生醫超音波技術

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Outline

- Fundamentals of ultrasound
- Focusing in acoustics
- Diffraction and array beamformation
- Image quality factors
- Ultrasonic blood flow estimation

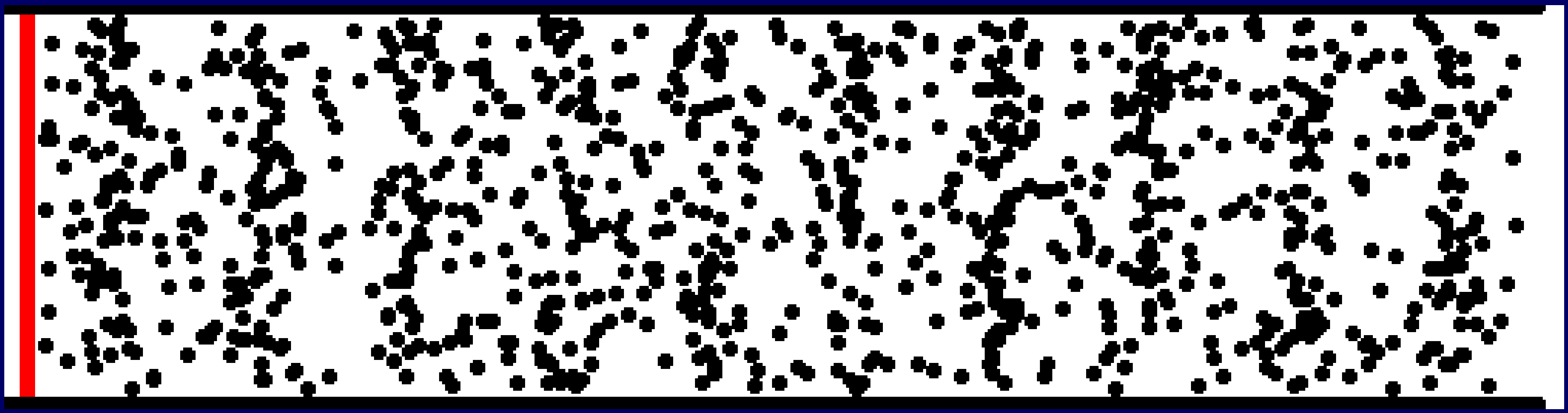
What is ultrasound?

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.

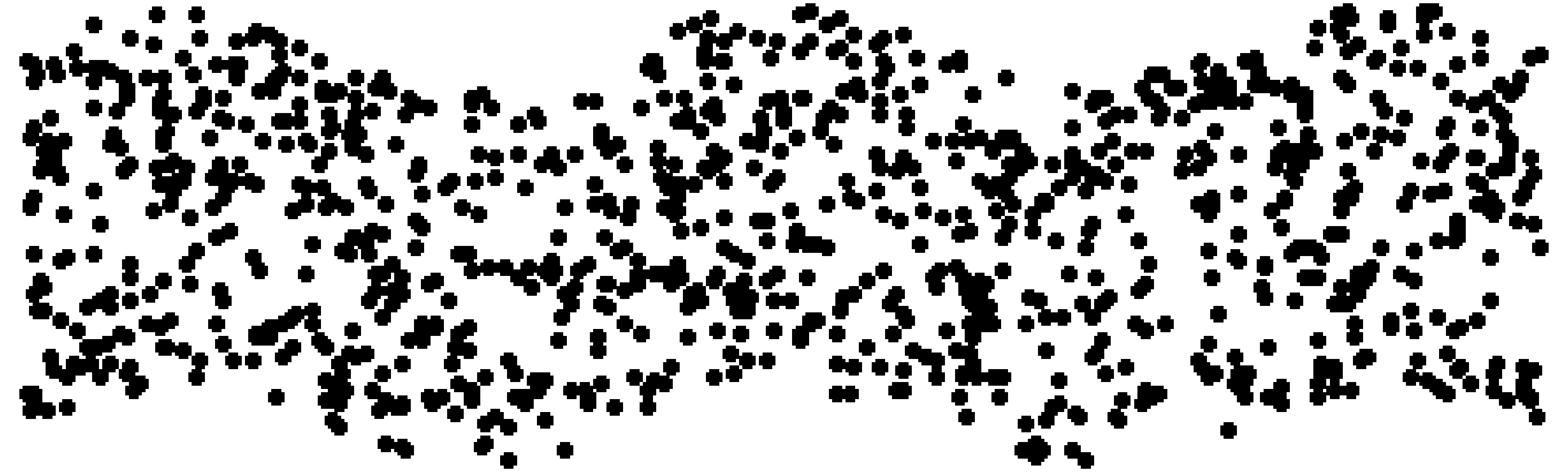
Basics of Acoustic Waves

- Longitudinal Wave:



Basics of Acoustic Waves

- Shear Wave:



Characteristics of Ultrasound

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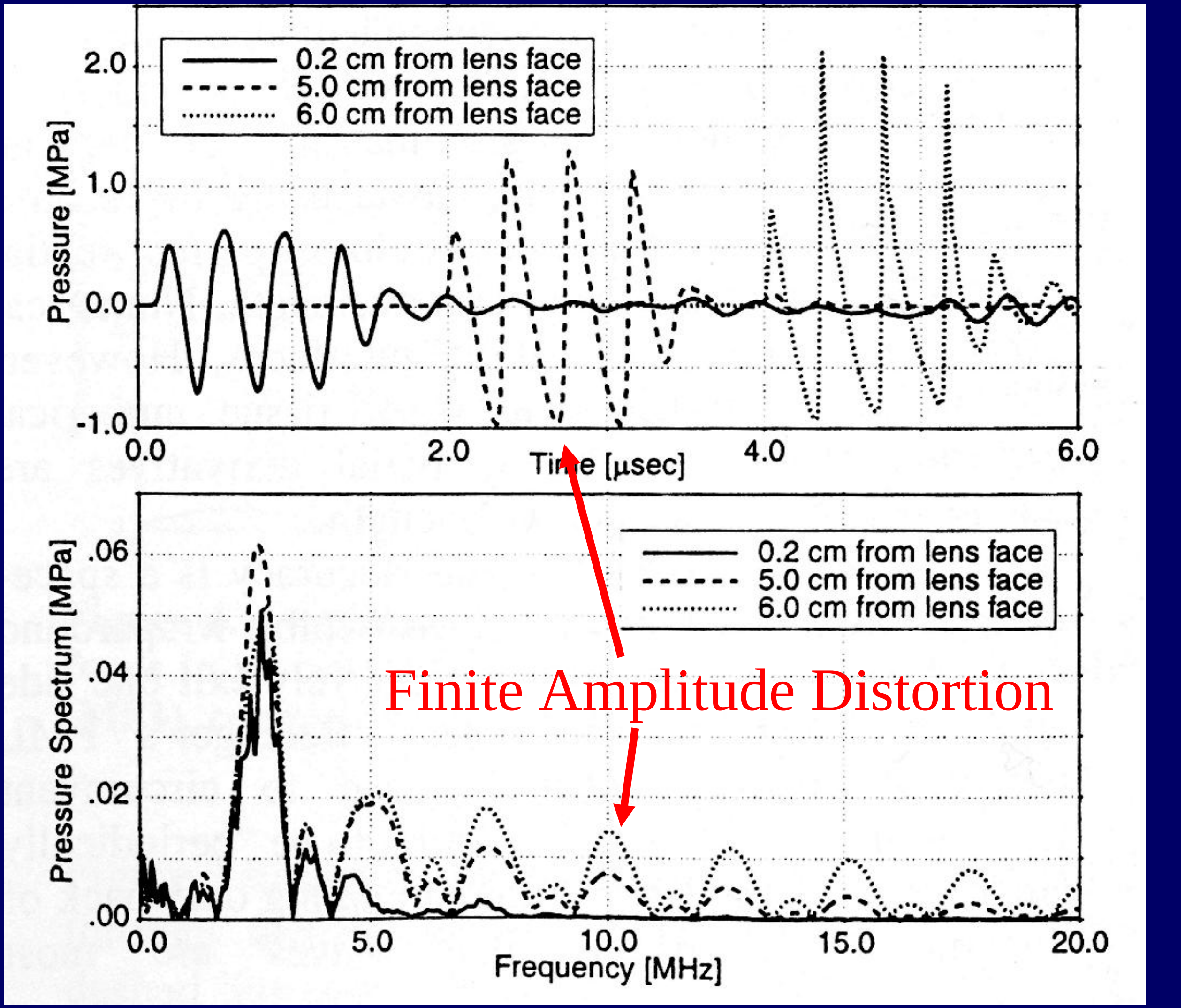
Sound Velocity and Density Change

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

Phase velocity

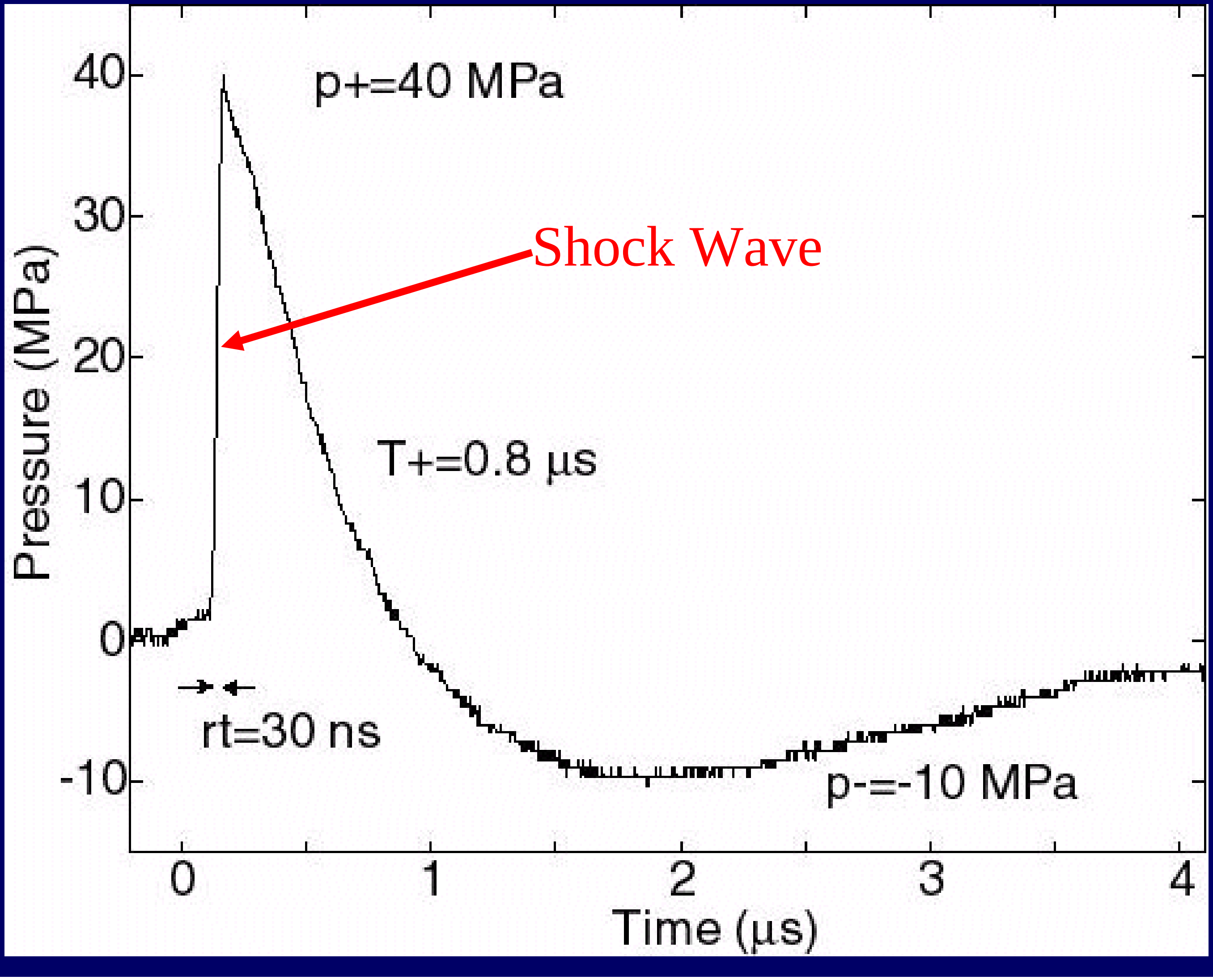
Nonlinearity

Particle velocity



Finite Amplitude Distortion

When Peak Pressure Is Very High



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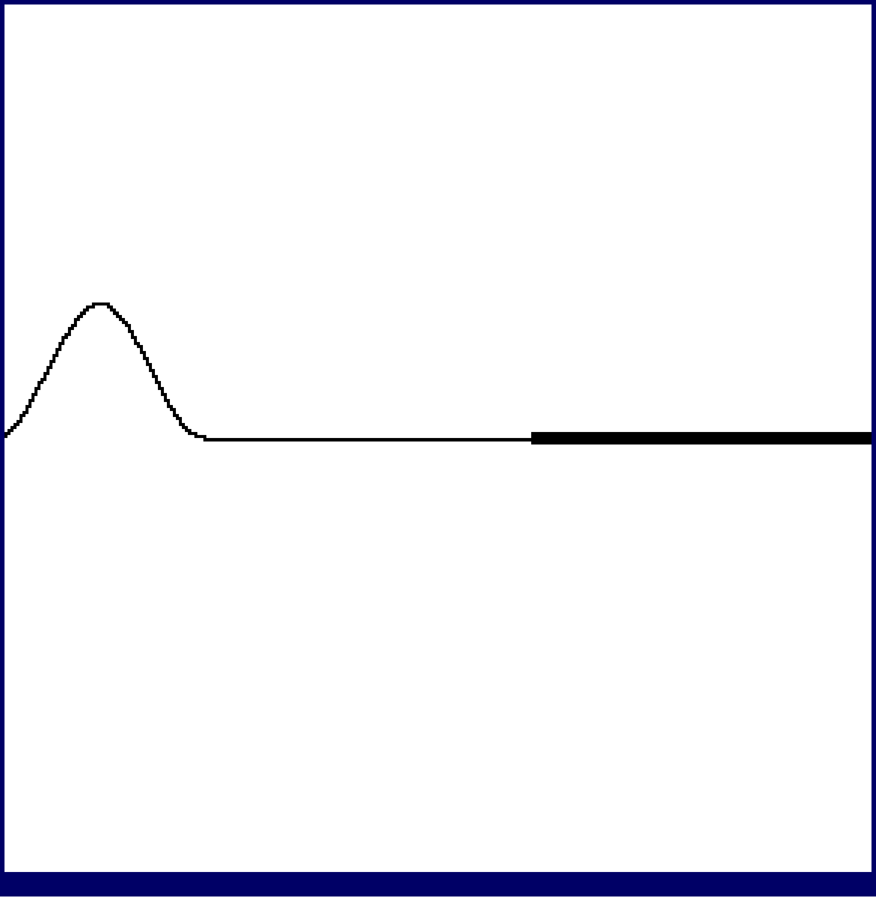
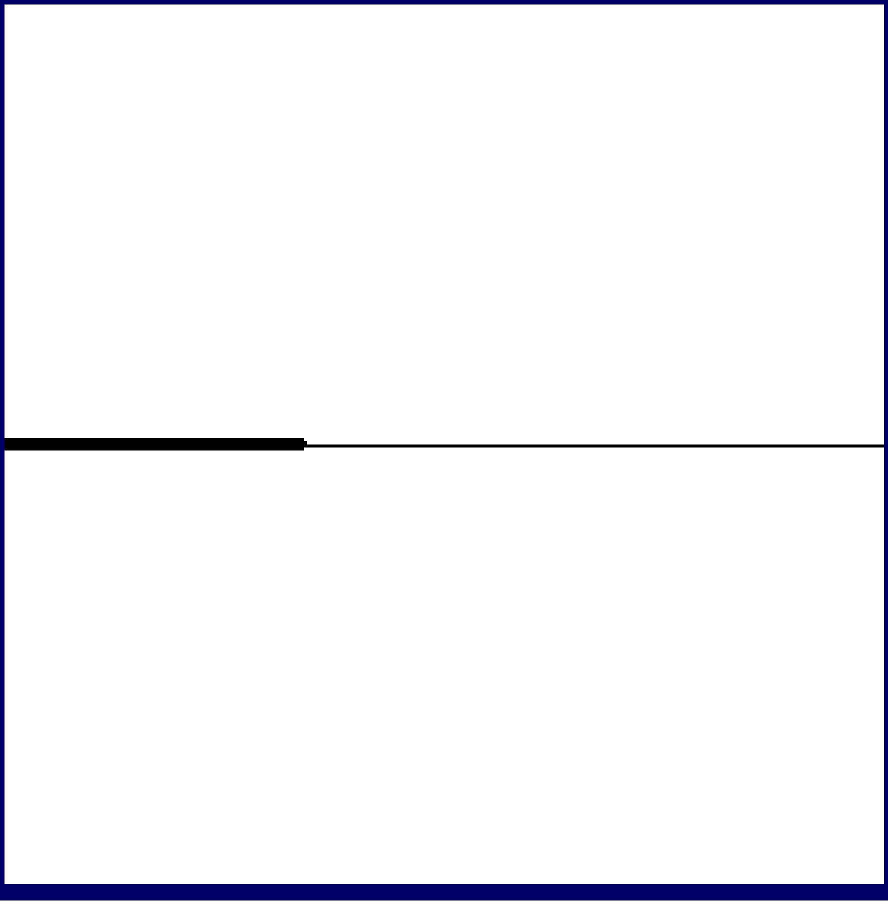
Reflection

