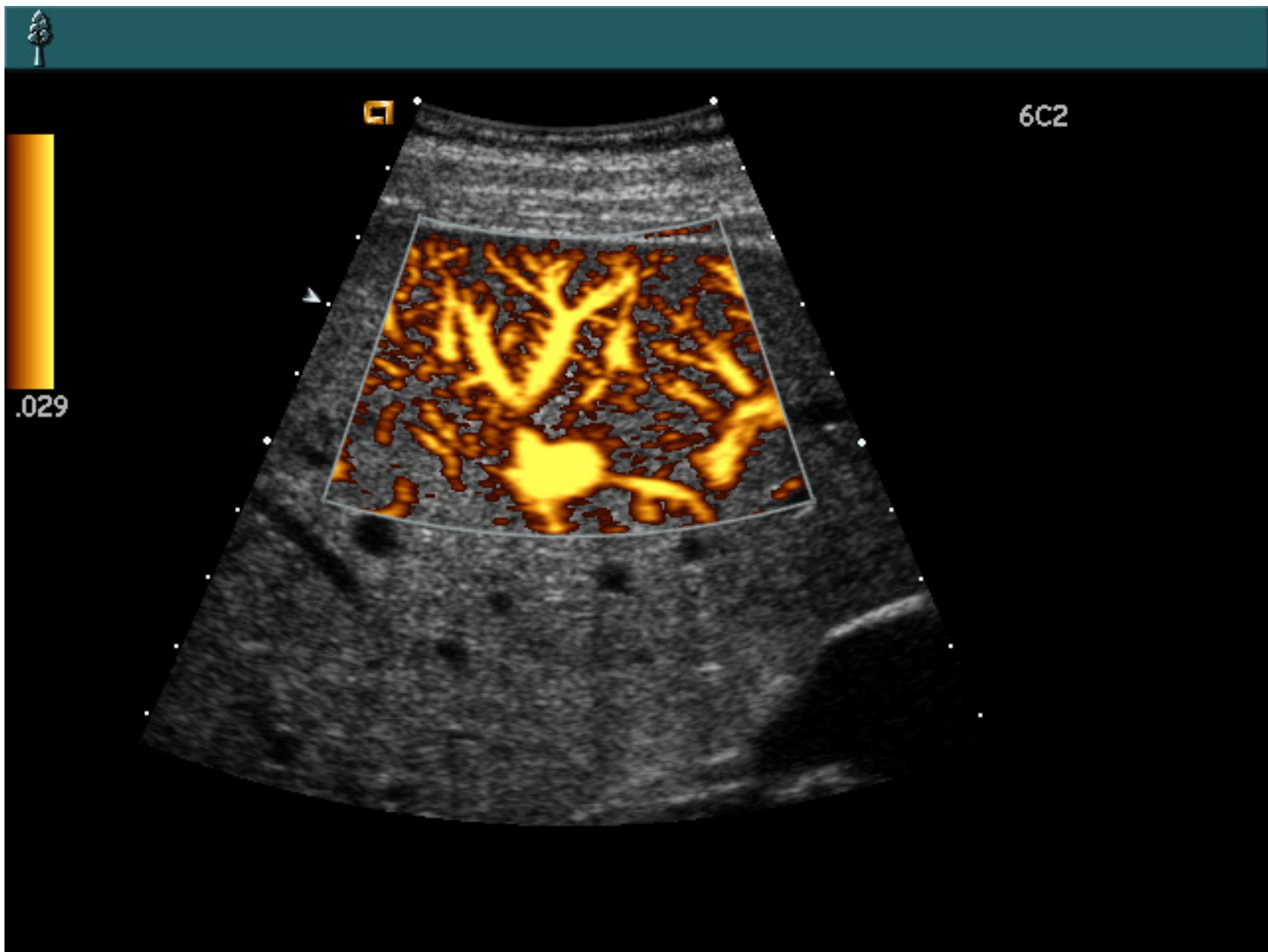
# Color Doppler Mode







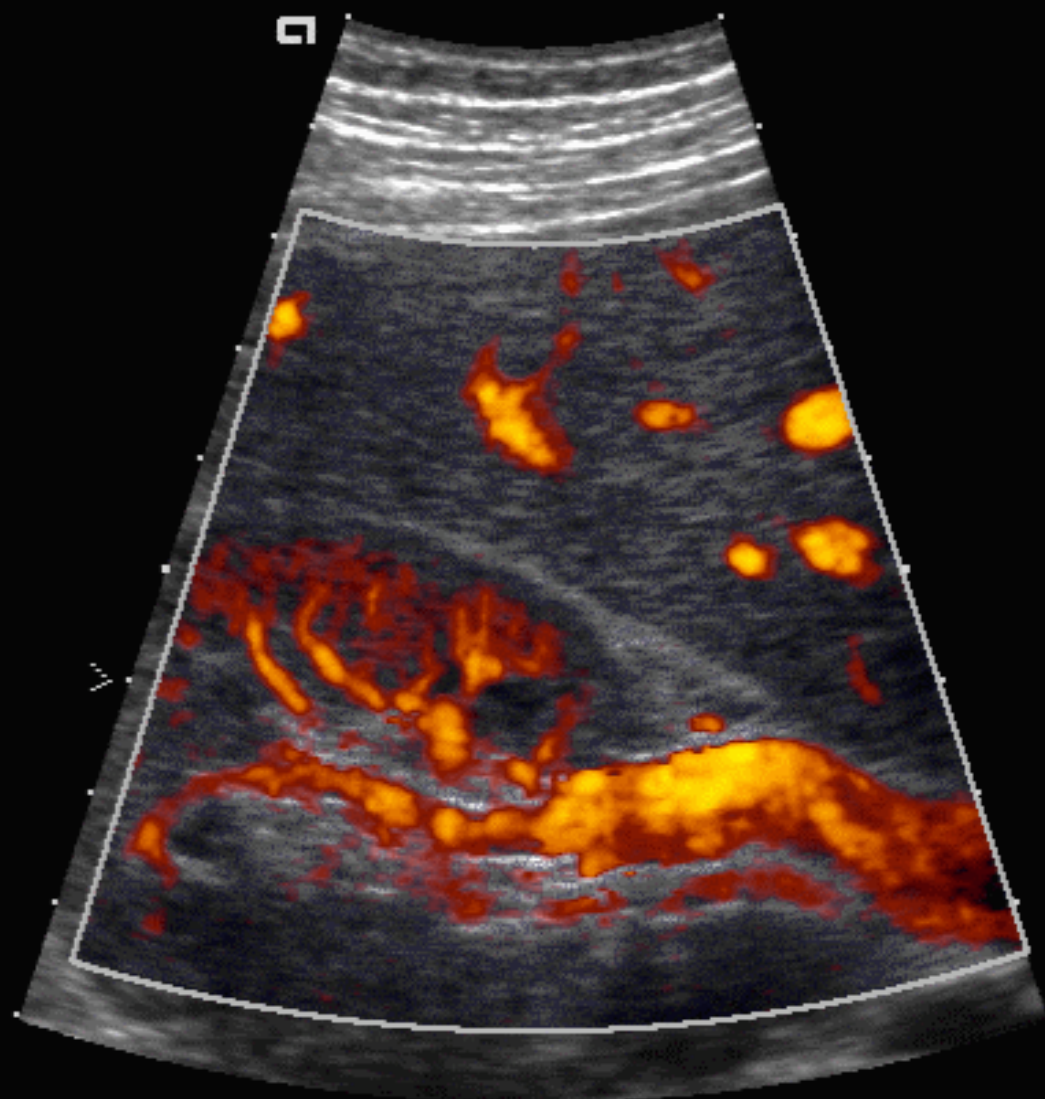
# Power Doppler



.037



.037



03:06:28PM

C7 # 35

5.0MHz R 0m

KIDNEY /V

PWR TIS

100% 7.3

0/ -/3/VEA+4

2/4/+25.0MHz

CEV 35dB

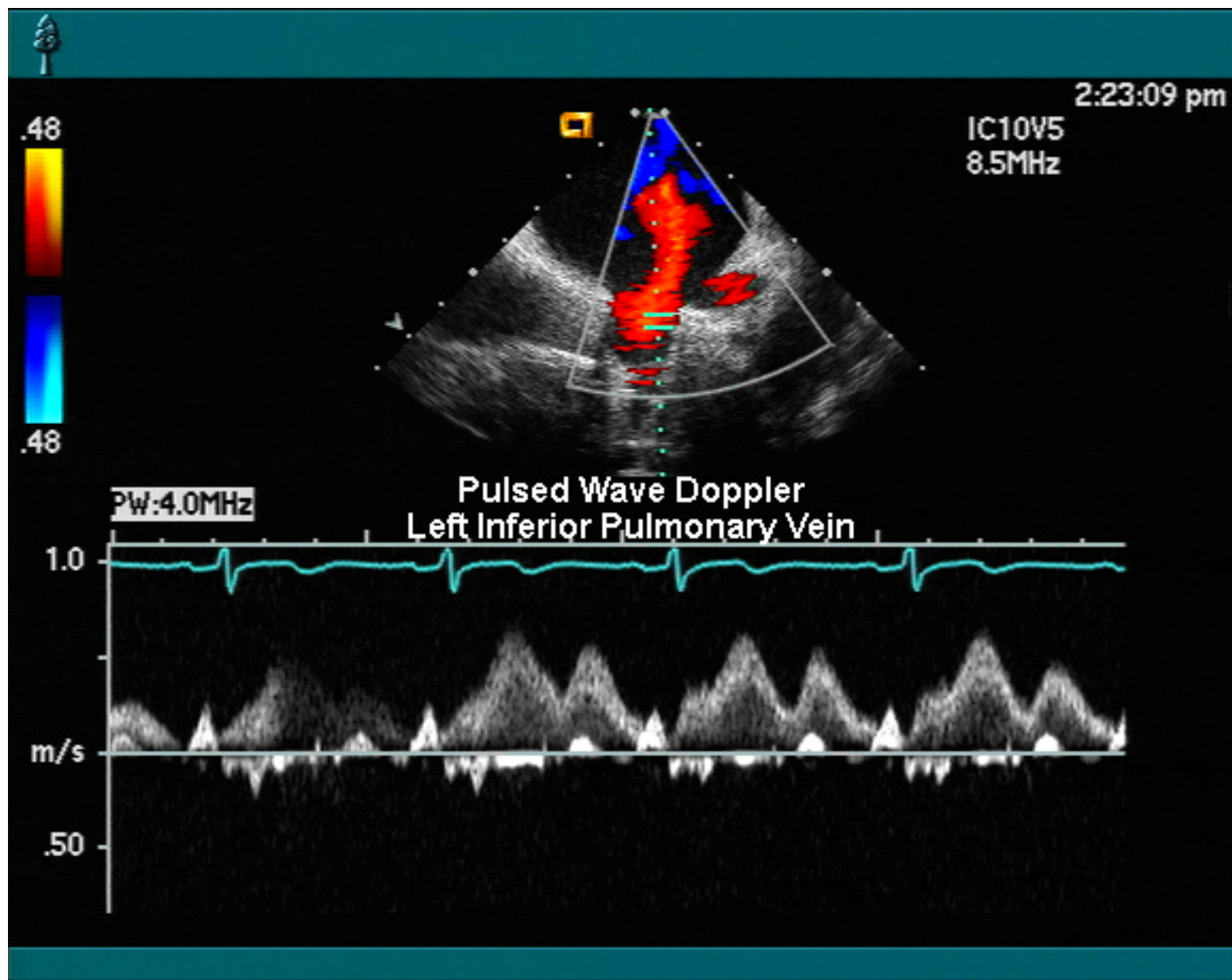
0:0 100%

LEVEL: 78



# PW Doppler (Spectral Doppler)





# CW Doppler (Spectral Doppler)



02:28:02 pm

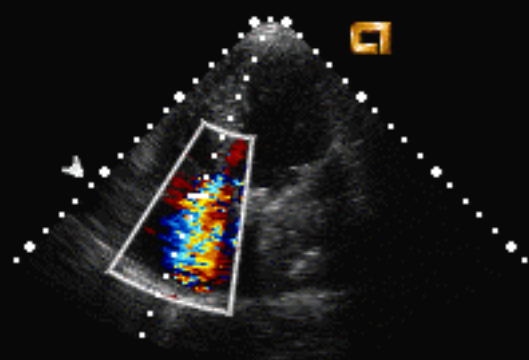
64 49dB 3 +/- 1/1/E  
CW Focus= 89mm  
CW Gain=-18dB

5V2 24sec

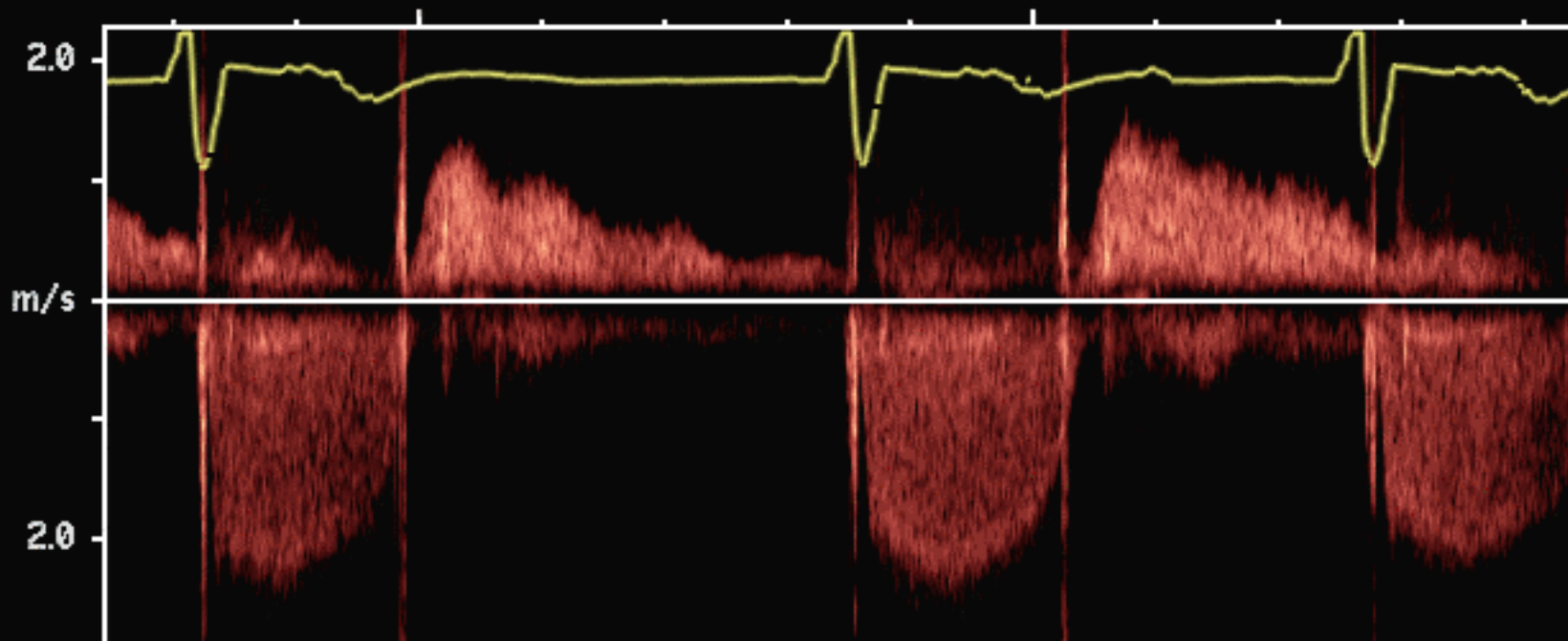
5.0MHz / 160mm

CARDIAC 1

HR=135bpm



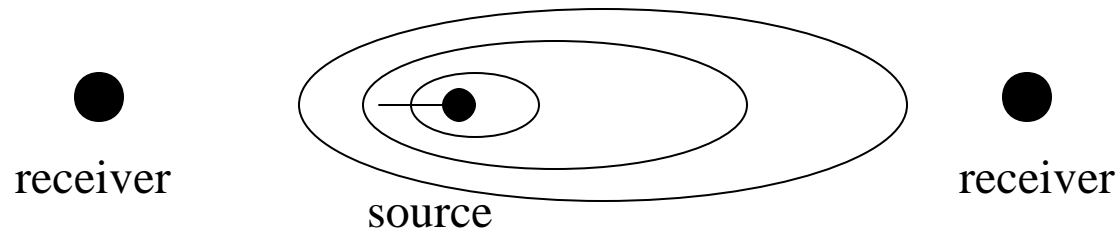
CW:2.5MHz



# 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

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

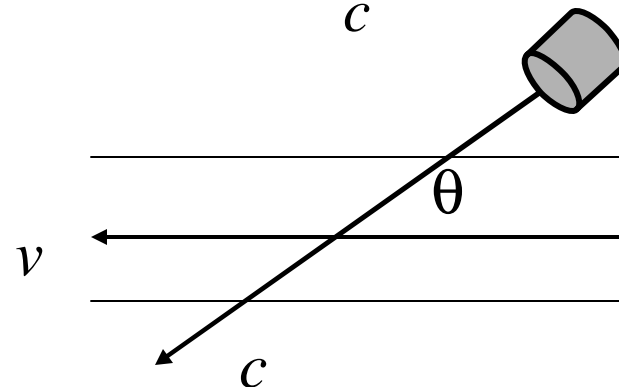
$$f_d \approx f_s \frac{(v_r + v_s)}{c}$$

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

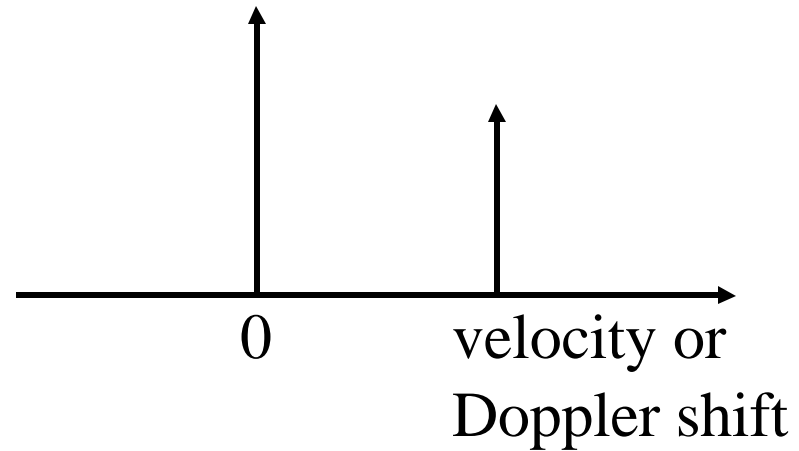
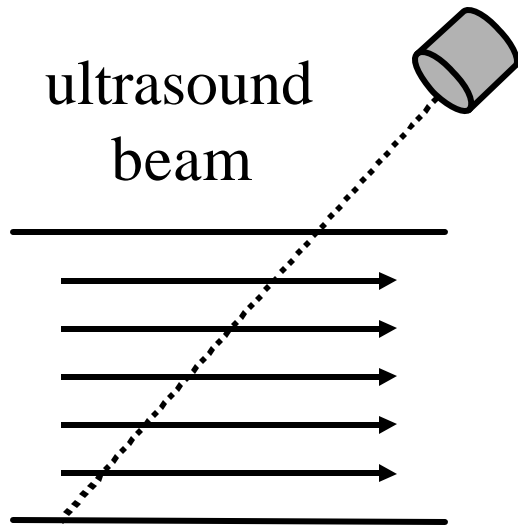
$$f_d = \frac{2vf_s}{c} \cos \theta$$


The diagram shows a probe (cylinder) emitting a wave (c) towards a moving reflector (v). The angle between the wave path and the flow direction is  $\theta$ .