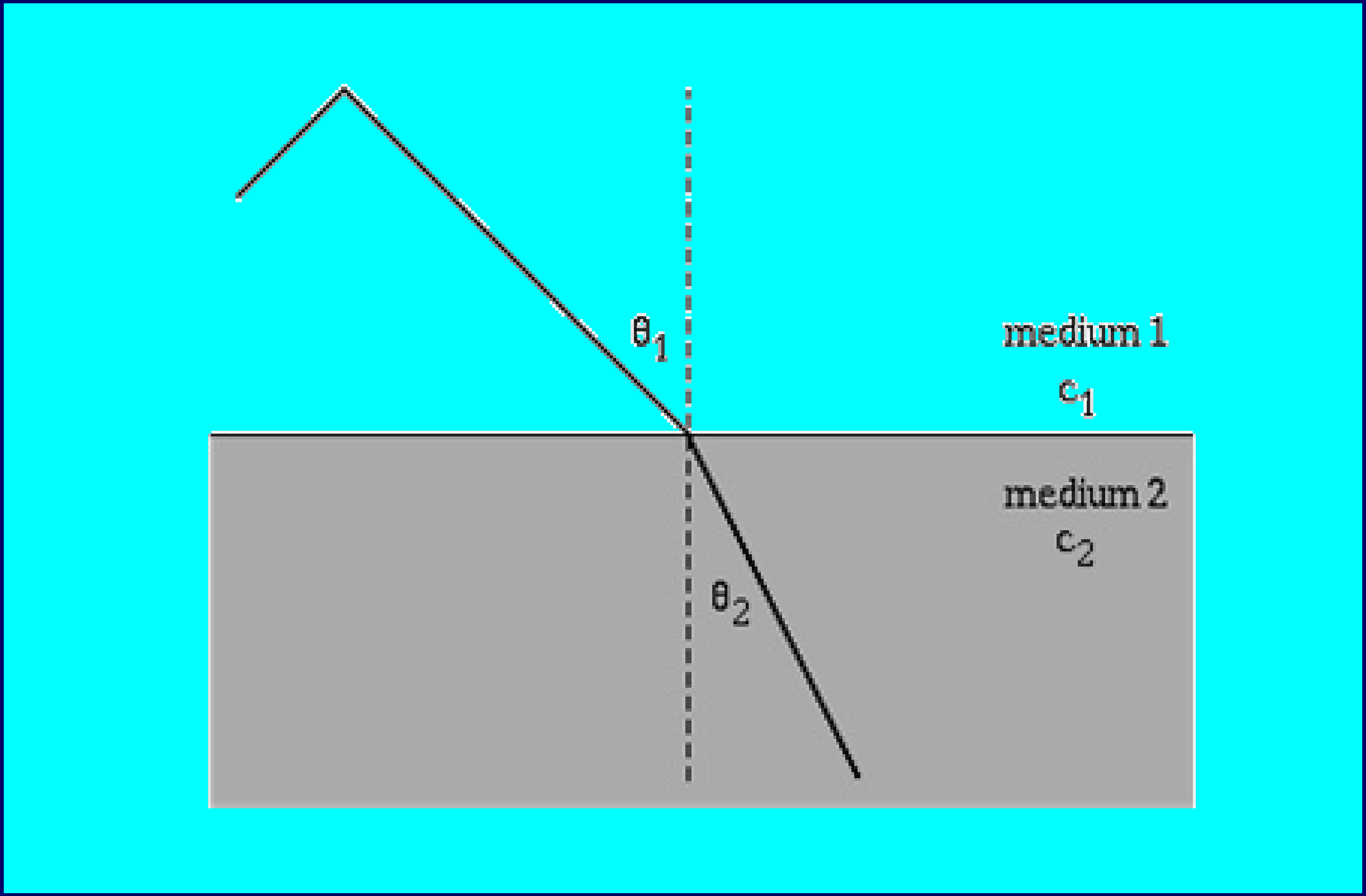
Low Density to High Density



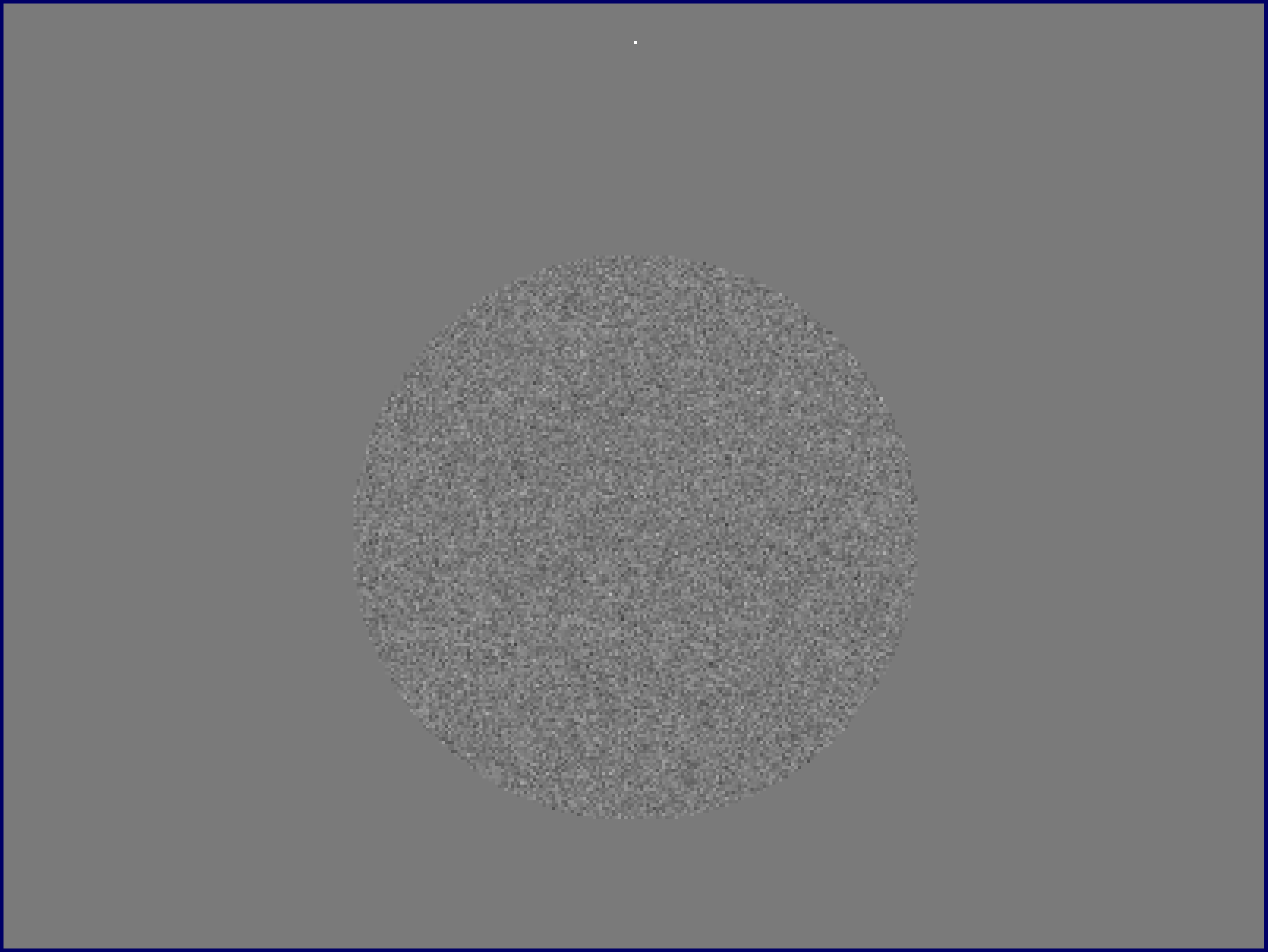
High Density to Low Density



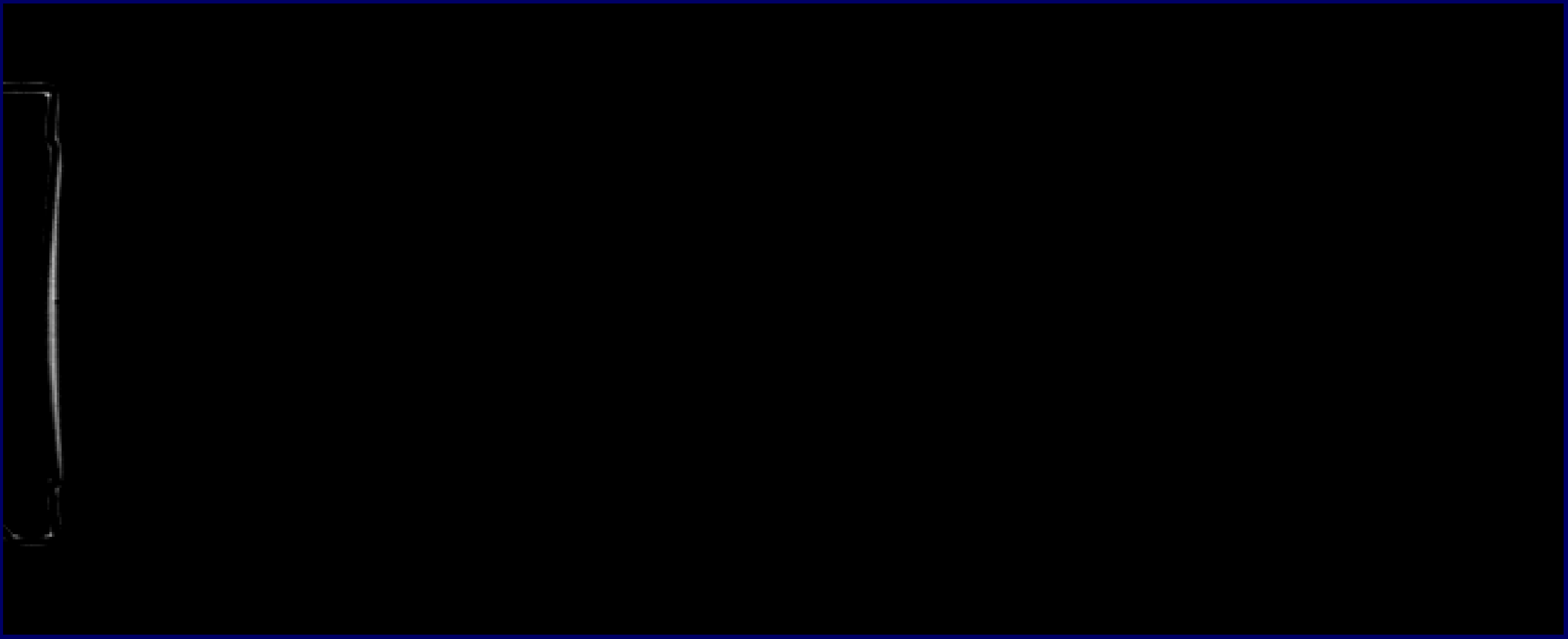
Refraction



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.
  - $c=f\cdot l$.
  - Sound (propagation) speed in soft tissues are around 1500m/sec. It becomes higher in hard tissues (e.g., bone).

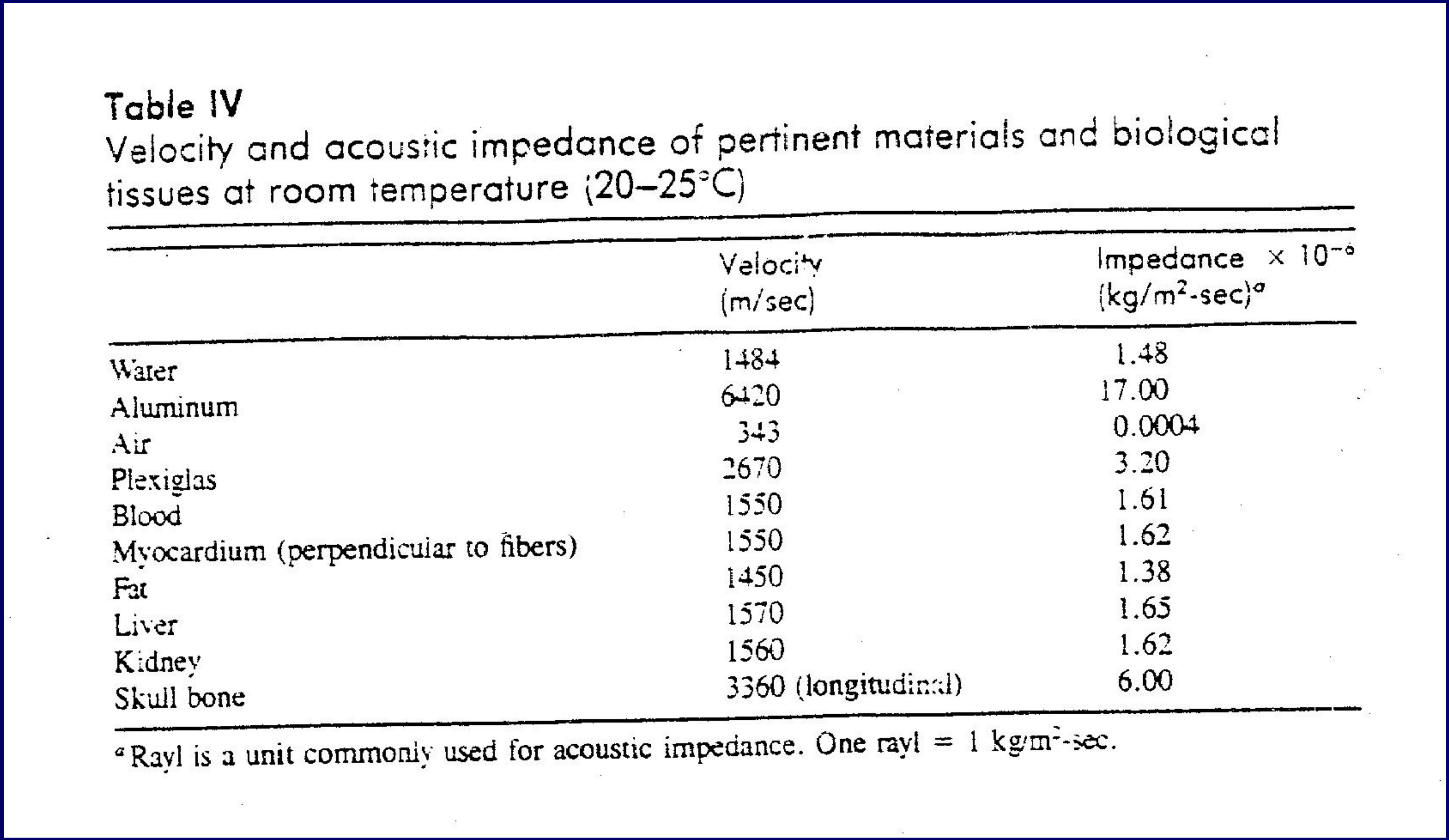


Table IV

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).