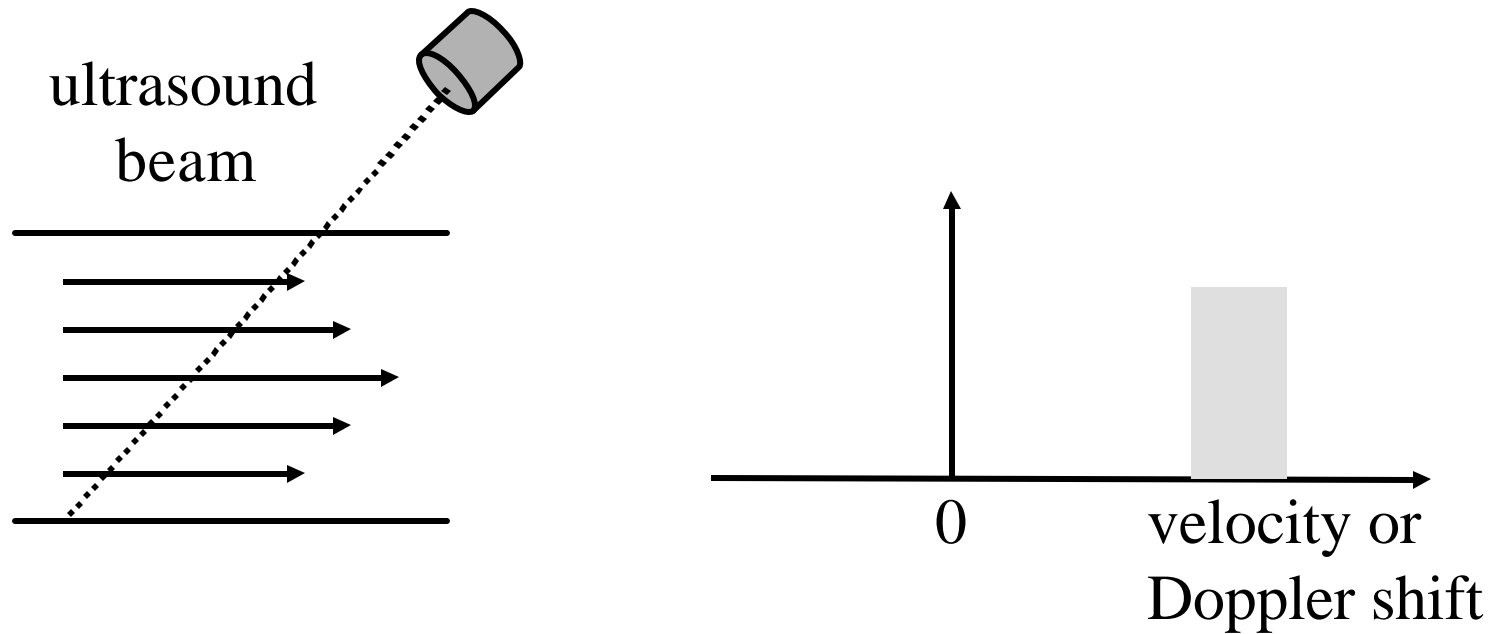
- Typical physiological flows (5-10m/sec at most) are much slower than sound velocity in the body ( $\sim 1500\text{m/sec}$ ).
- Doppler shift is doubled due to round-trip propagation.
- Only parallel flows can be detected.



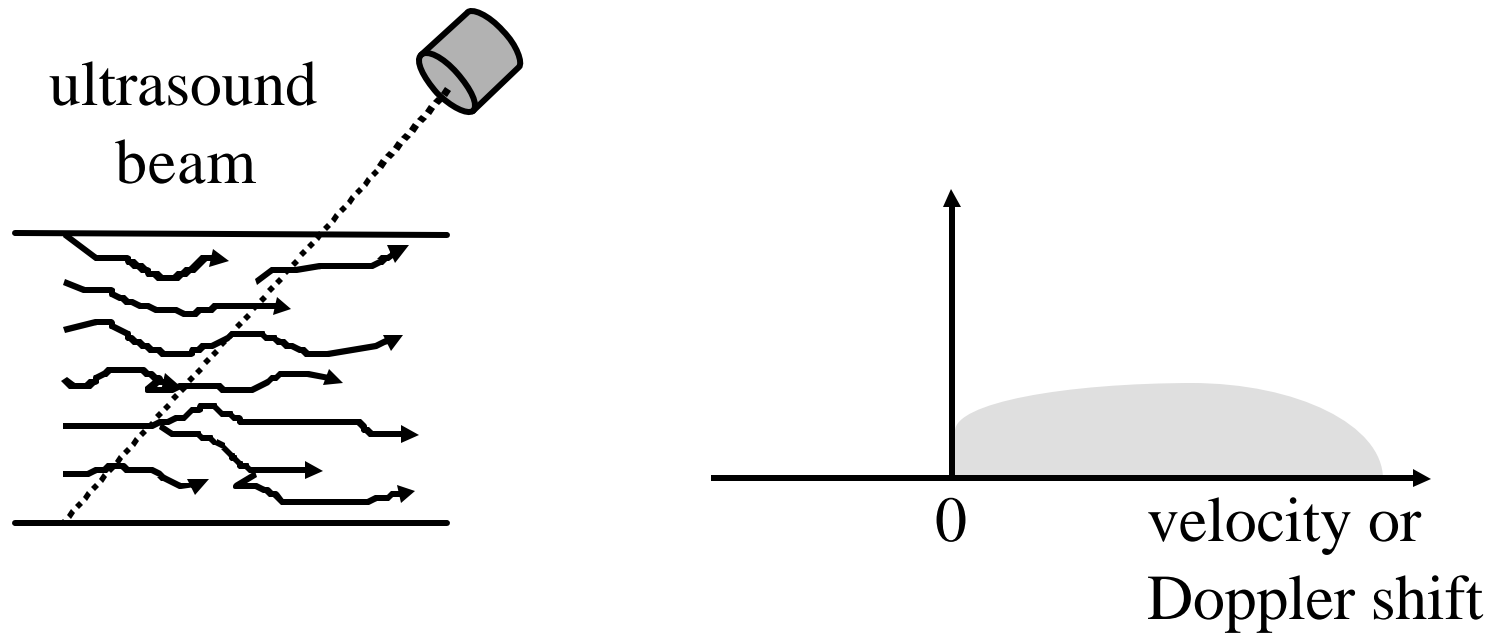
# Flow Pattern vs. Velocity Profile



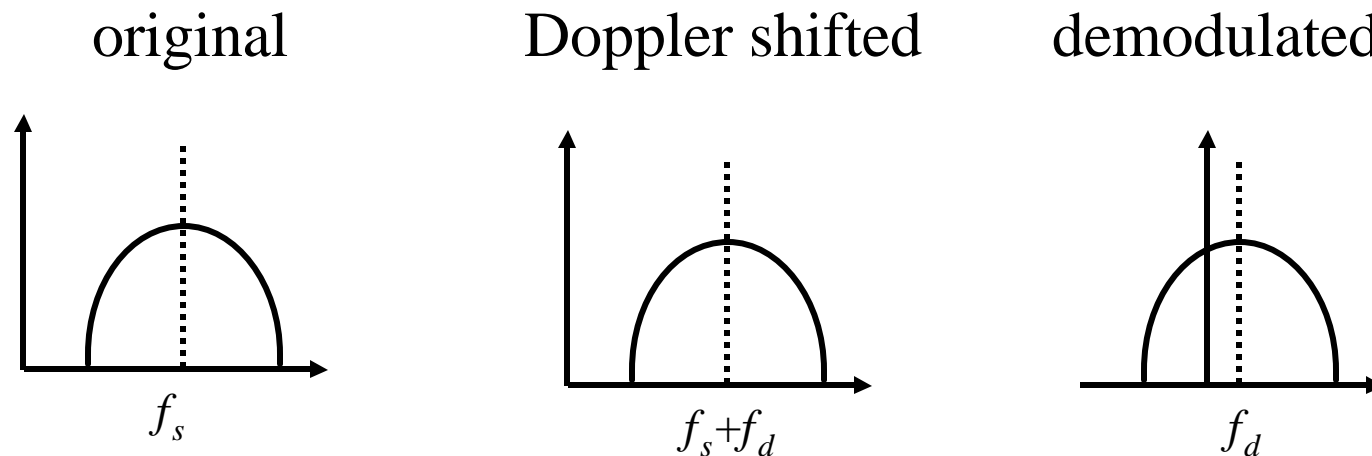
# Flow Pattern vs. Velocity Profile



# Flow Pattern vs. Velocity Profile

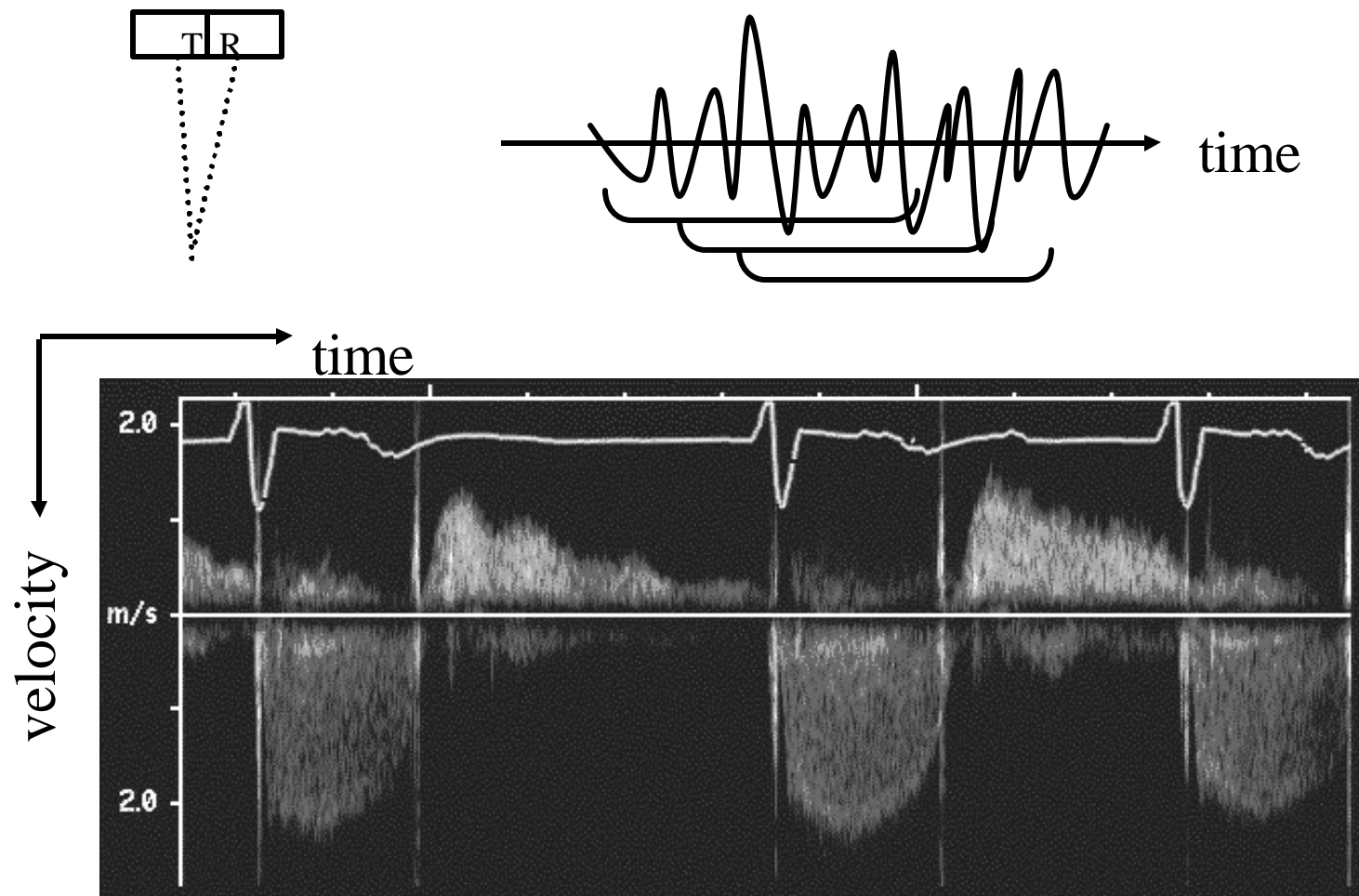


# Doppler Spectrum Estimation

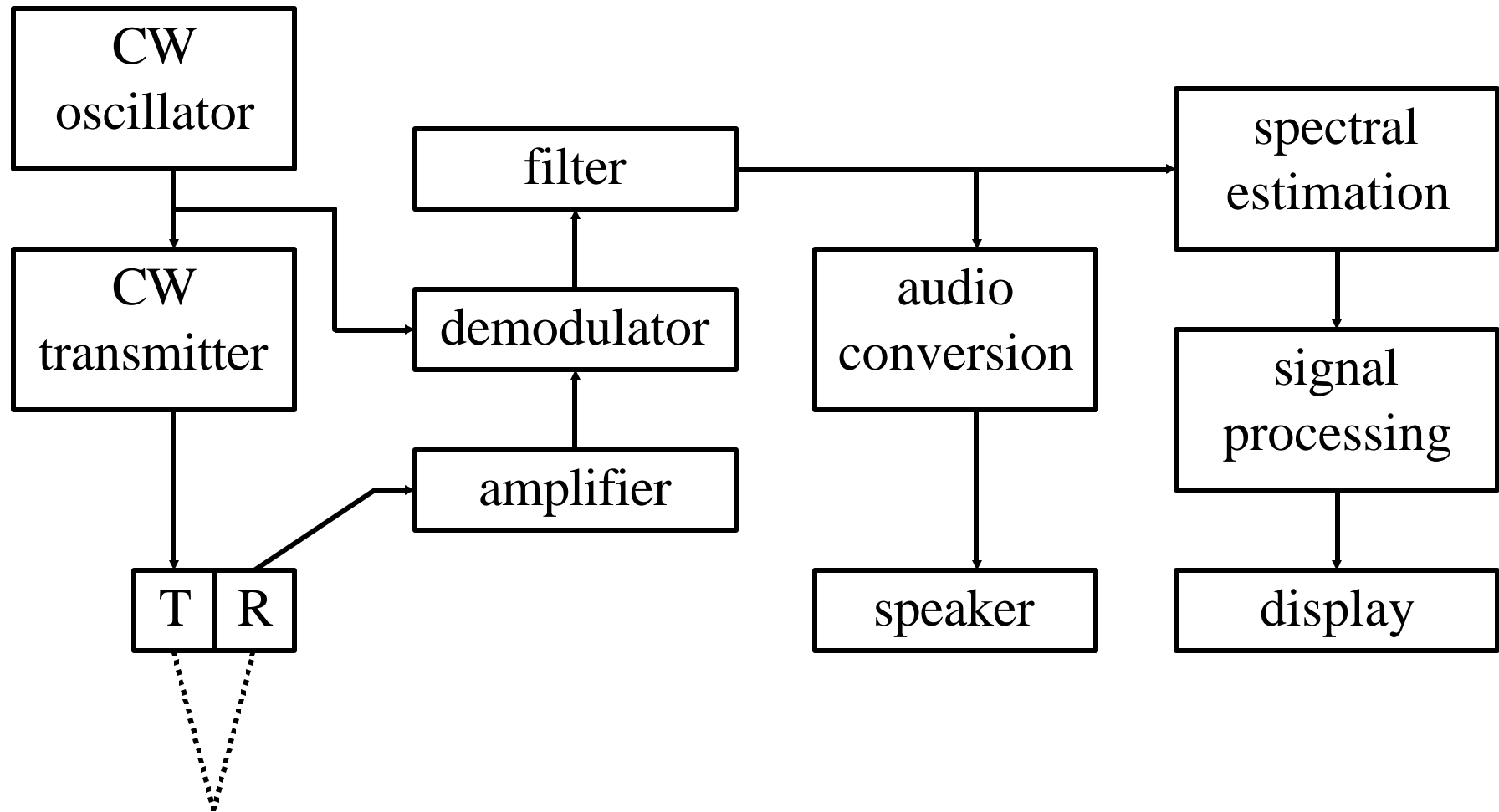


- Short-time Fourier transform (Spectral Doppler).
- Correlation based estimation (Color Doppler).