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

Characteristic impedance : $Z_0 = rc$

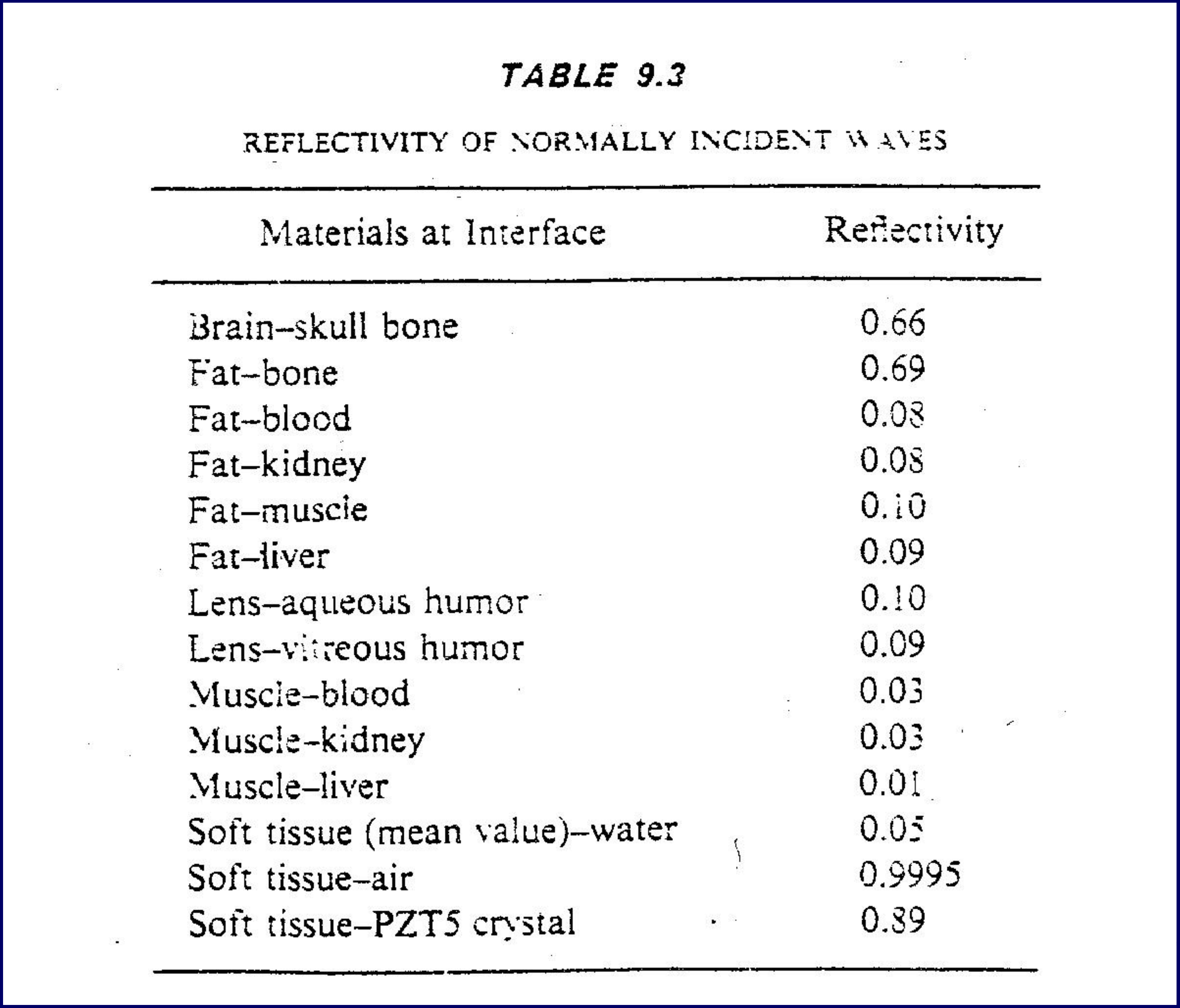


TABLE 9.3

REFLECTIVITY OF NORMALLY INCIDENT WAVES

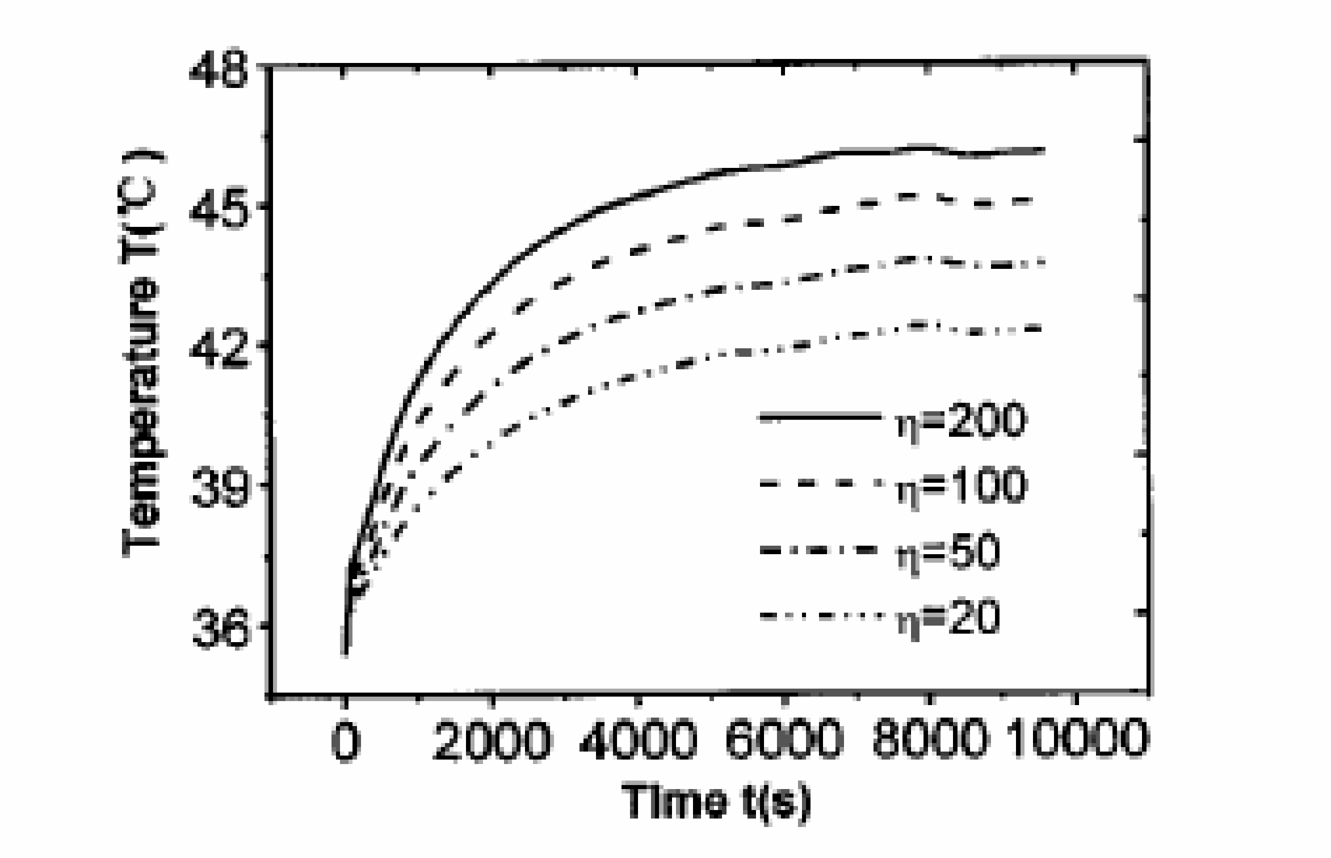
Materials at Interface	Reflectivity
Brain–skull bone	0.66
Fat–bone	0.69
Fat–blood	0.08
Fat–kidney	0.08
Fat–muscle	0.10
Fat–liver	0.09
Lens–aqueous humor	0.10
Lens–vitreous humor	0.09
Muscle–blood	0.03
Muscle–kidney	0.03
Muscle–liver	0.01
Soft tissue (mean value)–water	0.05
Soft tissue–air	0.9995
Soft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

Bio-Effects

- Heating
- Cavitation

Ultrasound Heating

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

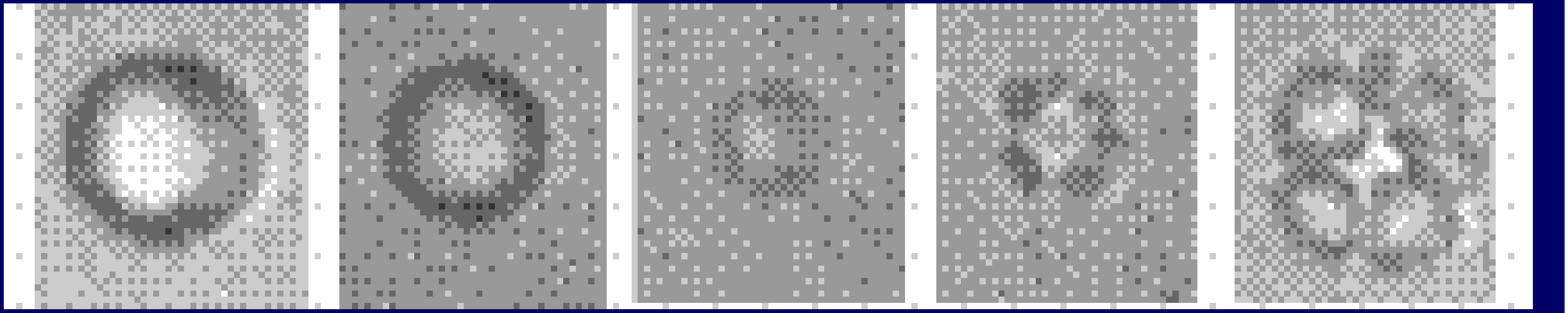


Bio-Effects

- 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.

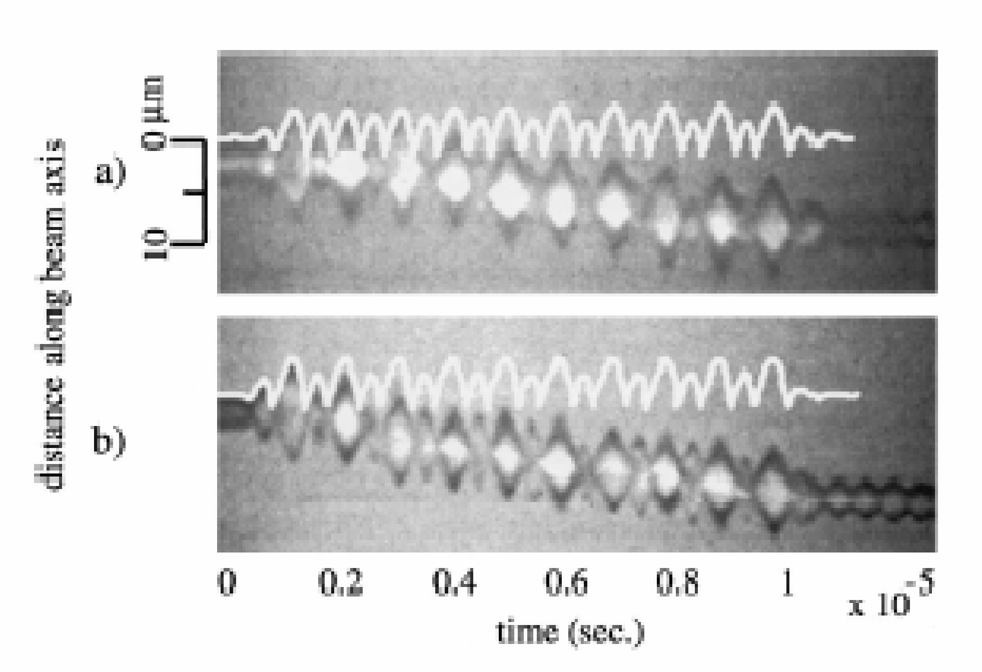


Other Acoustic Phenomena

- 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.

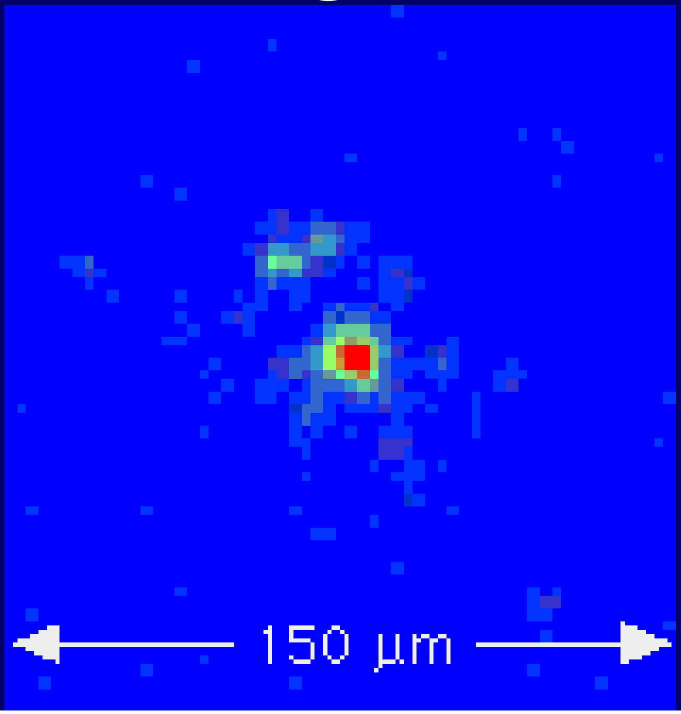


Other Acoustic Phenomena

- Radiation force.
- Sonoluminescence.
- …etc.

Sonoluminescence

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



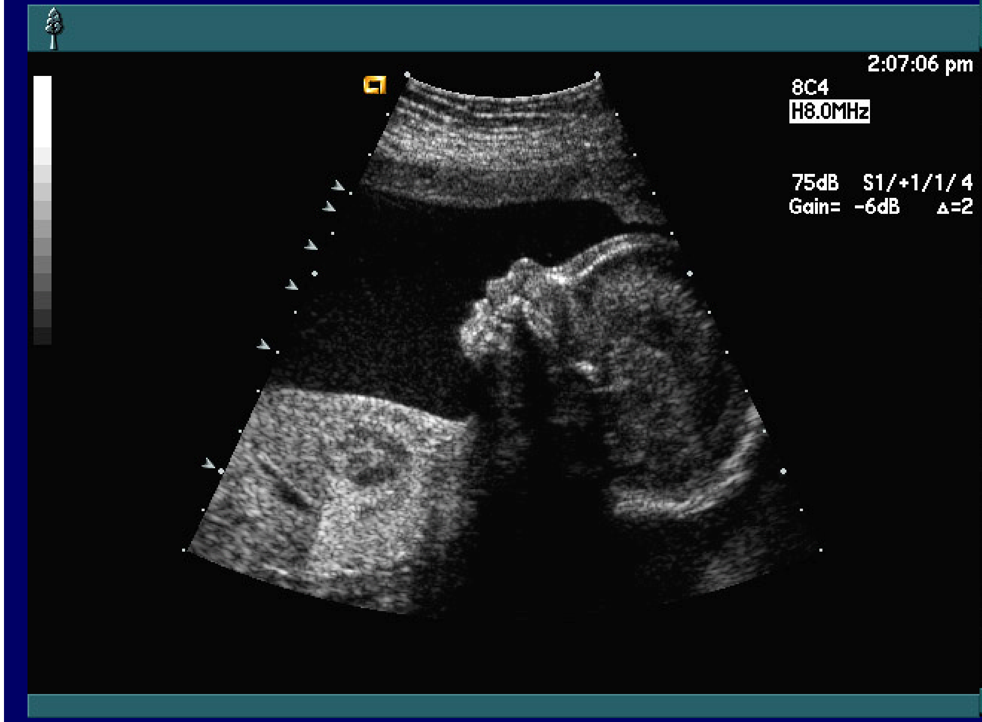
. . . ,etc.

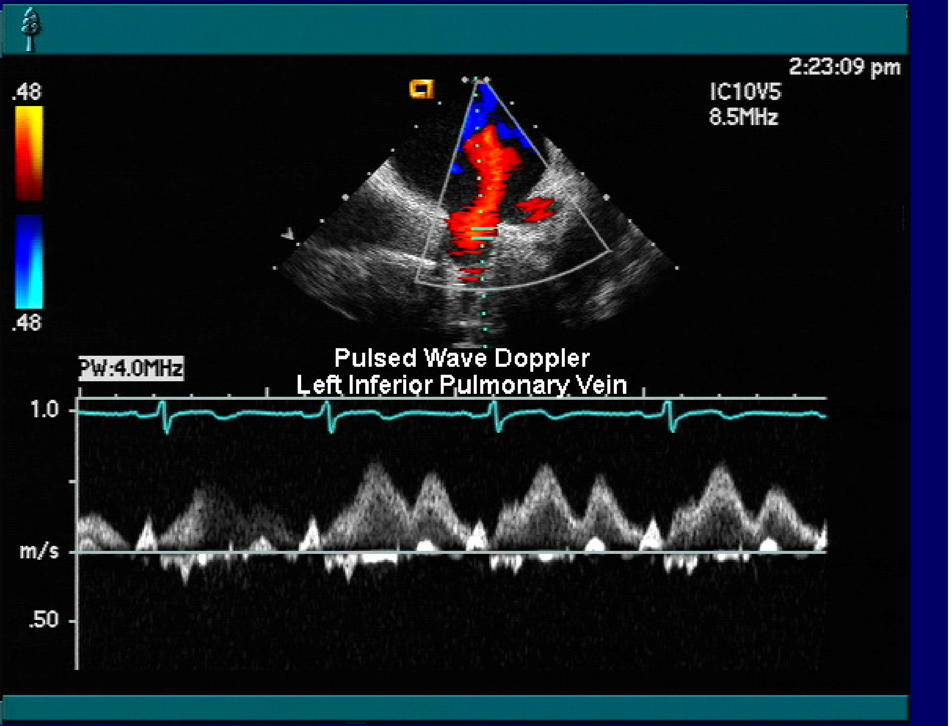
What can ultrasound do in medicine and biology?

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 ℃ or above, and maintaining this for 30-60 minutes.

Hyperthermia

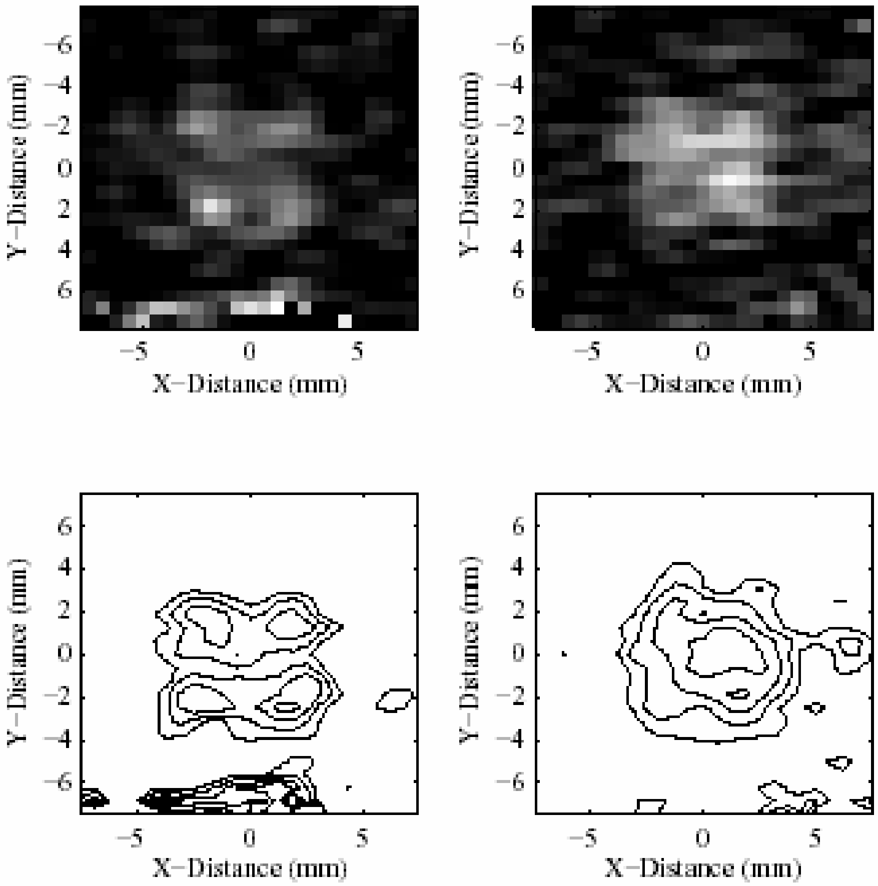


Figure 3: Thermal contour images for (left) non-switched and (right) switched sonications.

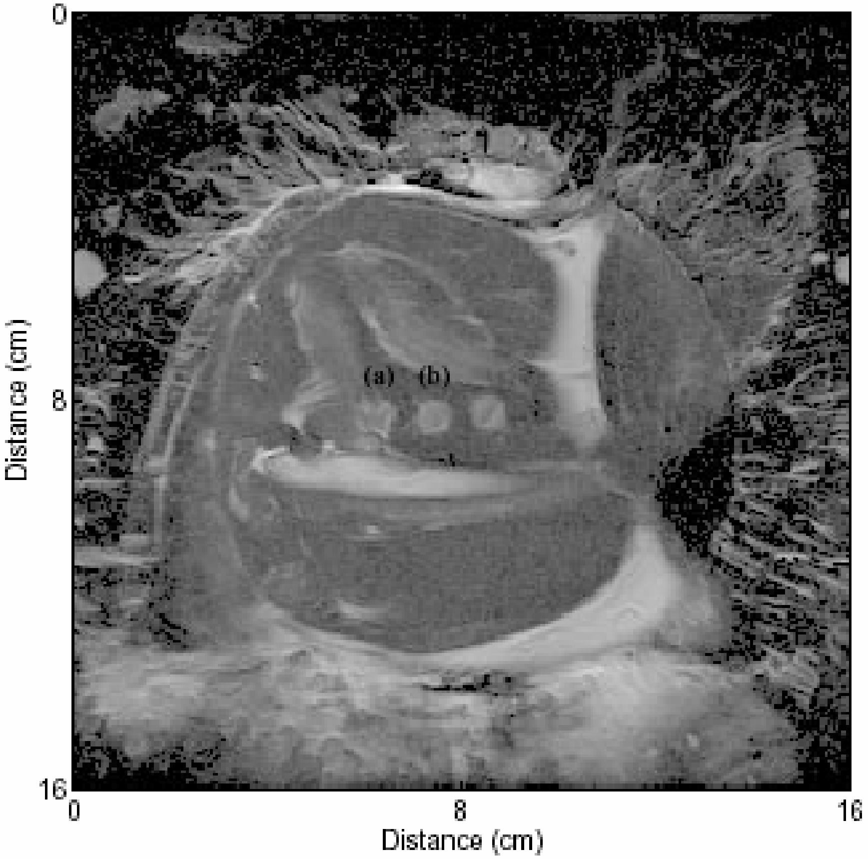


Figure 4: T2 weighted image of thermal necrosis caused by (a) single four focus pattern and (b) switched focus pattern across axis.

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 ℃) which destroys the cells located in the targeted zone.

HIFU for Prostate Cancer

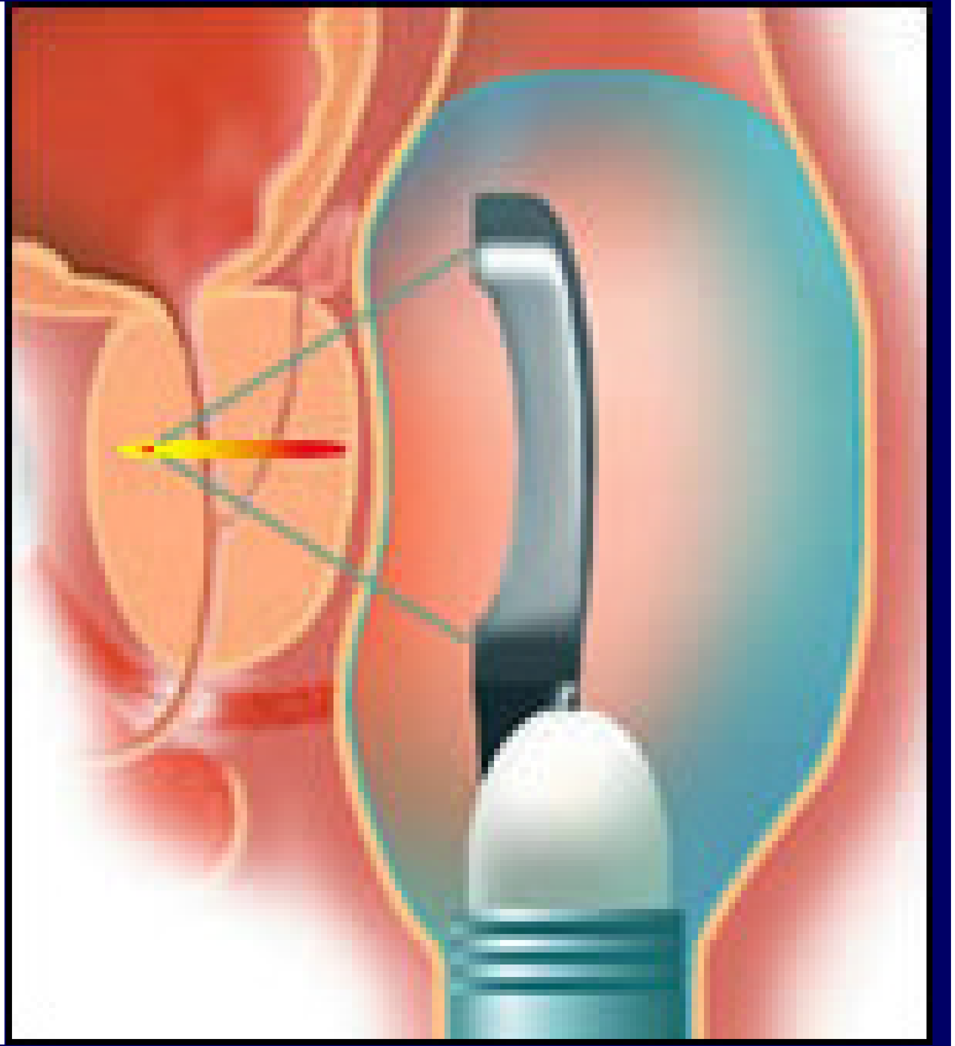


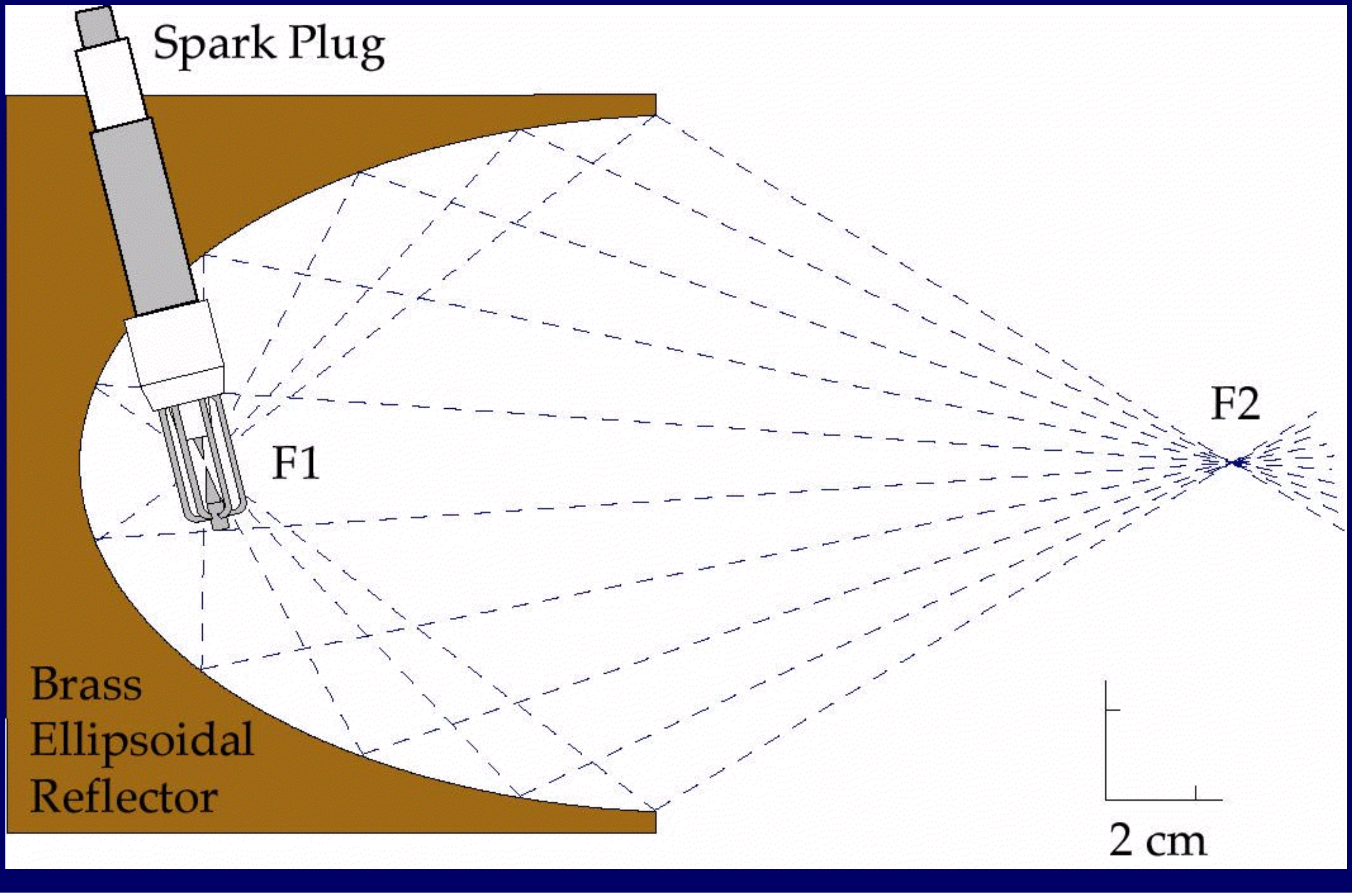
Image Guided HIFU

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

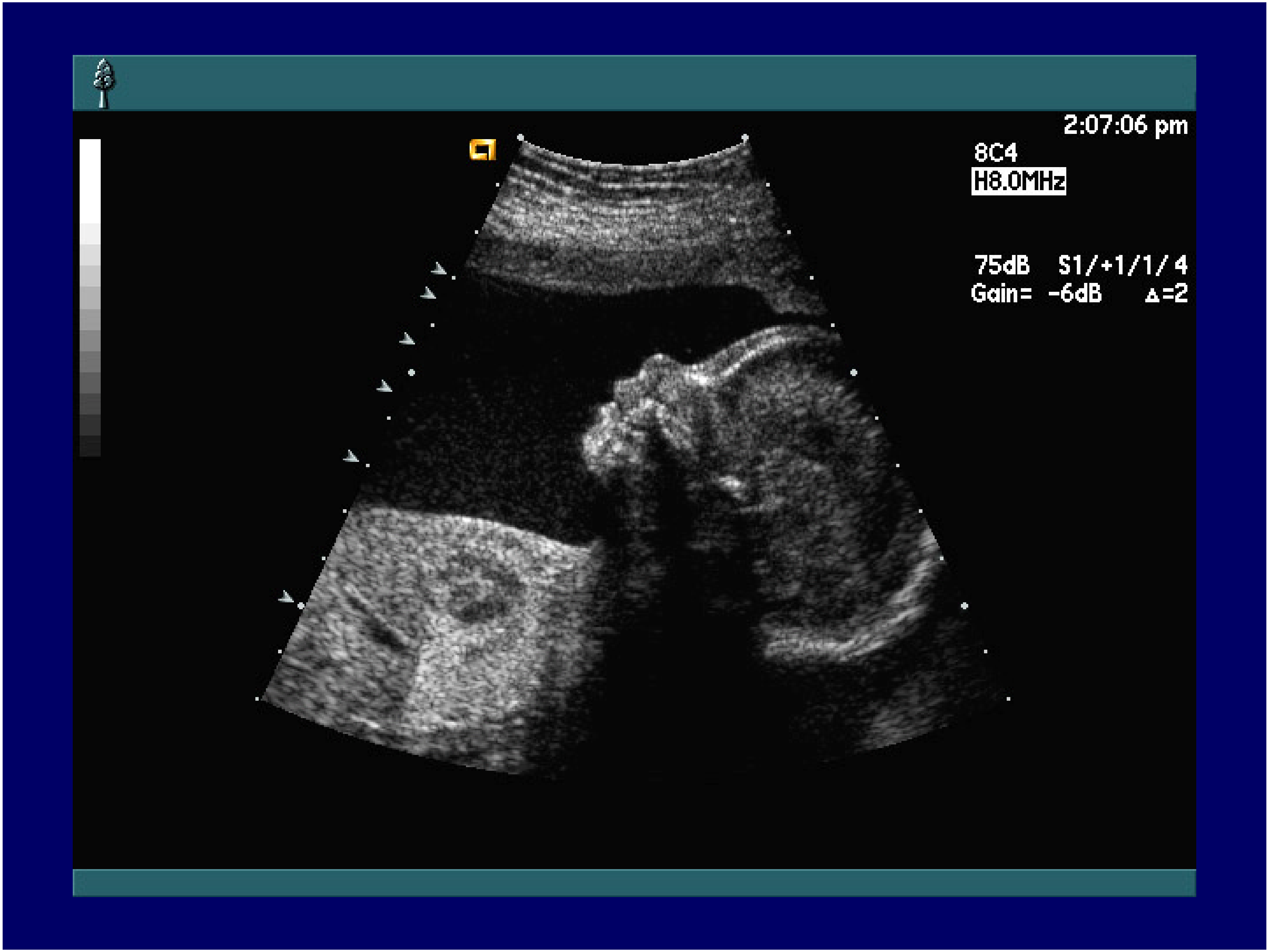
- Thermal index (TI):
  - TIS, TIB, TIC.
  - Analytical.

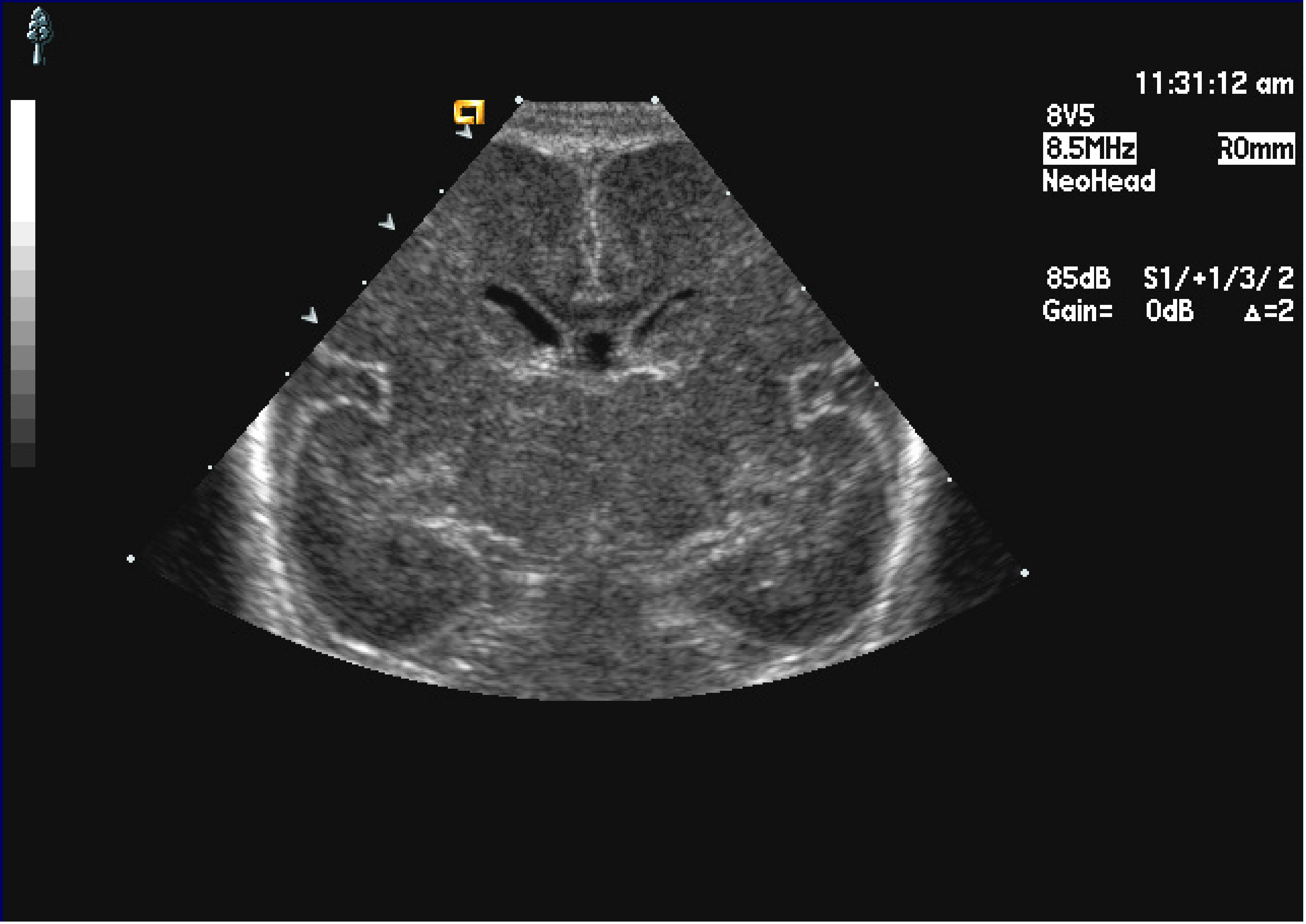
$$TI \equiv \frac{W_o}{W_{\deg}}$$

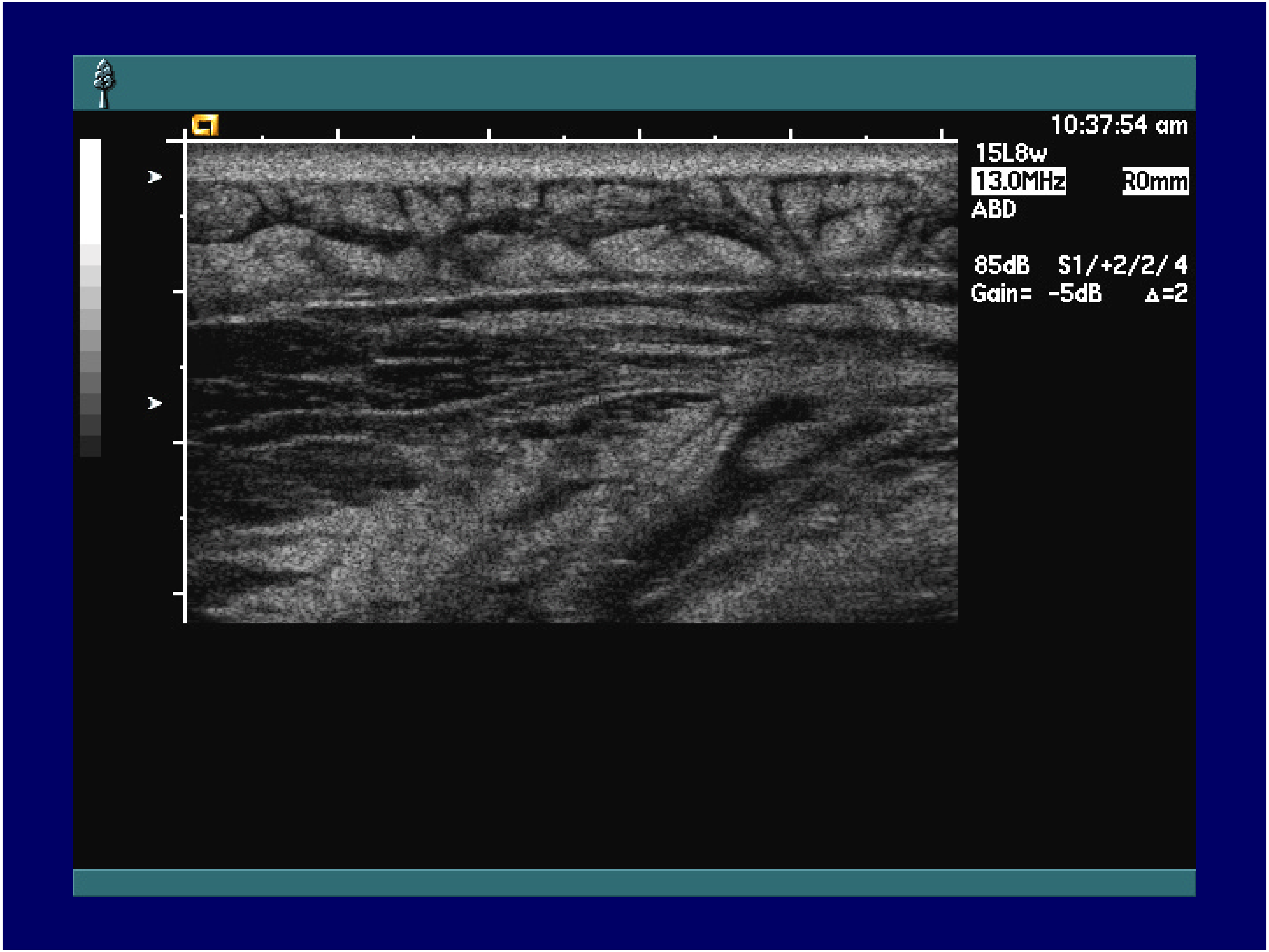
- Mechanical Index (MI):
  - Experimental.
  - Destruction of bubble with different sizes at various frequencies.