# Continuous Wave (CW) Doppler



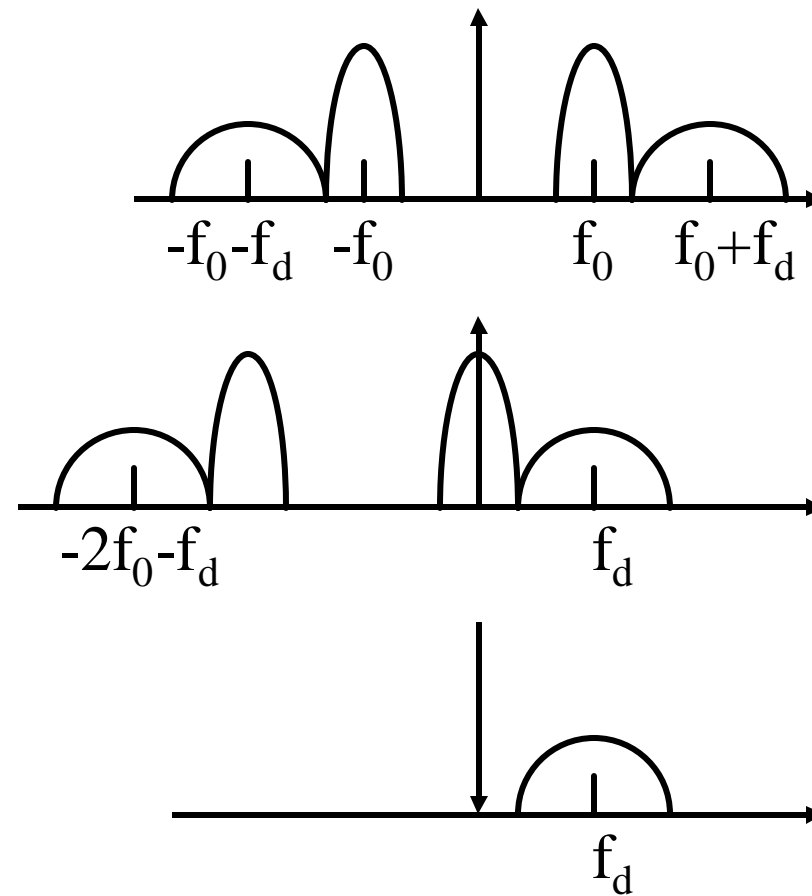
# CW Doppler



# CW 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



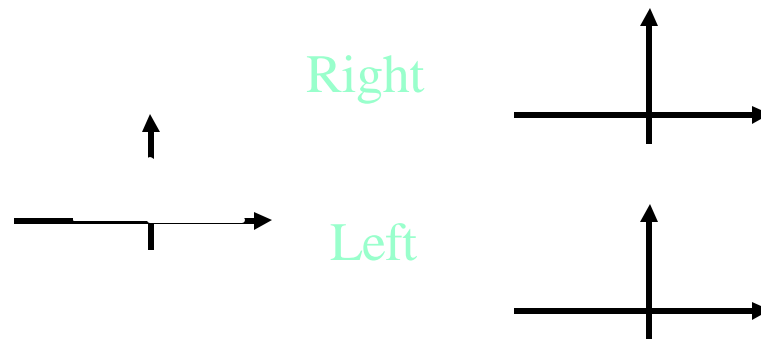


# CW Doppler Processing

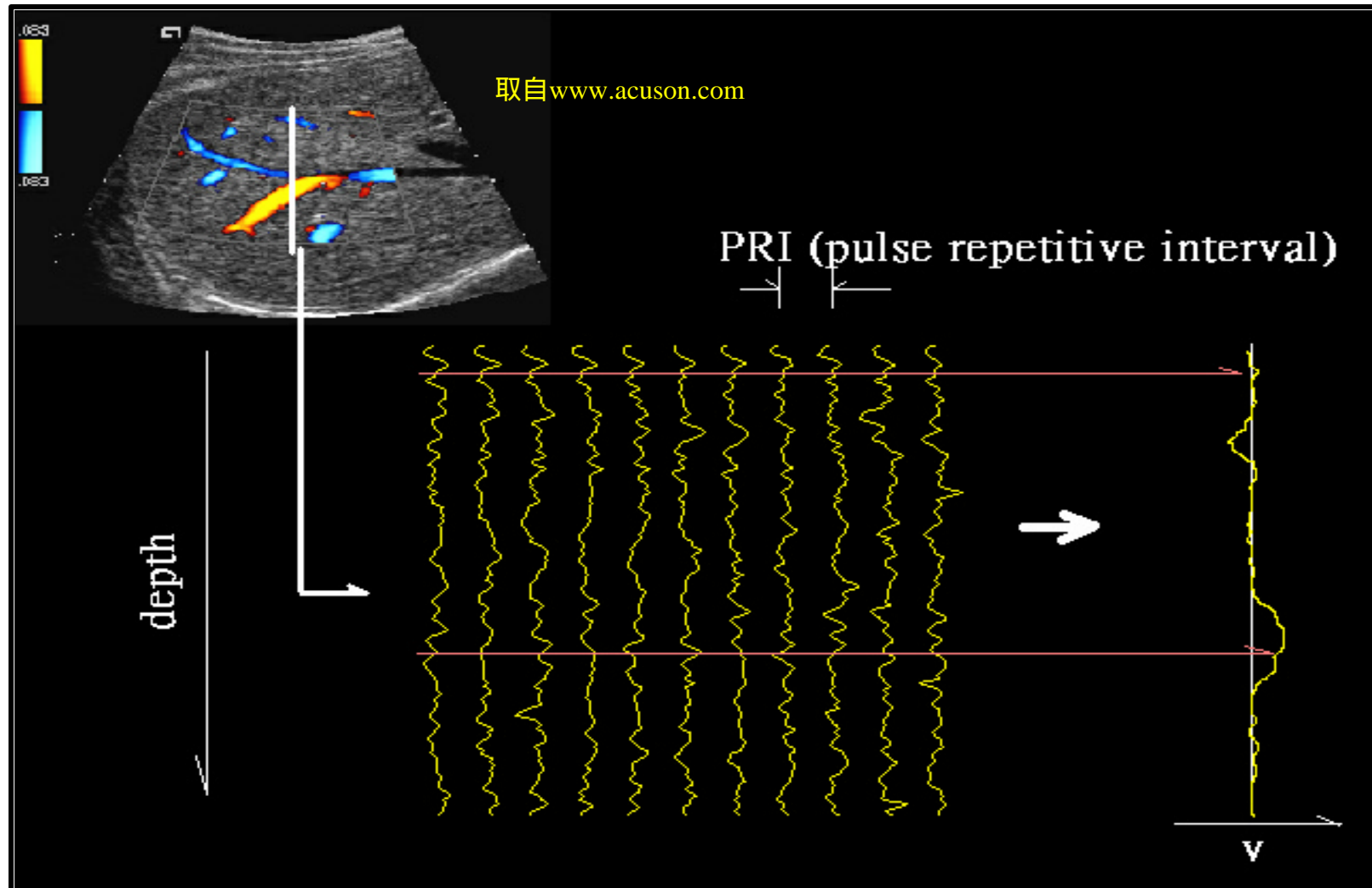
- Time-interval histogram.
- 32-128 ppt FFT.
- Mode-based spectrum estimation (AR), time-frequency analysis.
- Magnitudes are converted in dB and displayed.
- Post-processing similar to B-mode.

# Audio Doppler

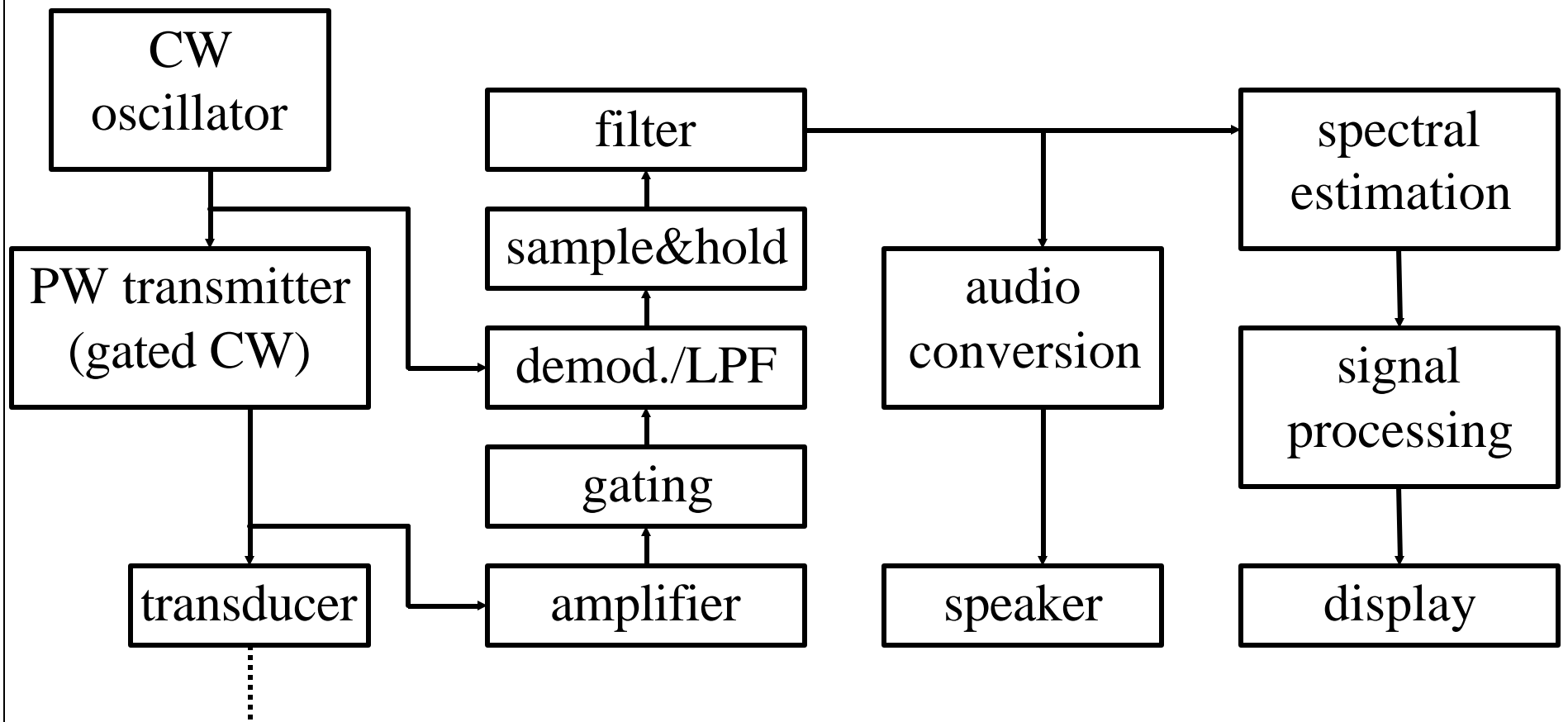
- For typical blood velocities and carrier frequencies, the Doppler shifts from blood happen to be in the human audible range (near DC to 20KHz).
- Positive shifts in one channel and negative ones in the other.
- Hilbert transform.
- Clinically useful.



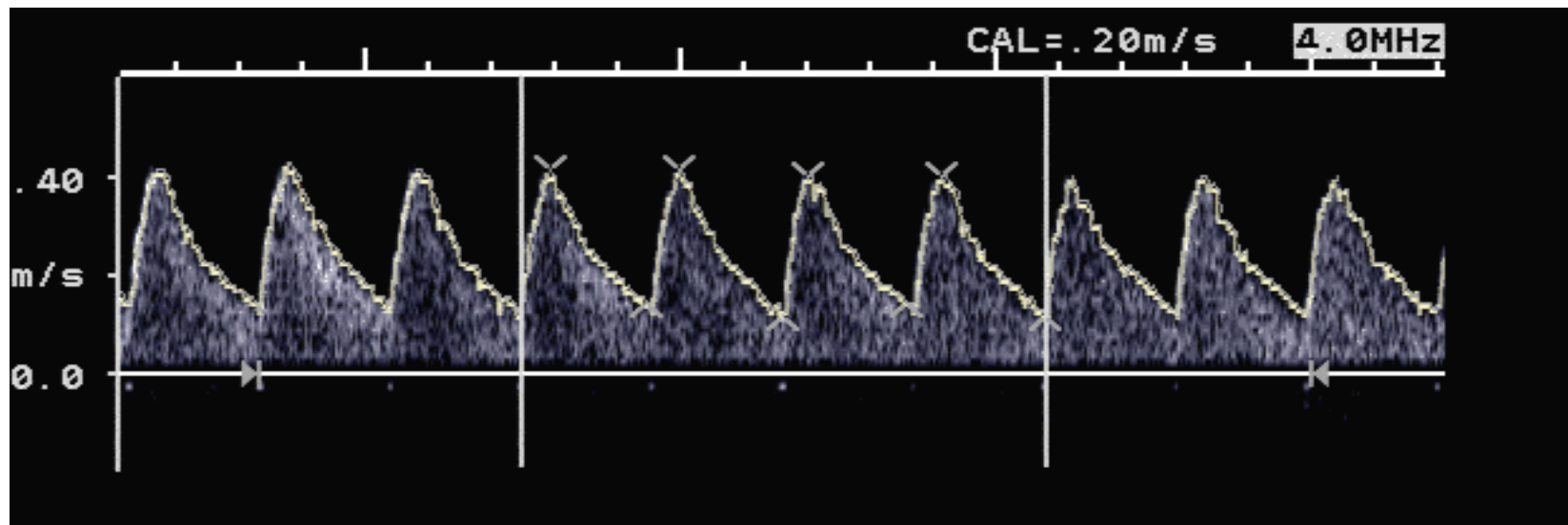
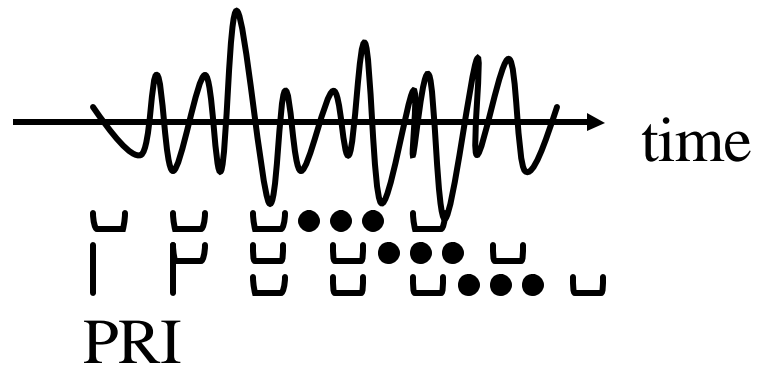
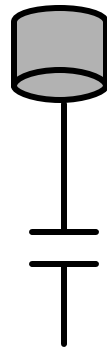
# PW Blood Flow Measurements