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

Imaging

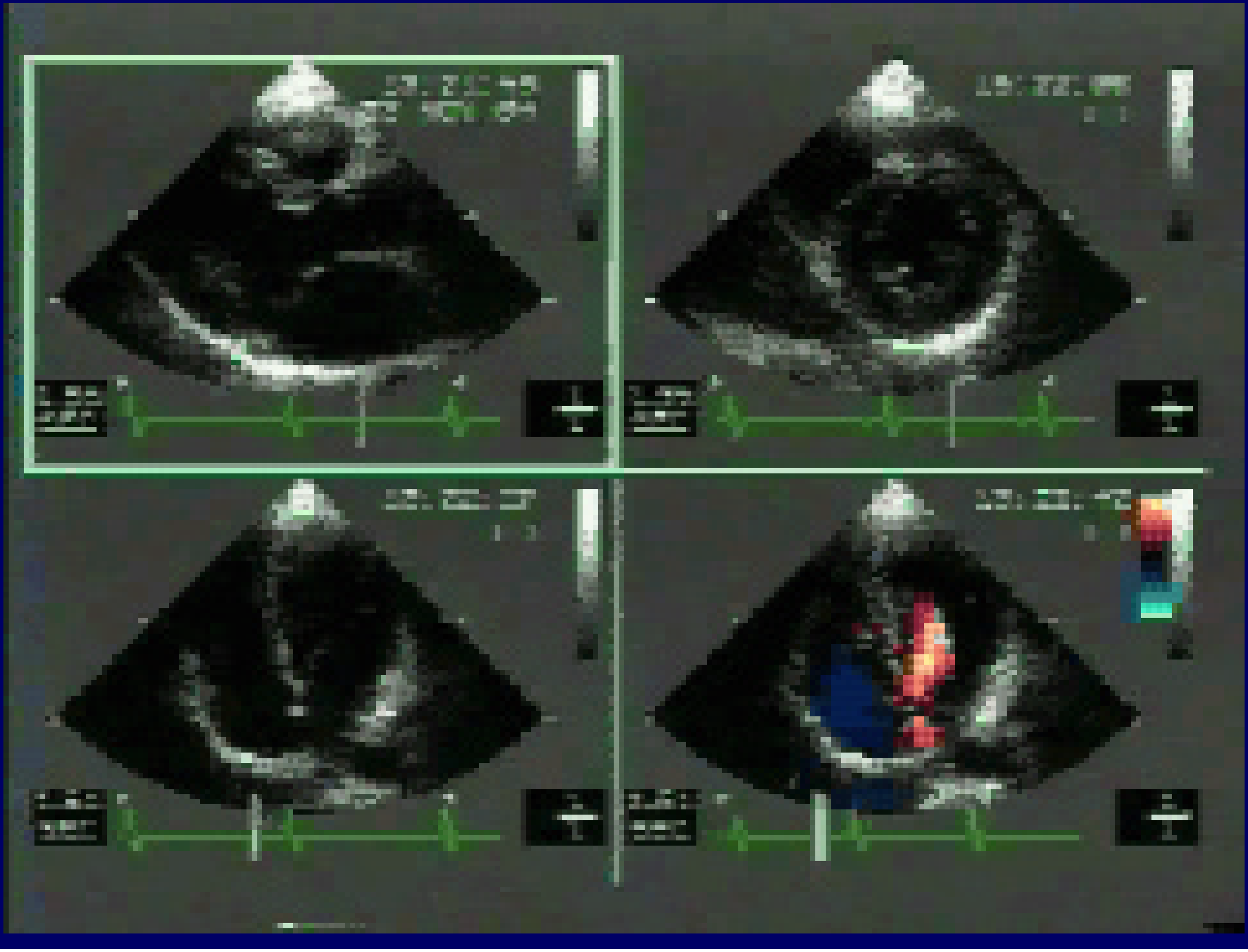

2:07:06 pm
8C4
H8.0MHz
75dB S1/+1/1/ 4
Gain= -6dB ▵=2

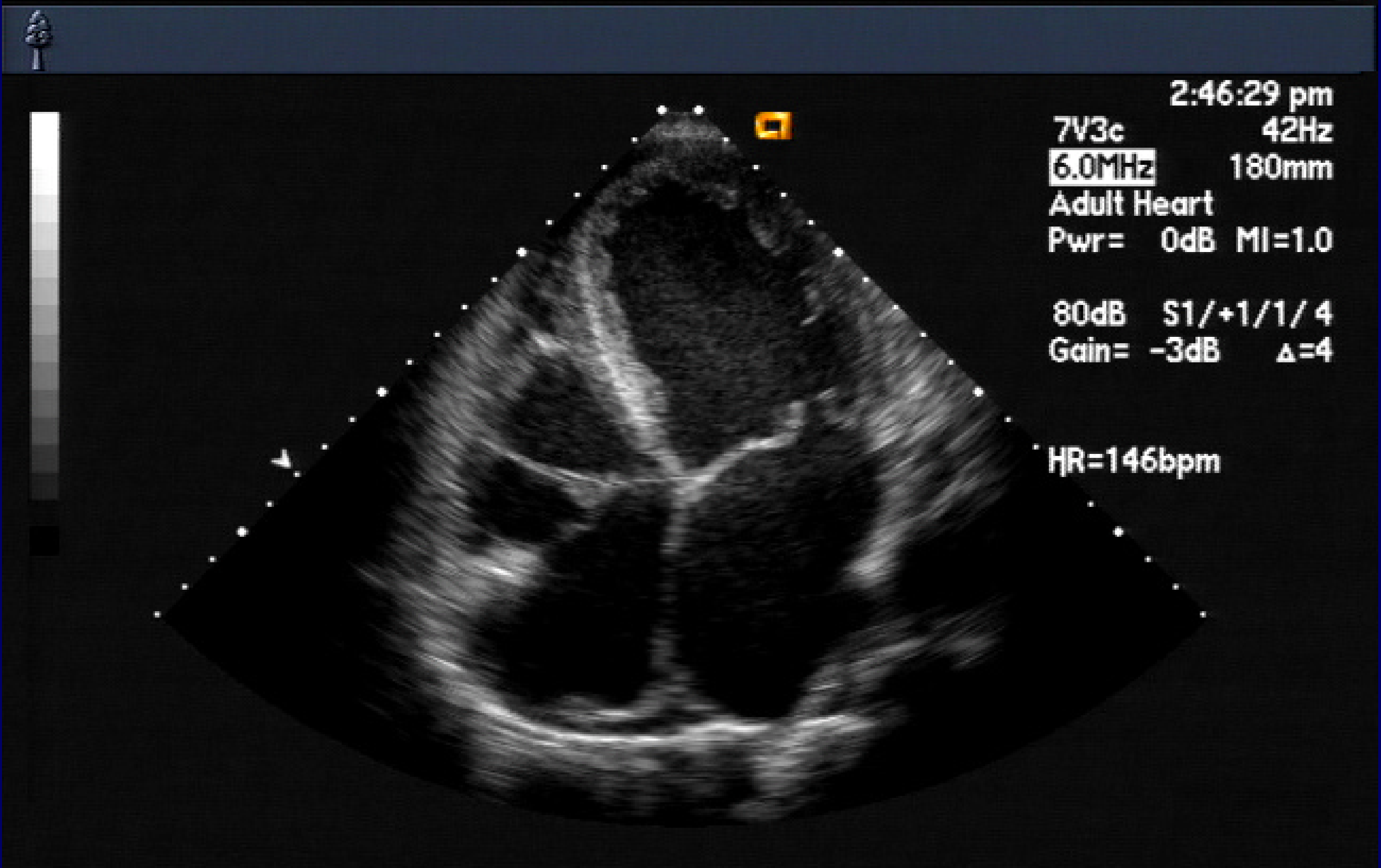

11:31:12 am
8V5
8.5MHz
R0mm
NeoHead
85dB
S1/+1/3/ 2
Gain=
0dB
▵=2



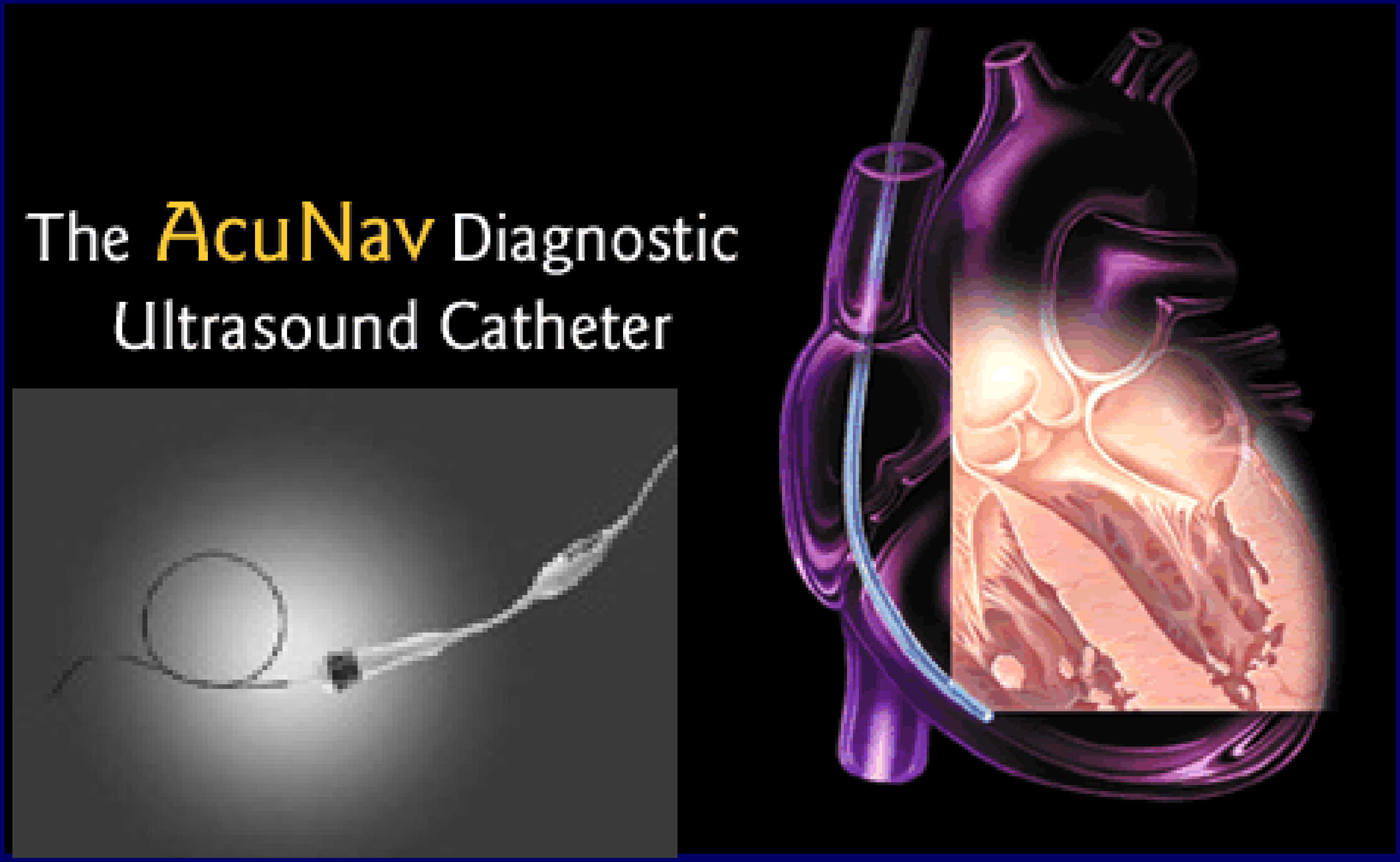
10:37:54 am
15L8w
13.0MHz
R0mm
ABD
85dB S1/+2/2/ 4
Gain= -5dB ▵=2