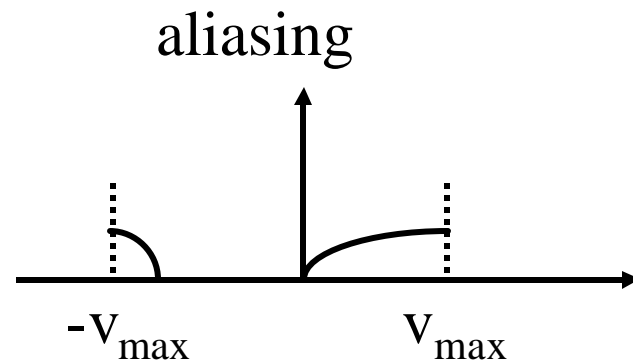
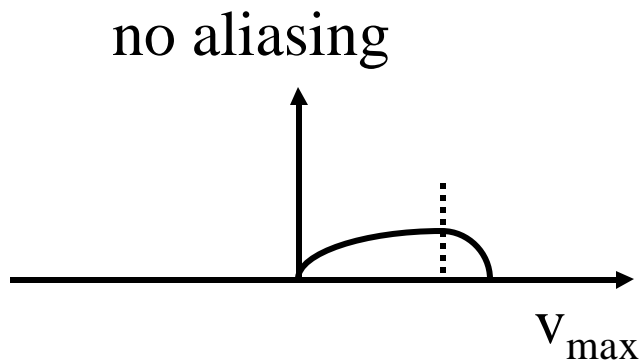
# PW System Diagram

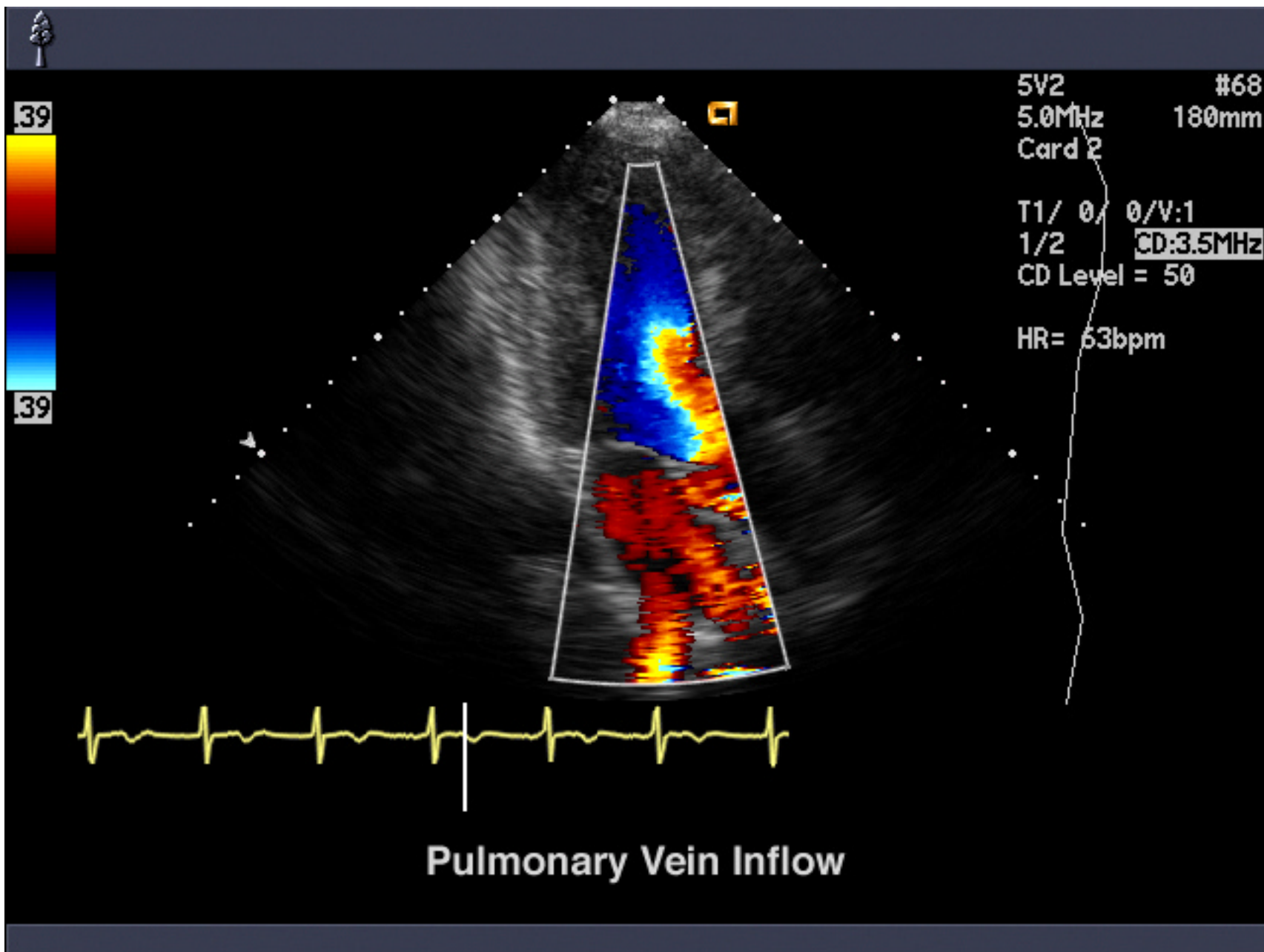


# Pulsed Wave (PW) Doppler

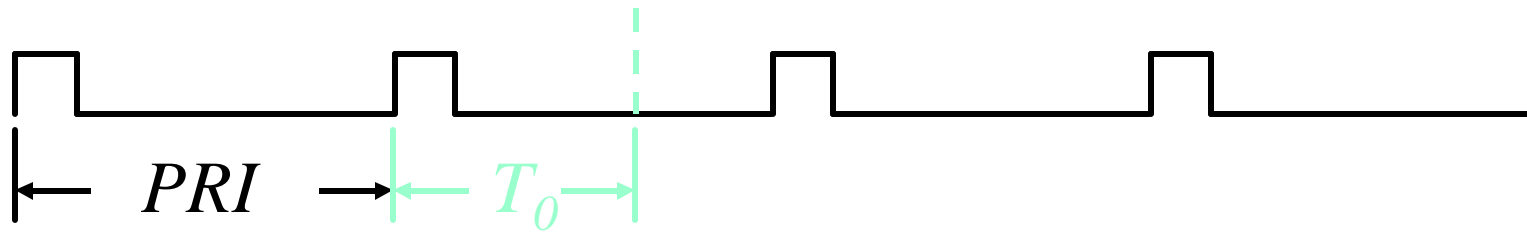


# Velocity Ambiguity





# Range Ambiguity

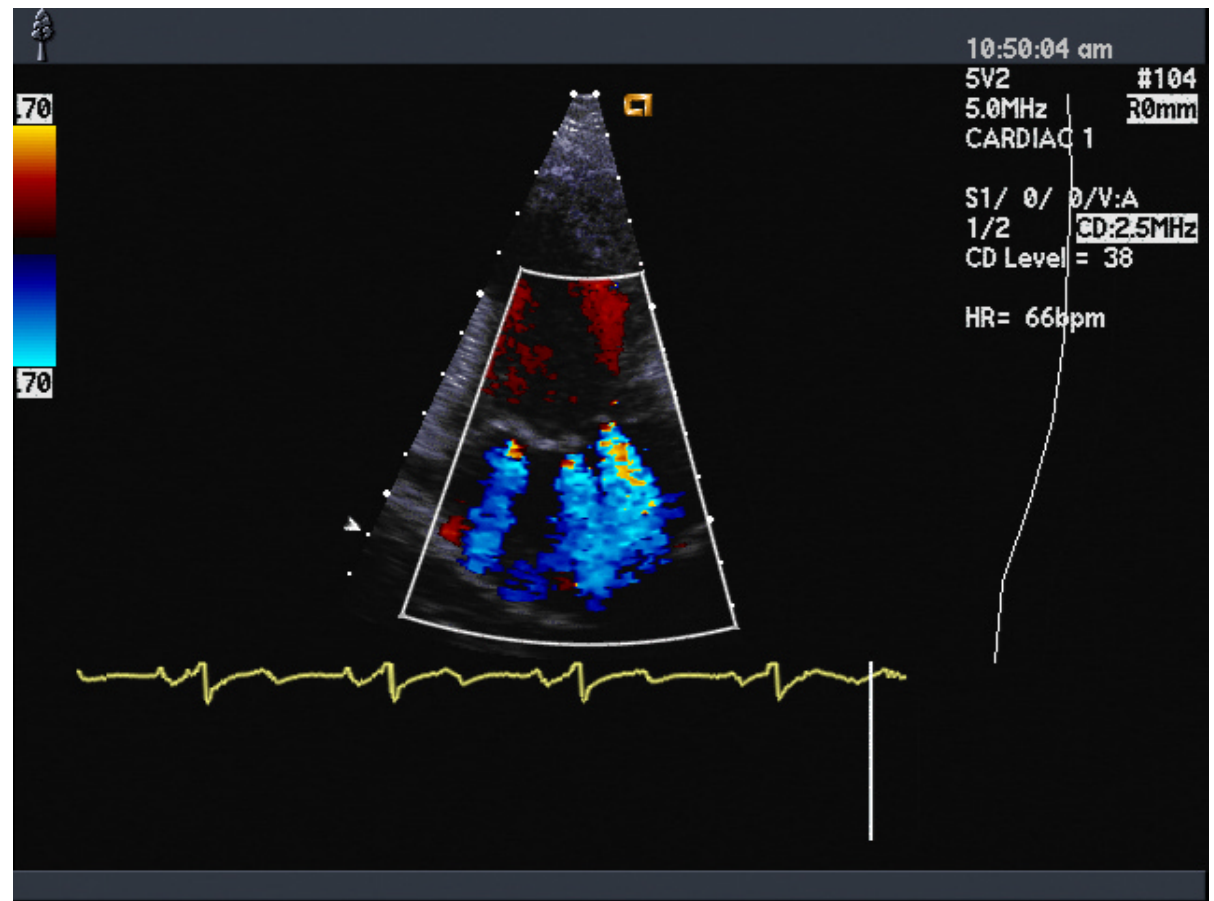
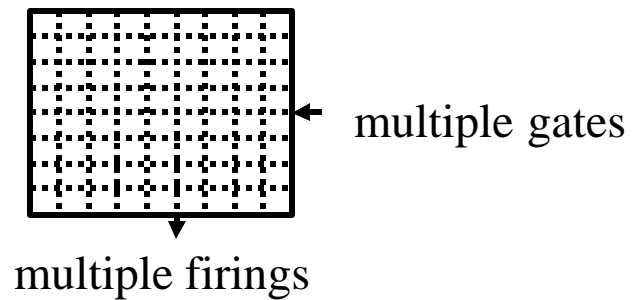




# Pulse Wave (PW) Doppler

- 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.