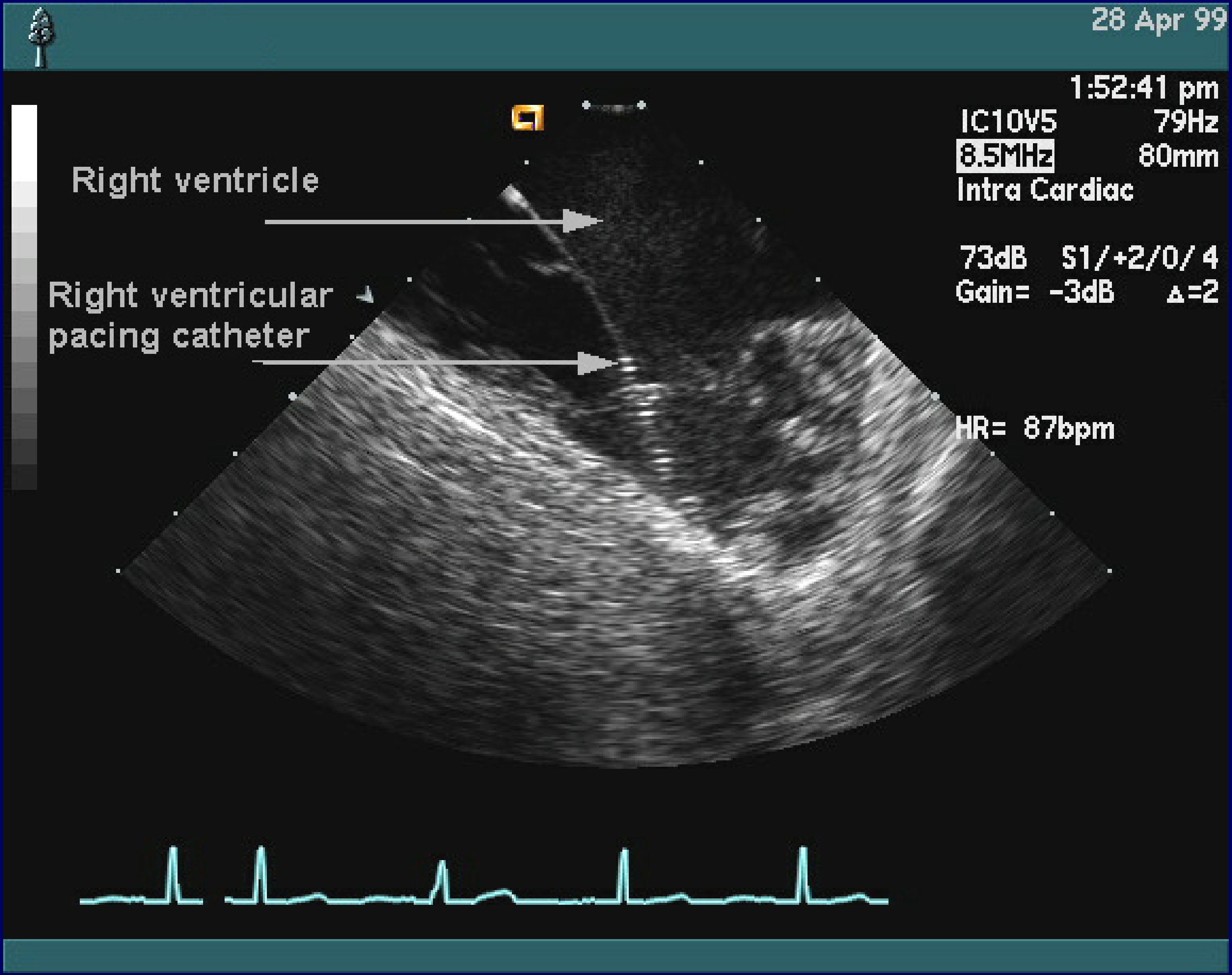
Real-Time Imaging





Apical 4 Chamber

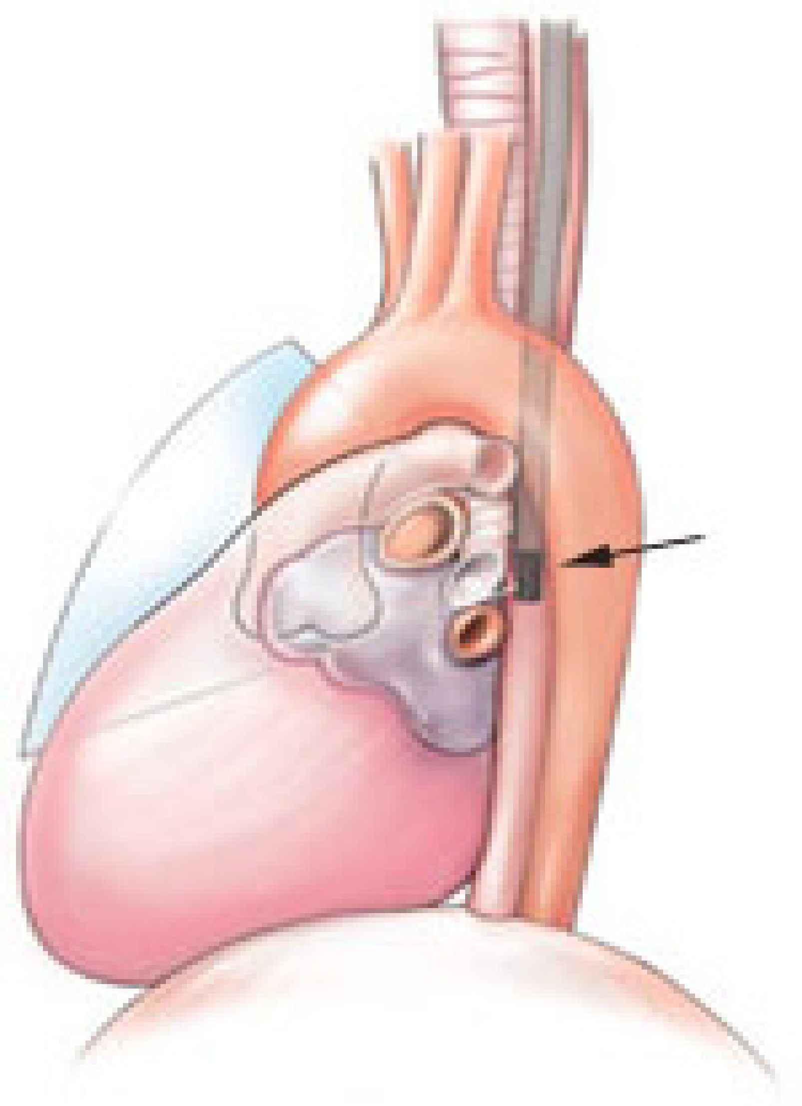

The AcuNav Diagnostic
Ultrasound Catheter

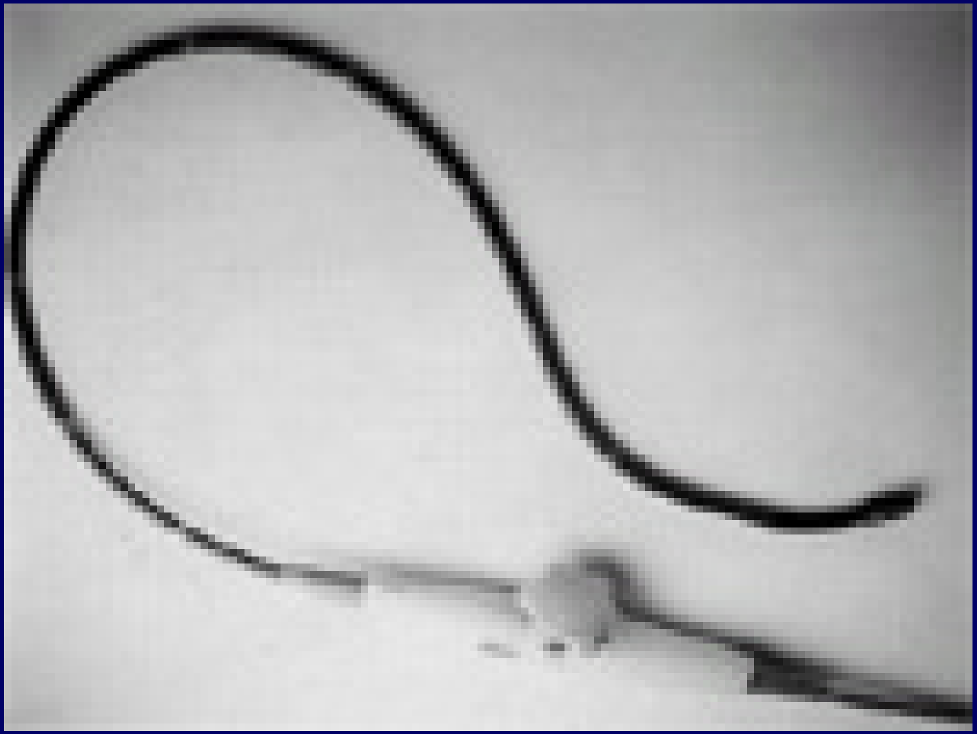


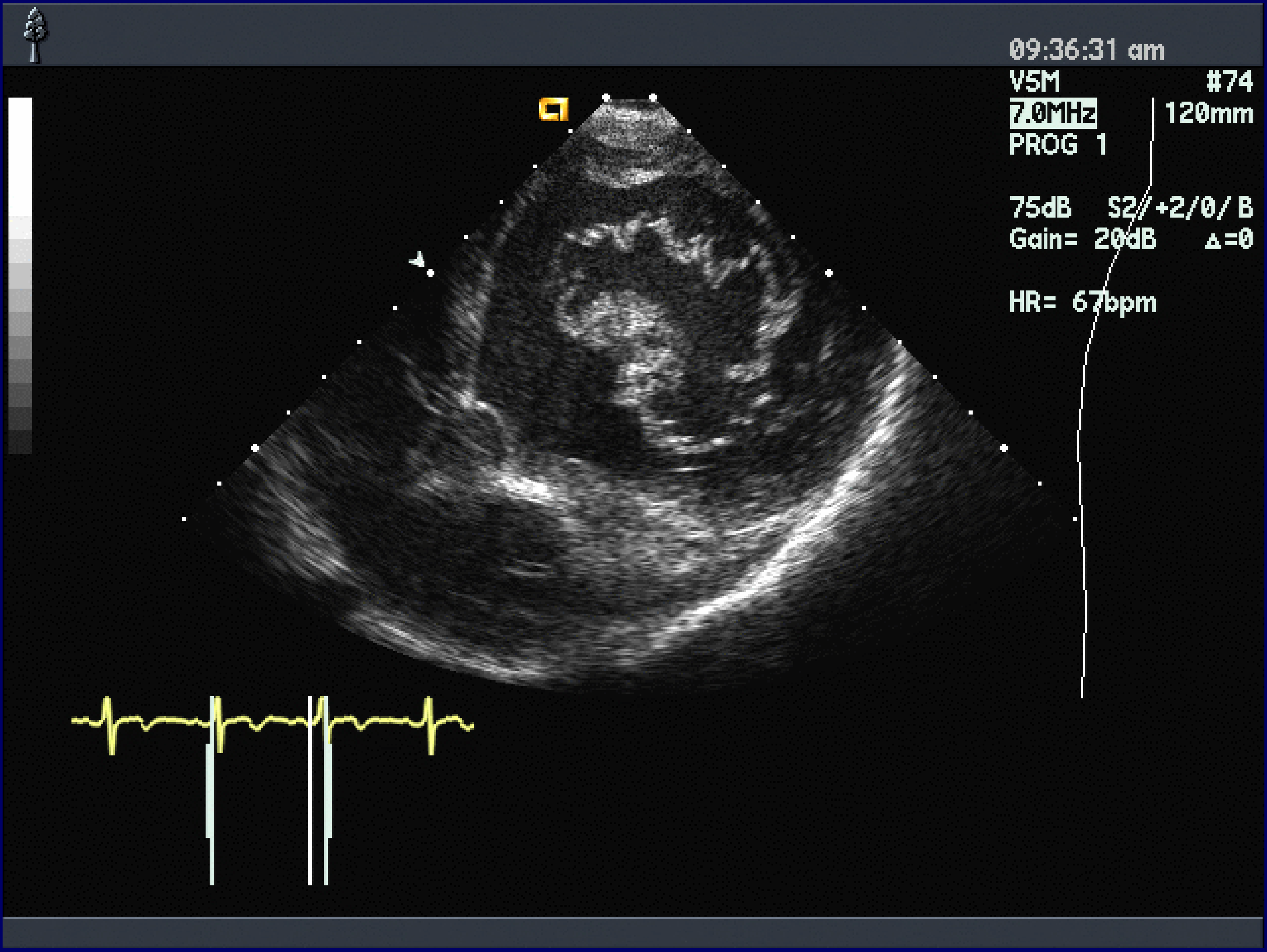
Right ventricle

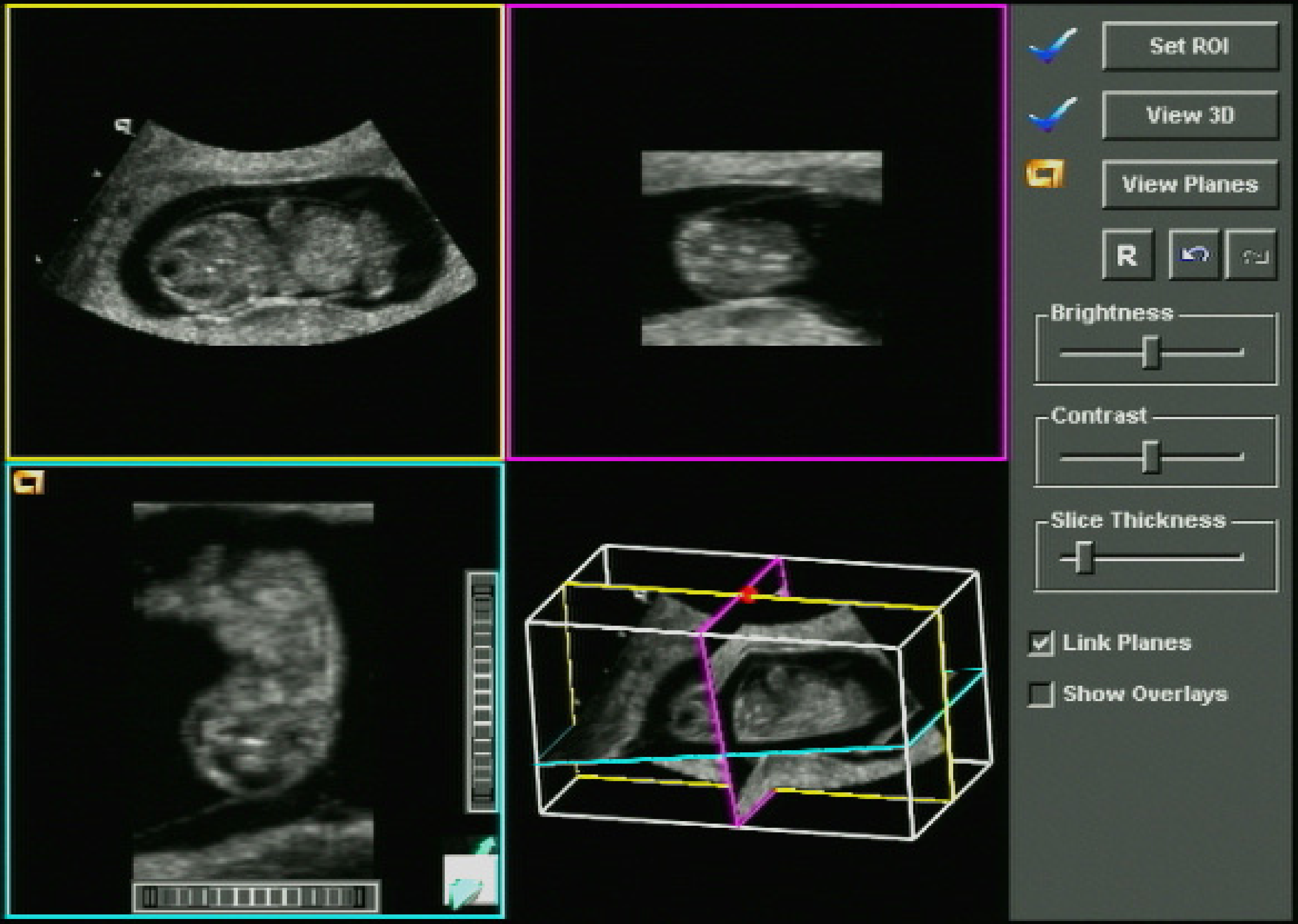
Right ventricular pacing catheter

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



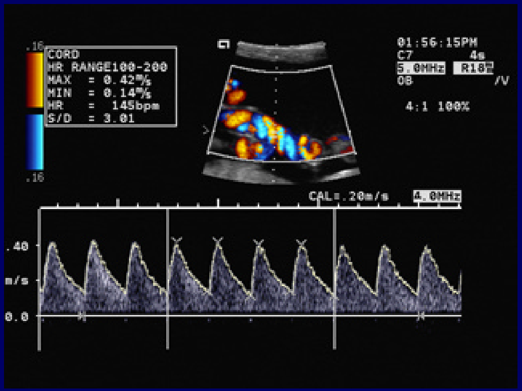
☑ Link Planes

☐ Show Overlays

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.

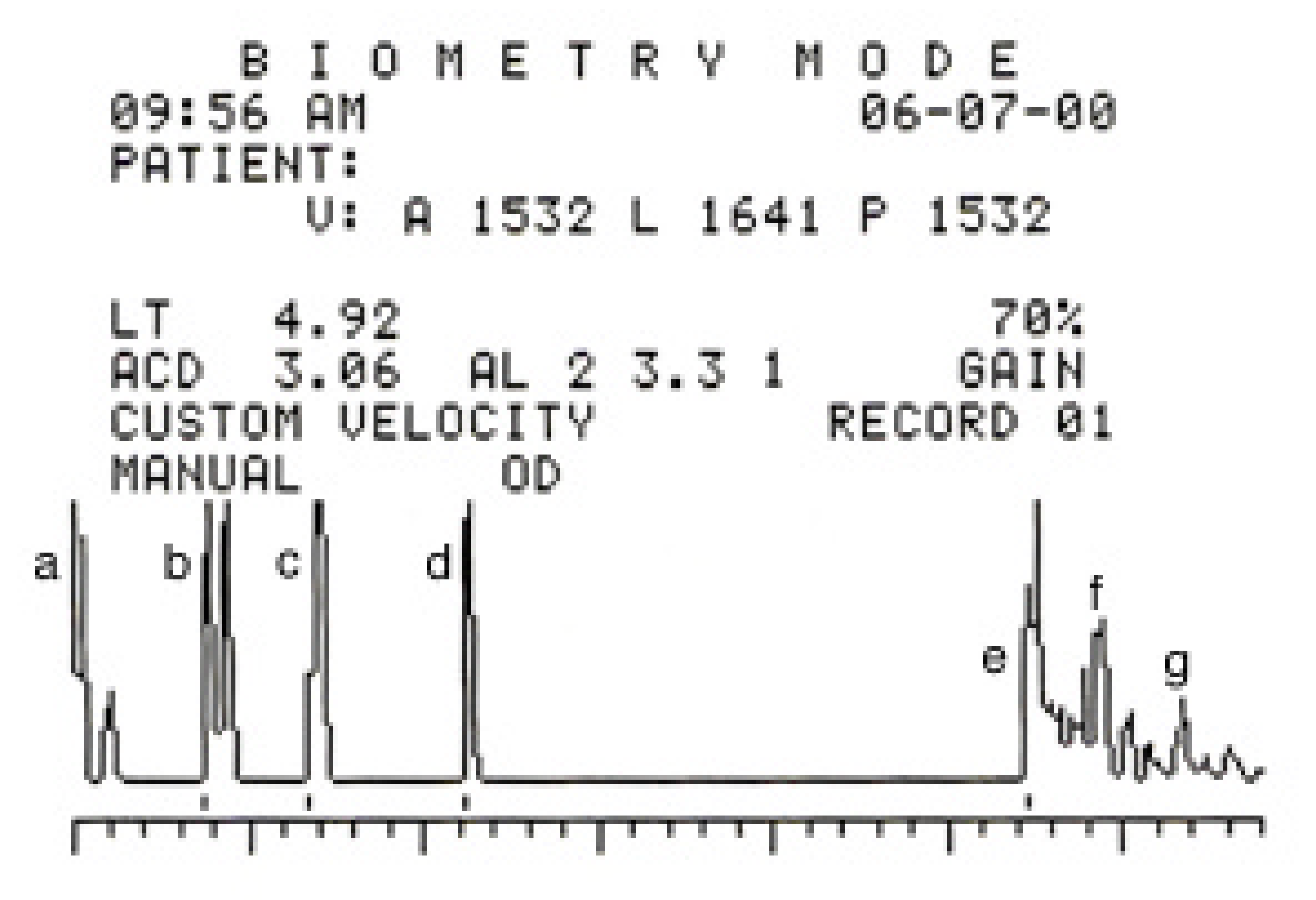
Characteristics of Diagnostic Ultrasound

- 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)



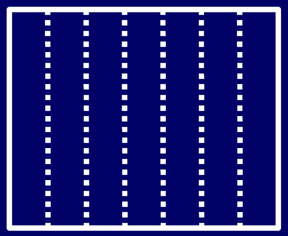
```
         BIOMETRY MODE
09:56 AM                    06-07-00
PATIENT:
      V: A 1532 L 1641 P 1532

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

B-Scan (Brightness, 2D)

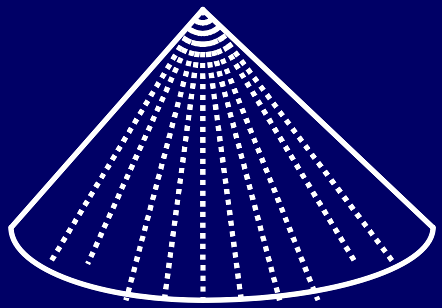
2D Scan Formats

linear



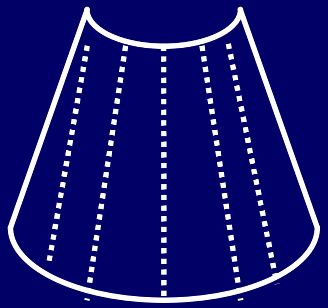
easy access
limited view

sector



limited access
wide view

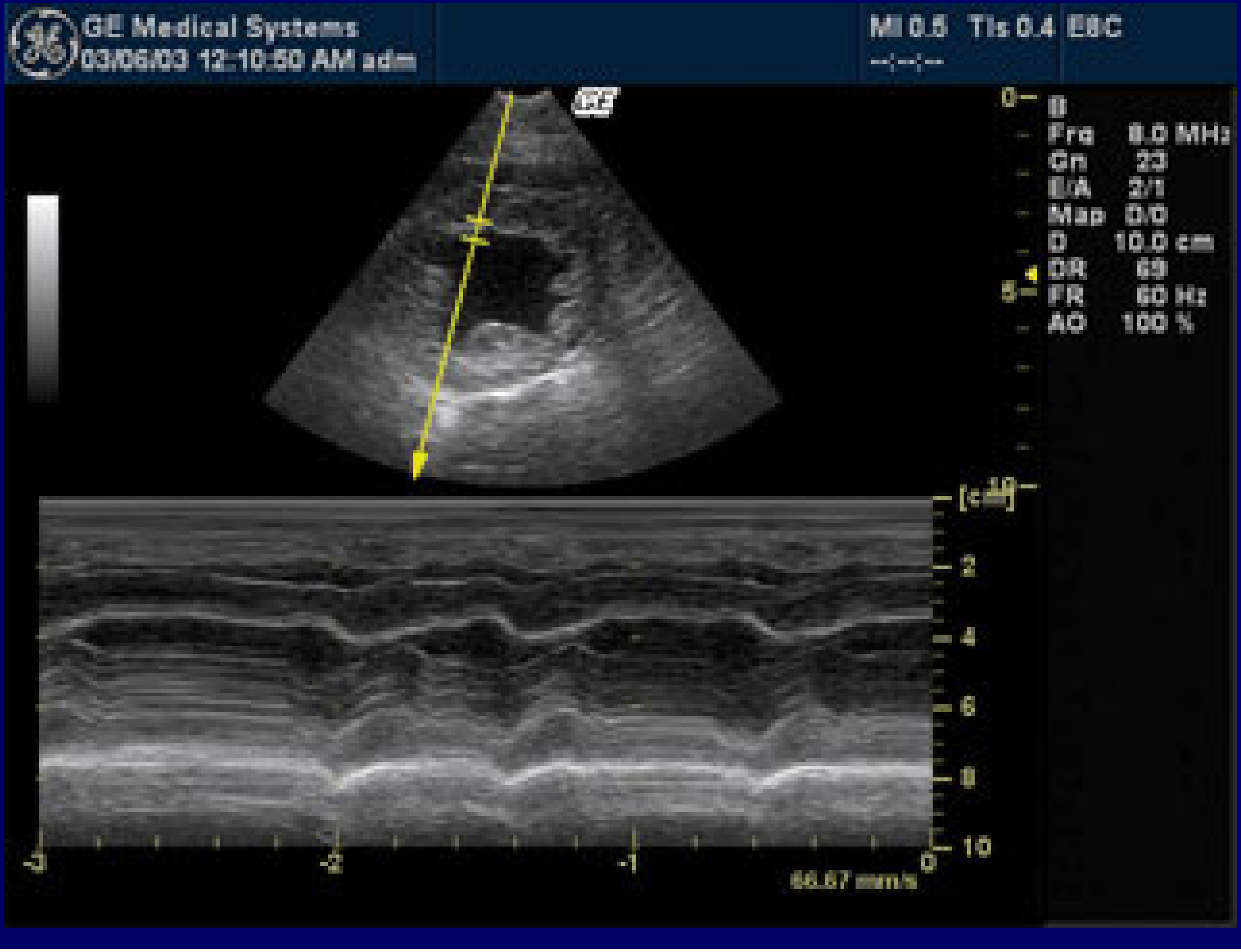
curved linear



easy access
wide view

3D Ultrasound

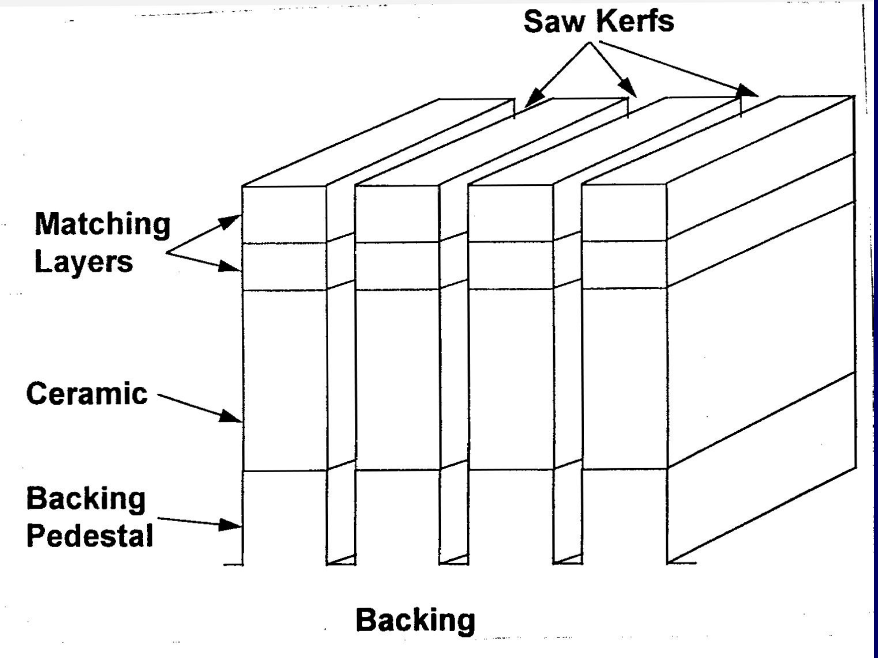
M-Mode (Motion)



Transducers: Generation and Detection of Sound Waves (Section II)

Ultrasonic Array Transducers

(From www.acuson.com)

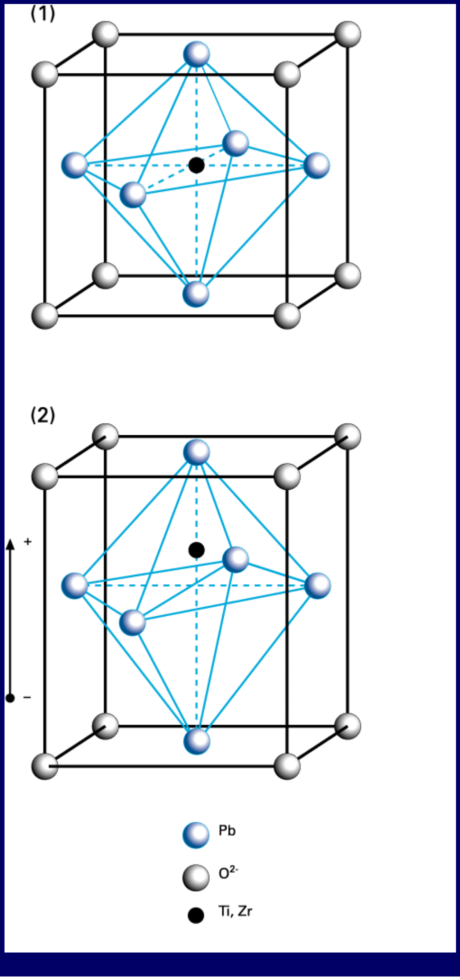


Transducer

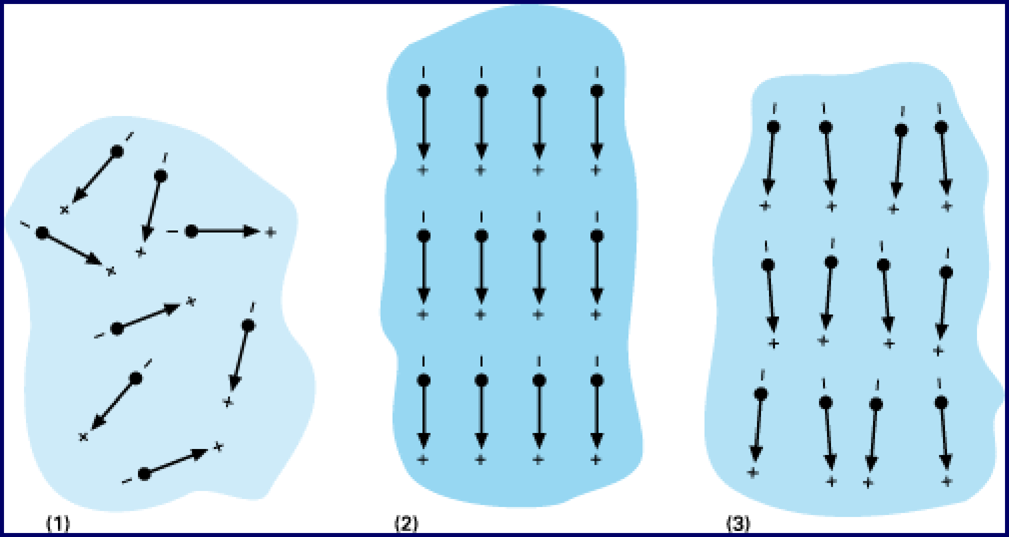
- Energy conversion: electrical ? mechanical.
- Generation and detection (speaker and microphone).
- Medical ultrasound: same device in MHz range.
- Piezoelectricity: electrical polarization ? mechanical strain.
- PZT, PVDF and composite materials are commonly used.

Piezoelectricity

Anisotropy

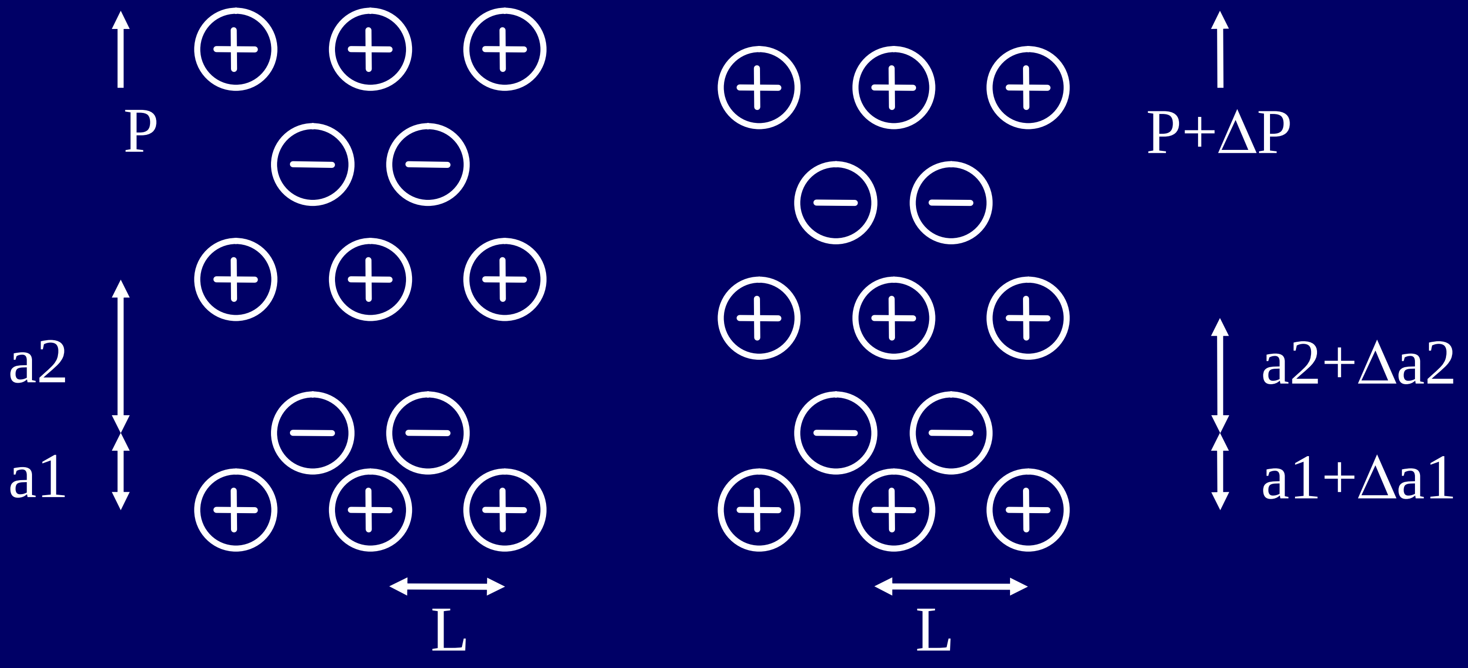


Poling



Curie temperature: 320^0 – 370^0C.

Piezoelectricity



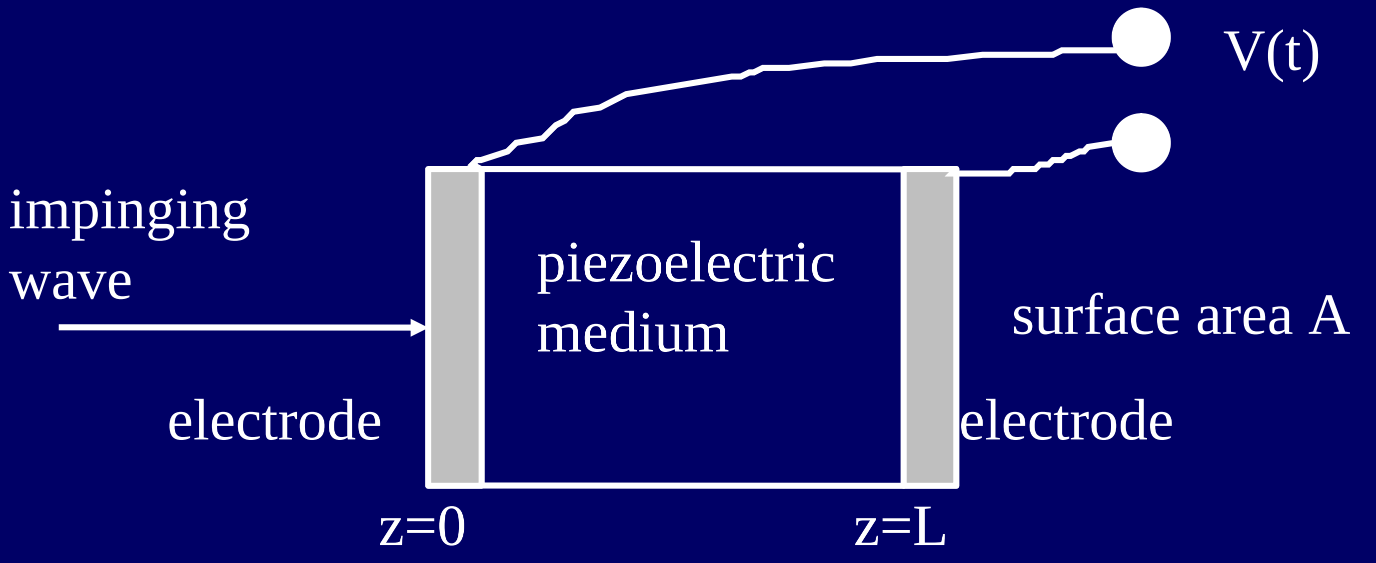
$$P \equiv \frac{\text{dipole strength of unit cell}}{\text{volume of unit cell}} = \frac{q\,(a2 - a1)}{L^2\,(a2 + a1)}$$

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

e: Piezoelectric stress constant

Detection of Ultrasound

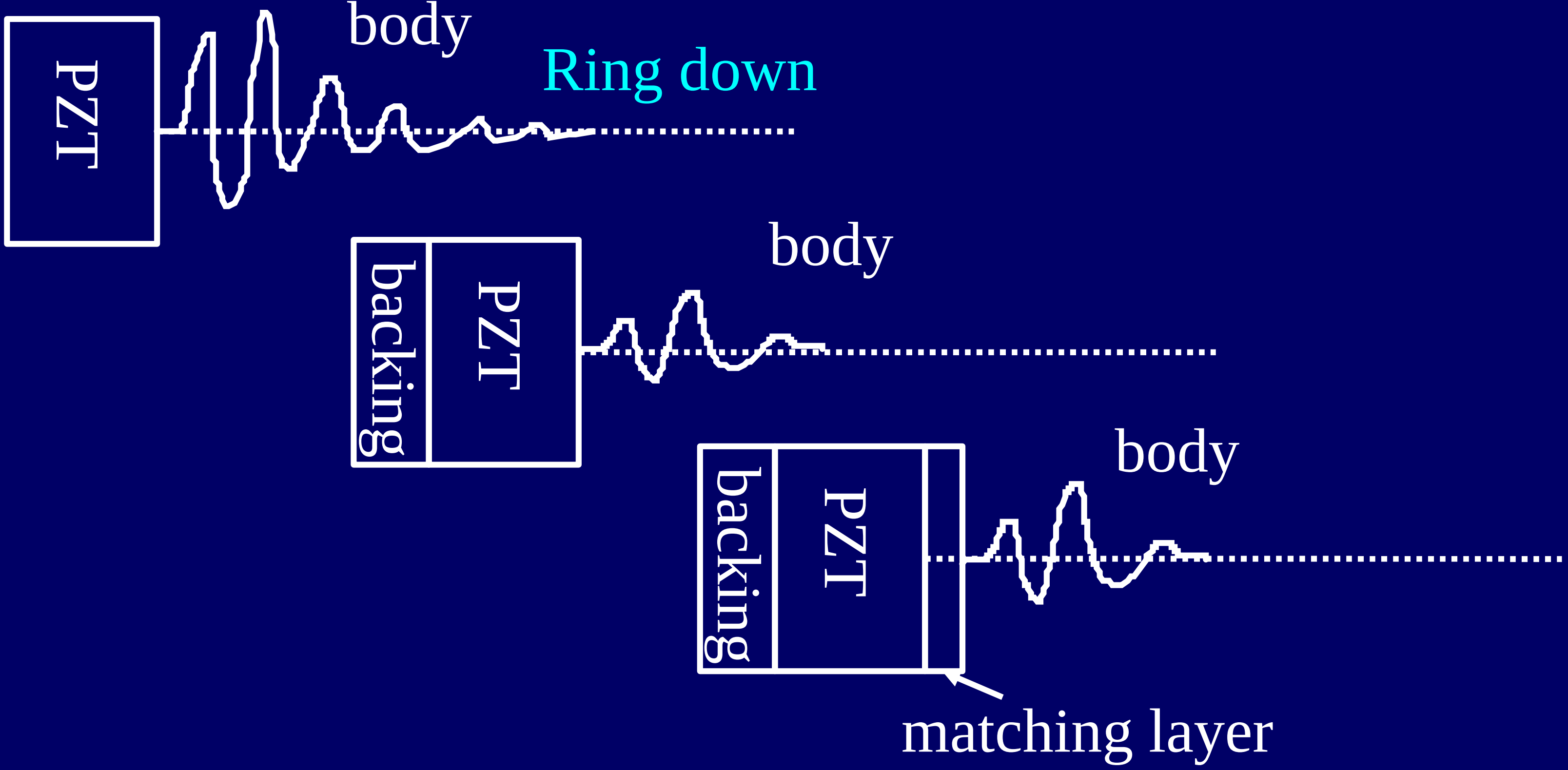
- Reciprocal to generation.



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

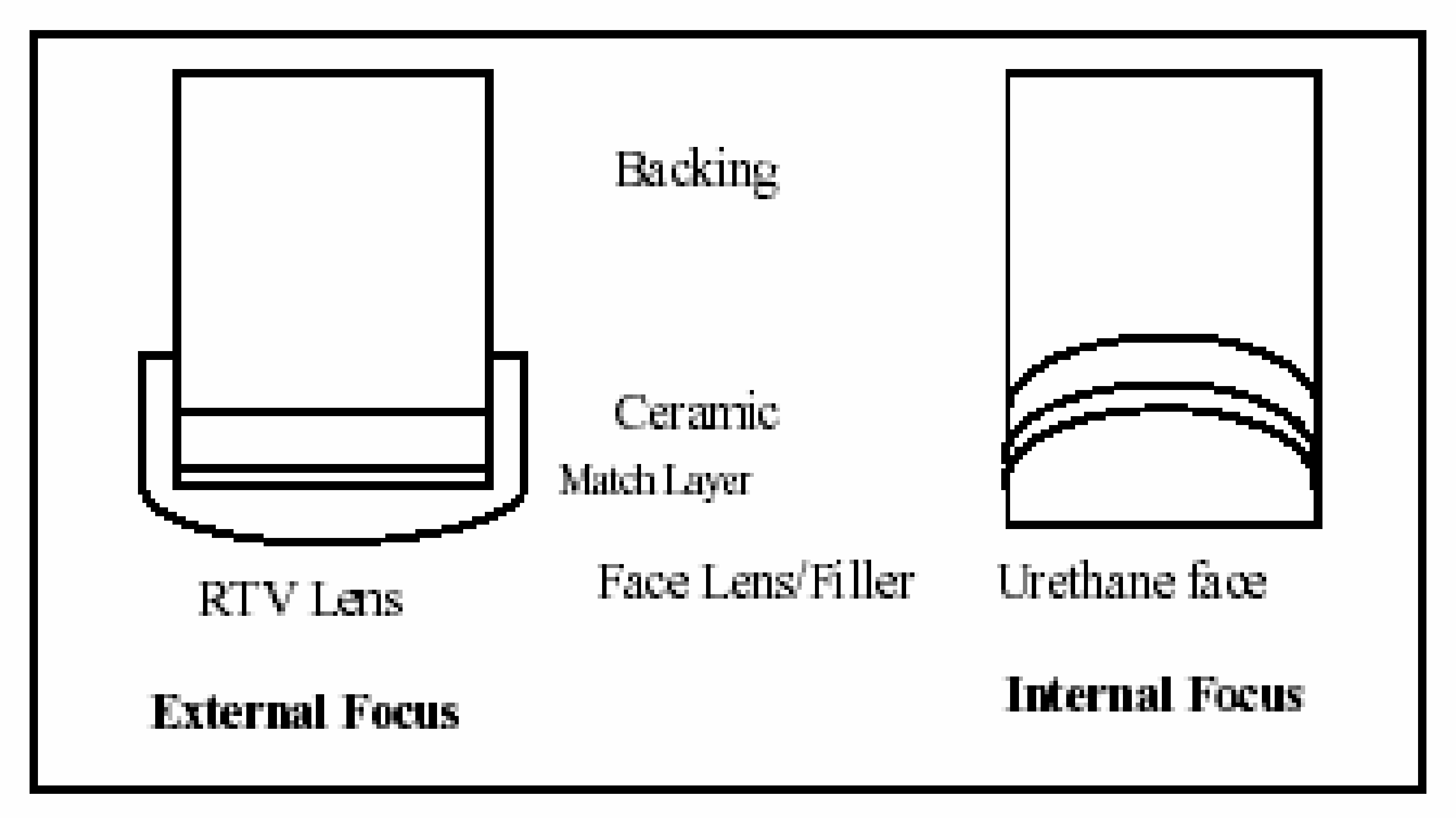
Design Considerations

- Bandwidth and sensitivity.

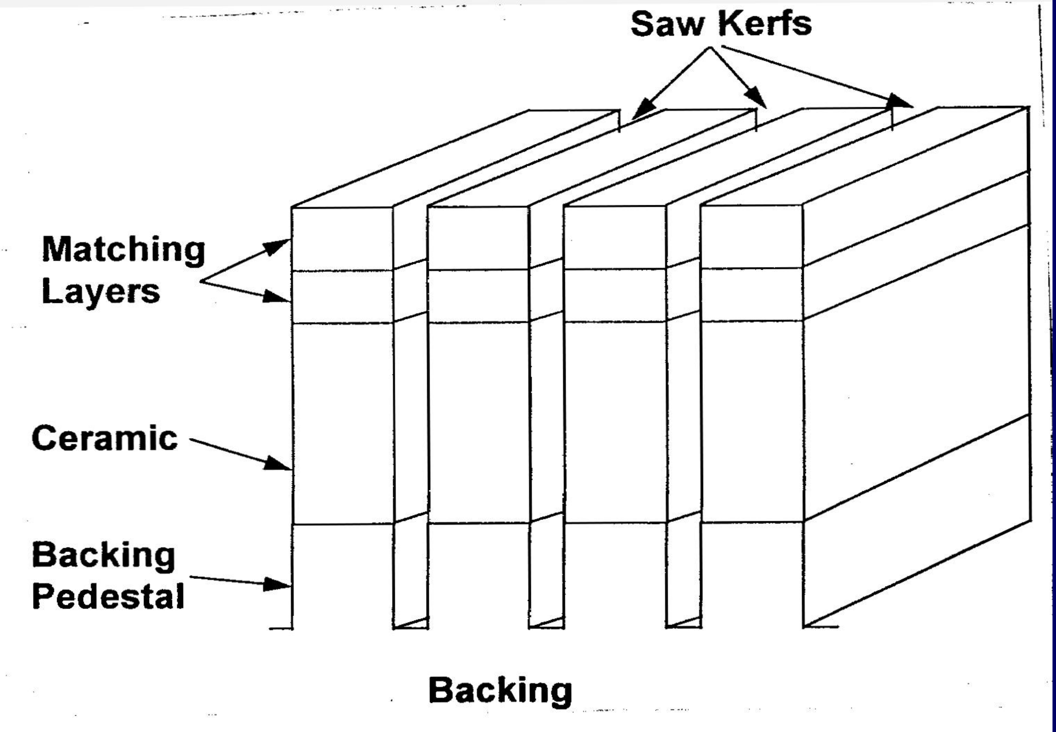