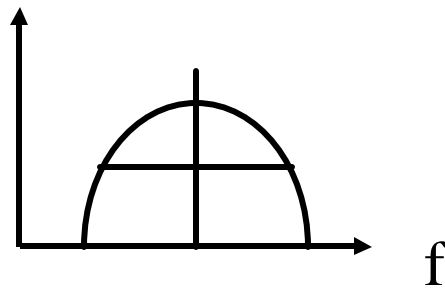
# Color Doppler



# 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

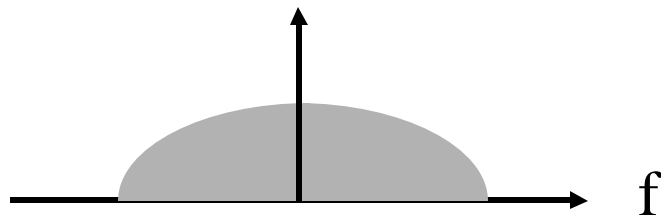


- Use efficient time domain correlation techniques to calculate flow characteristics.
- Auto-correlation of the Doppler signal.
- Commonly derived parameters are mean velocity (including directionality), variance and energy (power).

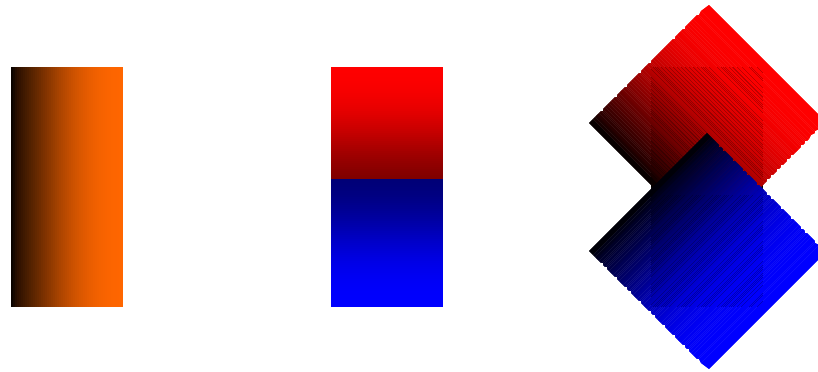
# Color Doppler: Mean Velocity

# Color Doppler: Variance

# Color Doppler: Energy



# 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.

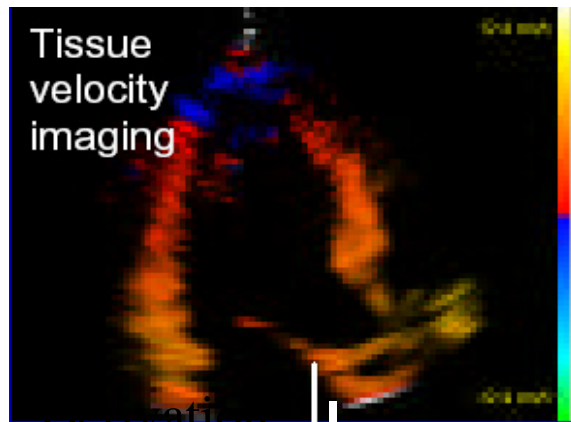
# Doppler: Tissue Motion Imaging

- 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

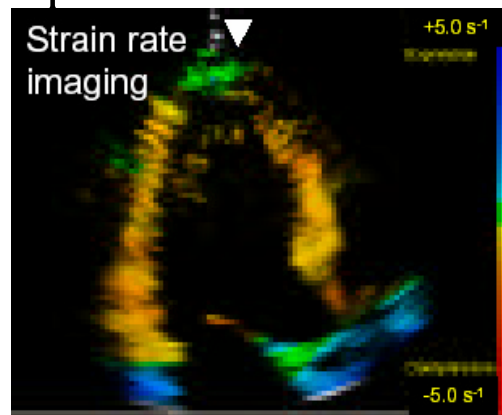
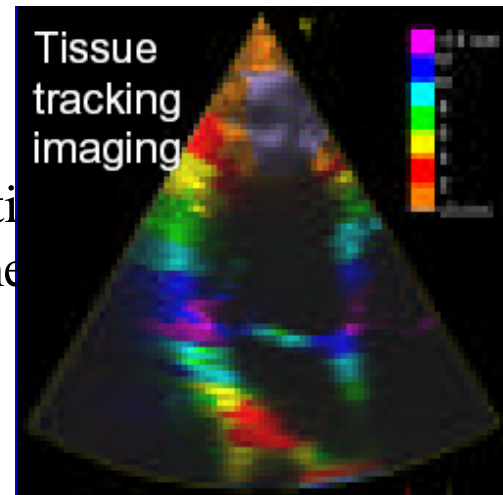
- Heart motion parameters:
  - Velocity:  $v = dw/dt$ .
  - Displacement  $w$ : temporal integration of  $v$ .
  - Strain rate:  $r = dv/dz$ .
  - Strain  $s$ : temporal integration of  $r$ .

# Doppler Tissue Imaging

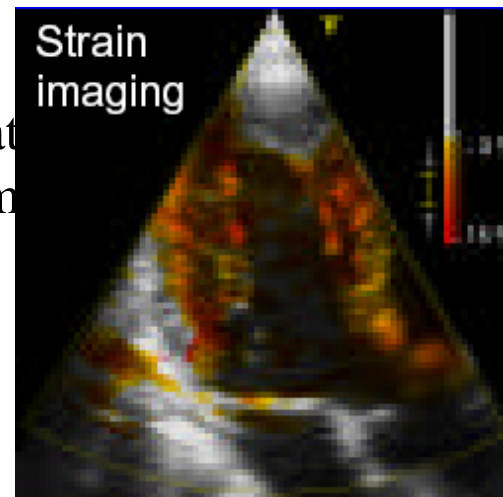


Derivation  
in space

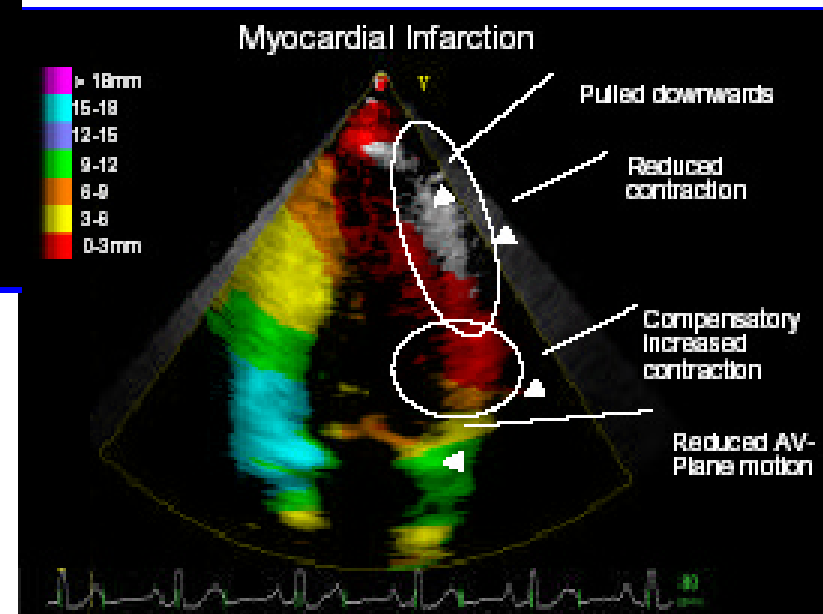
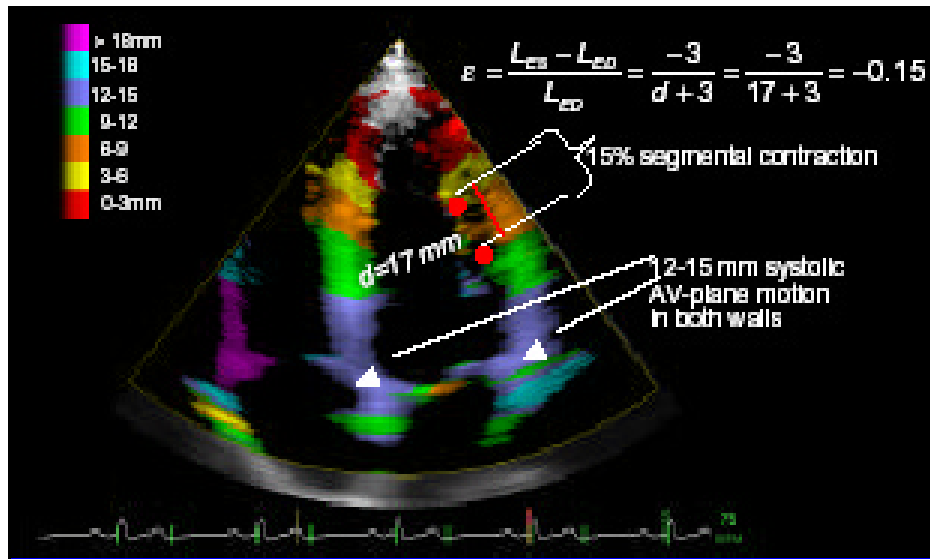
Integration  
in time



Integration  
in time



# Doppler Tissue Imaging



# Ultrasonic Nonlinear Imaging- *Tissue Harmonic Imaging*

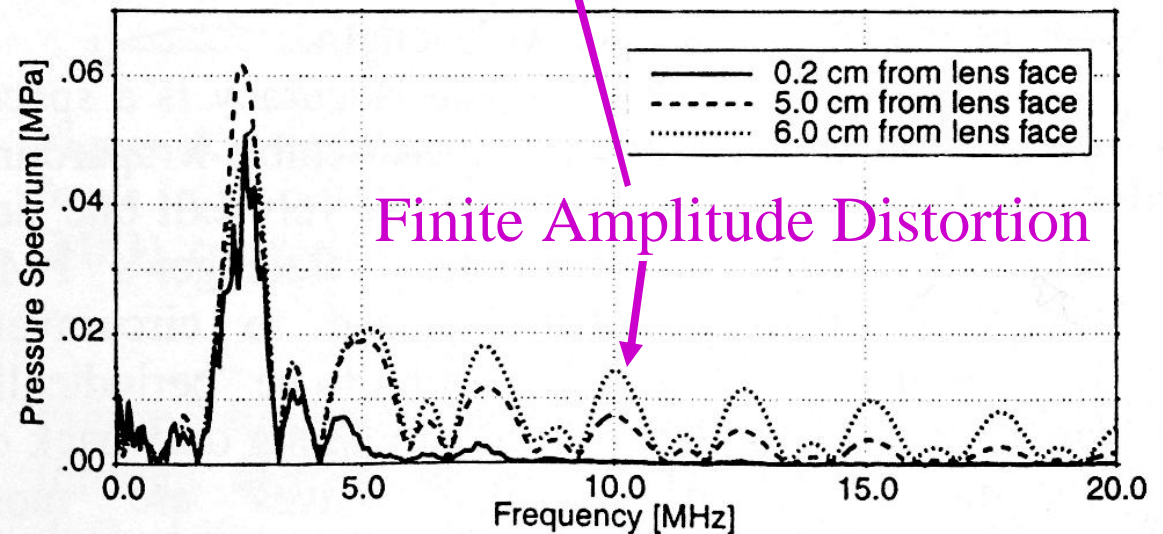
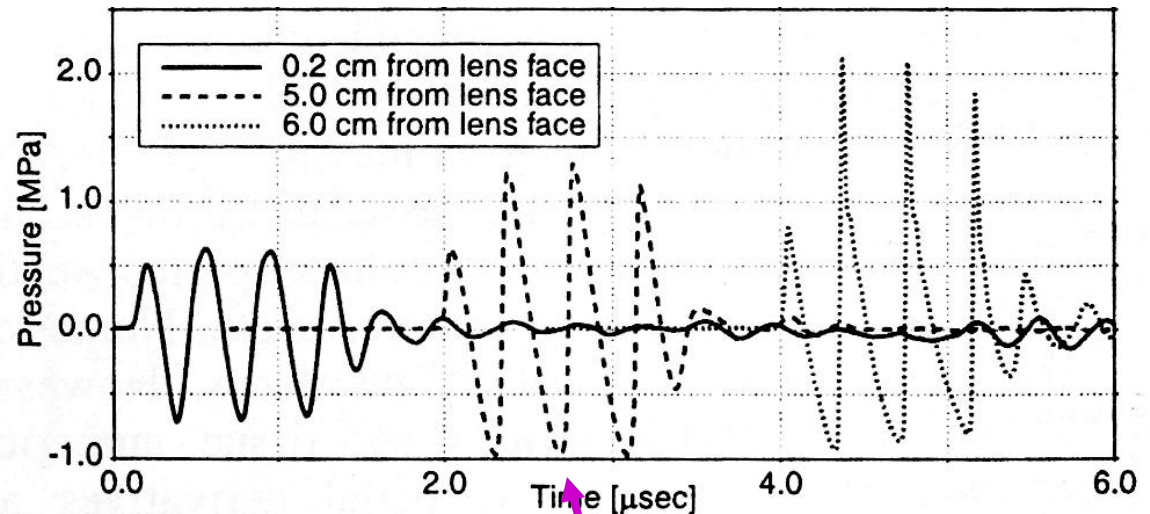
# Sound Velocity and Density Change

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

Phase velocity

Nonlinearity

Particle velocity





# Non-linear Parameter B/A

$$P = P_0 + \left( \frac{\mathcal{I}P}{\mathcal{I}r} \right)_{s;r=r_0} (r - r_0) + \frac{1}{2} \left( \frac{\mathcal{I}^2 P}{\mathcal{I}r^2} \right)_{s;r=r_0} (r - r_0)^2 + \dots$$

$$P - P_0 = A \left( \frac{r - r_0}{r_0} \right) + \frac{B}{2} \left( \frac{r - r_0}{r_0} \right)^2$$

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

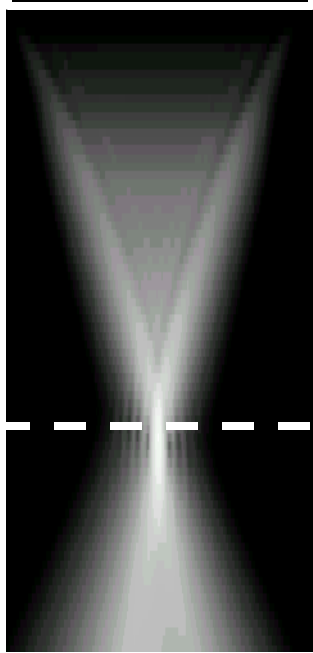
# B/A Parameters: Typical Values

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

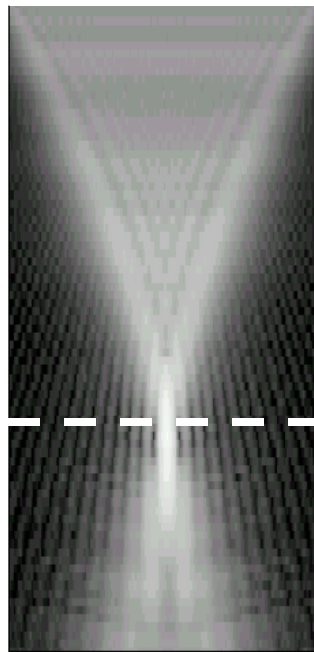
# Tissue Non-linearity

- 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.

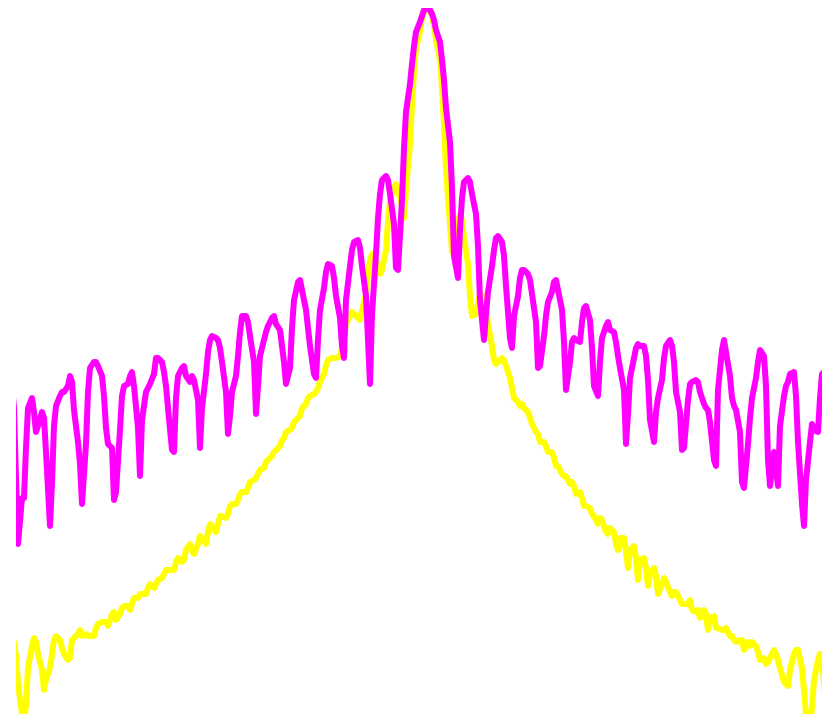
# Comparison of Radiation Patterns



$2f_0$



$f_0$



# What If We Use the Second Harmonic Signal for Imaging?

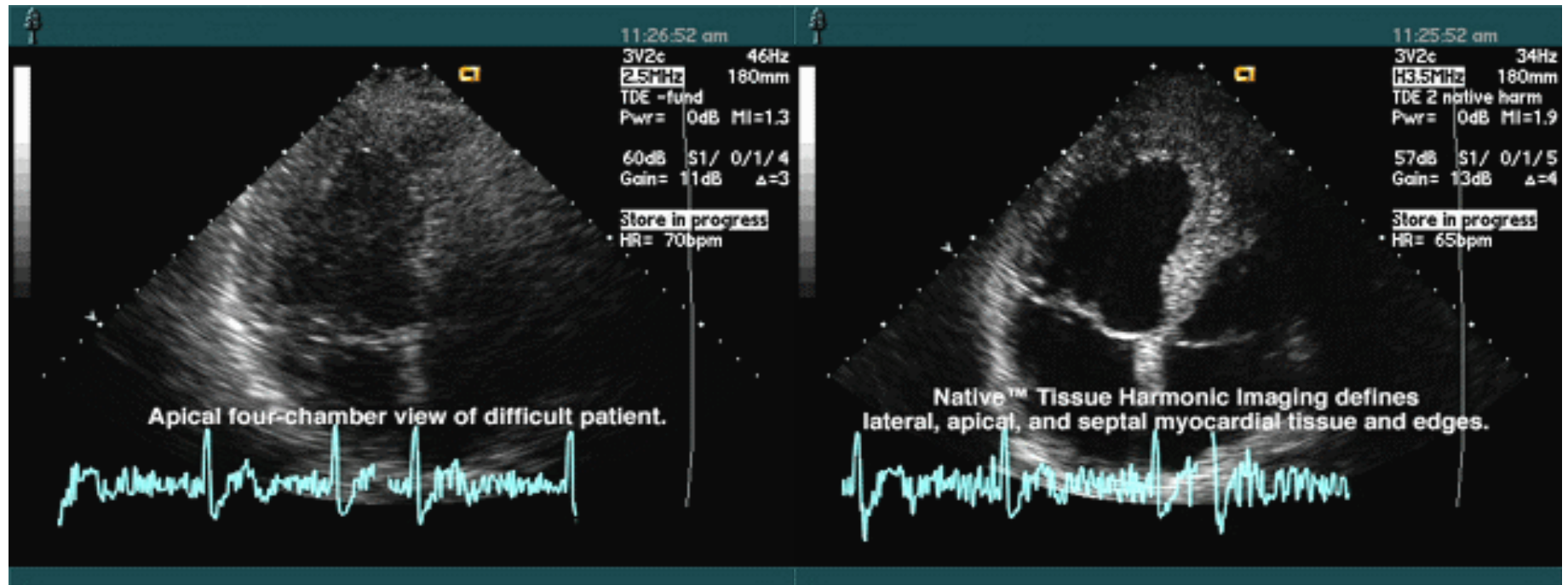
# Advantages of Tissue Harmonic Imaging

- 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