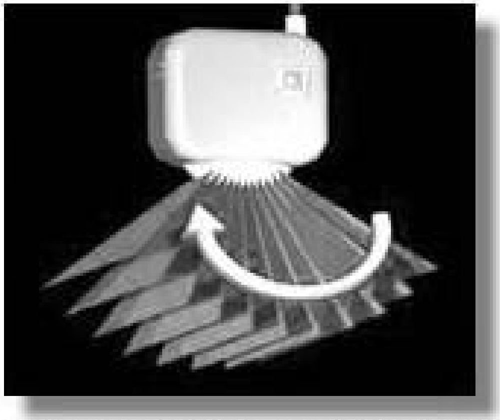
Acoustic Lens

- Fixed geometric elevational focusing.

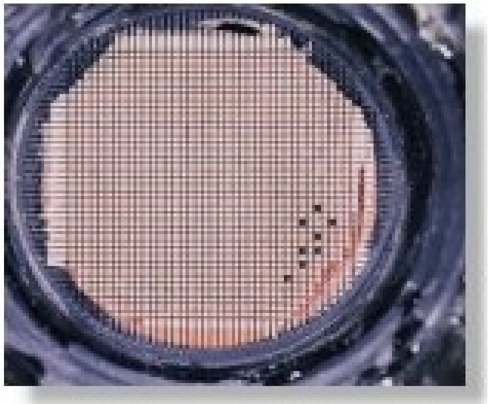


1-D and 2-D Arrays





Hand-held 3-D probe from Kretztechnik



2-D matrix-array at Duke

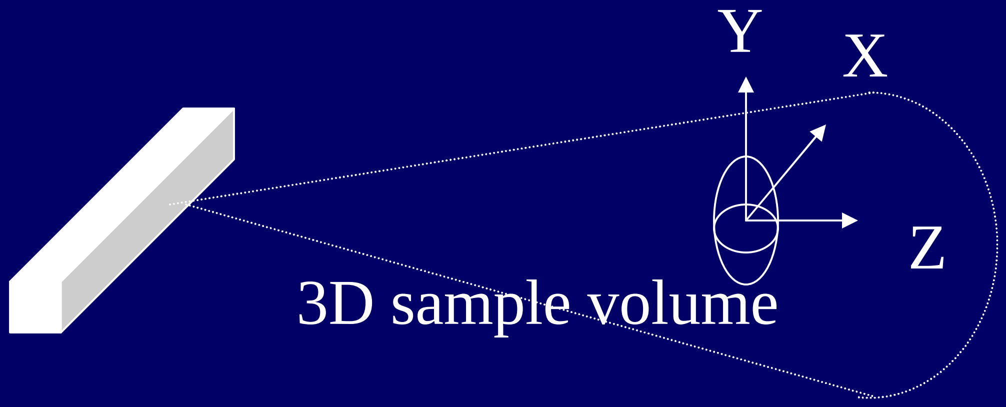
Factors in Image Quality

Factors of Image Quality

- Spatial resolution.
- Contrast resolution.
- Temporal resolution.
- Uniformity.
- Sensitivity.
- Penetration.

Spatial Resolution

- Lateral and elevational : diffraction limited.
- Axial resolution : the width of the pulse.
- Given limited total bandwidth, there exists a tradeoff between axial and lateral/elevational resolutions.

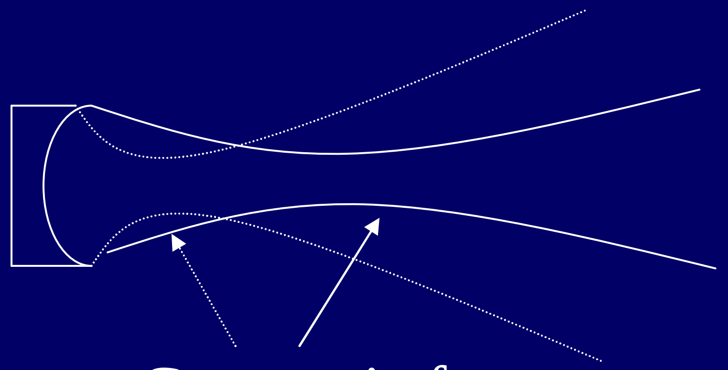


Lateral Resolution (X)

- Diffraction limited.
- Determined by frequency, active aperture size and depth.
- Fixed transmit and dynamic receive focusing.
- Is dynamic transmit focusing possible?
- Is a bigger aperture always better?

Elevational Resolution (Y)

- Fixed lens (geometric focus).
- Determined by frequency, aperture size and depth.
- 2D array and alternative 1D array designs.



Geometric focus

Axial Resolution (Z)

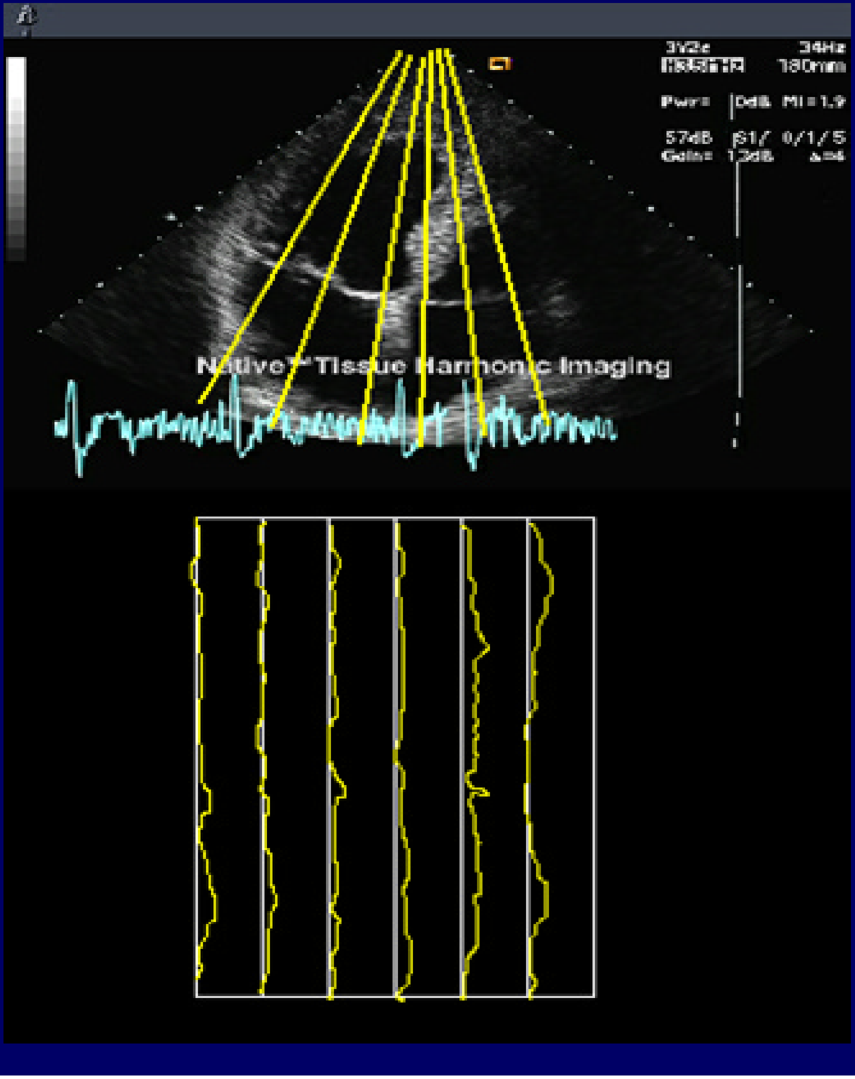
- Pulse width (absolute bandwidth).
- System and transducer bandwidth.
- Transmit power.
- Attenuation consideration.
- Coded waveform – long pulse + large bandwidth.

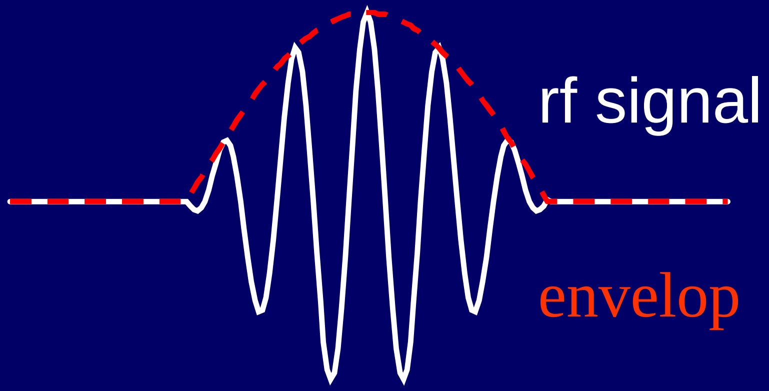
Focusing and Diffraction: Resolution in the *x*-*y* plane

(Section III)

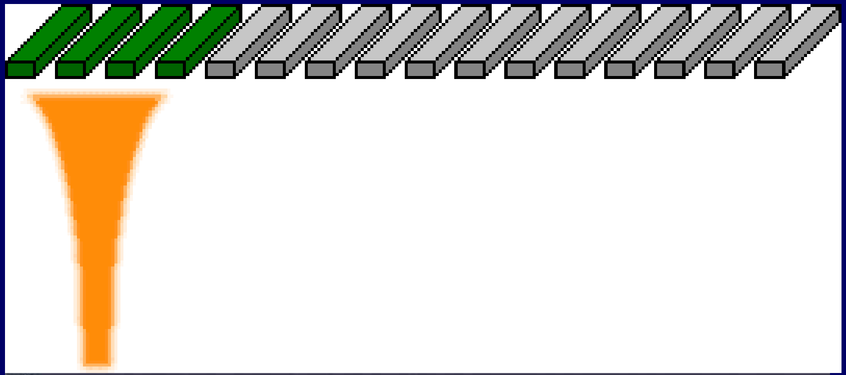
B-mode Imaging

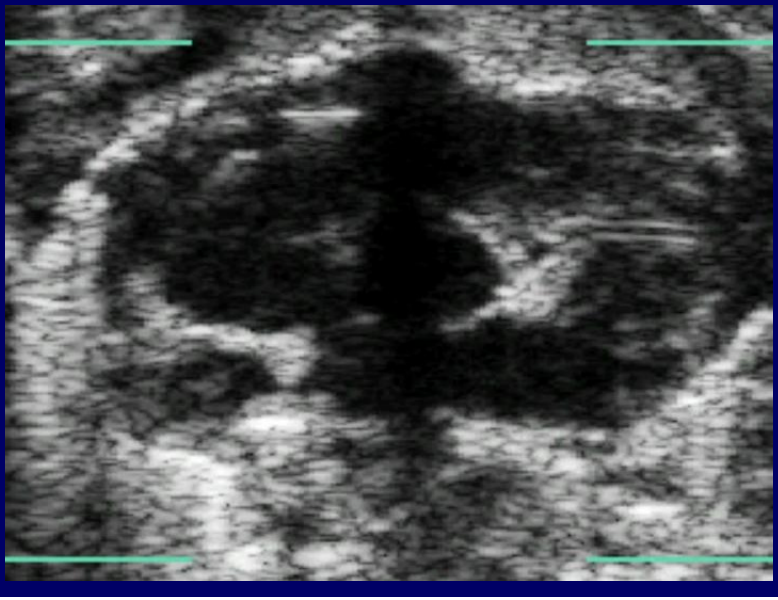
取自www.acuson.com

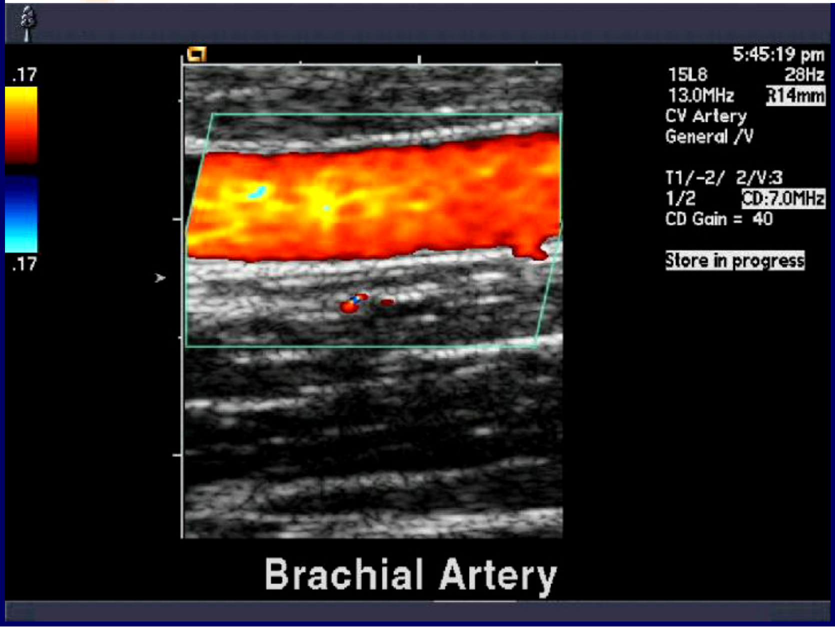




Linear Scanning

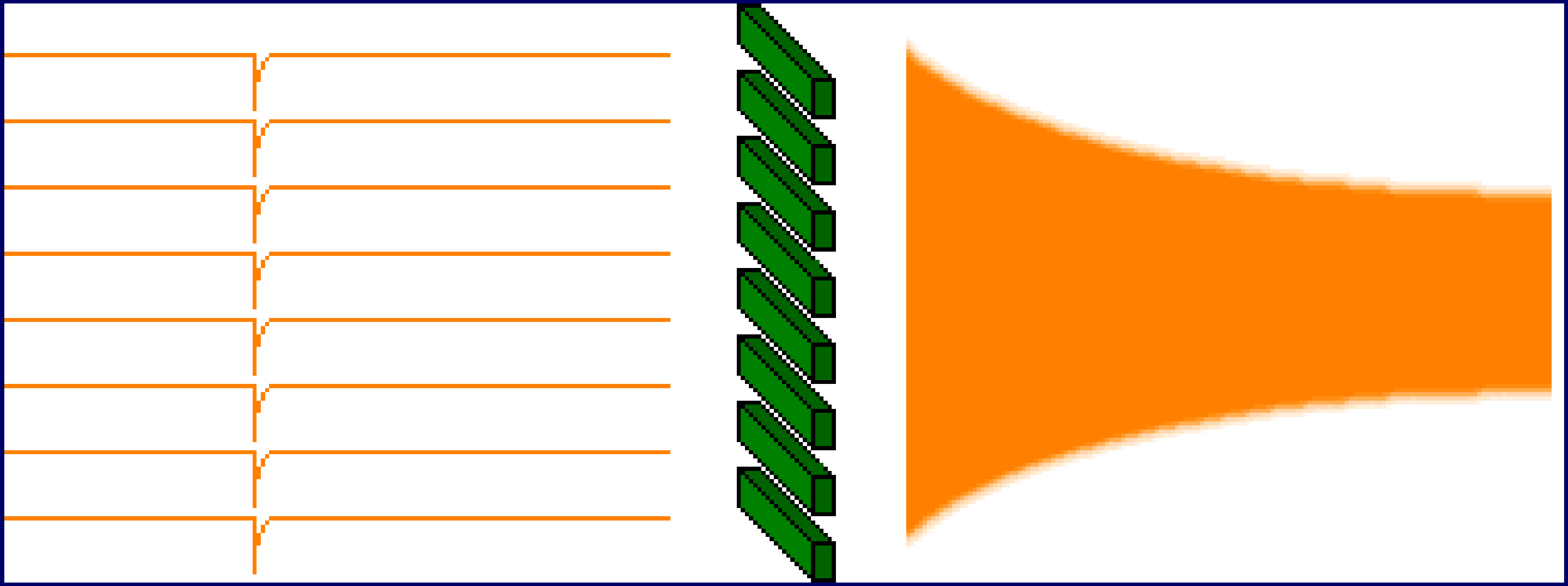




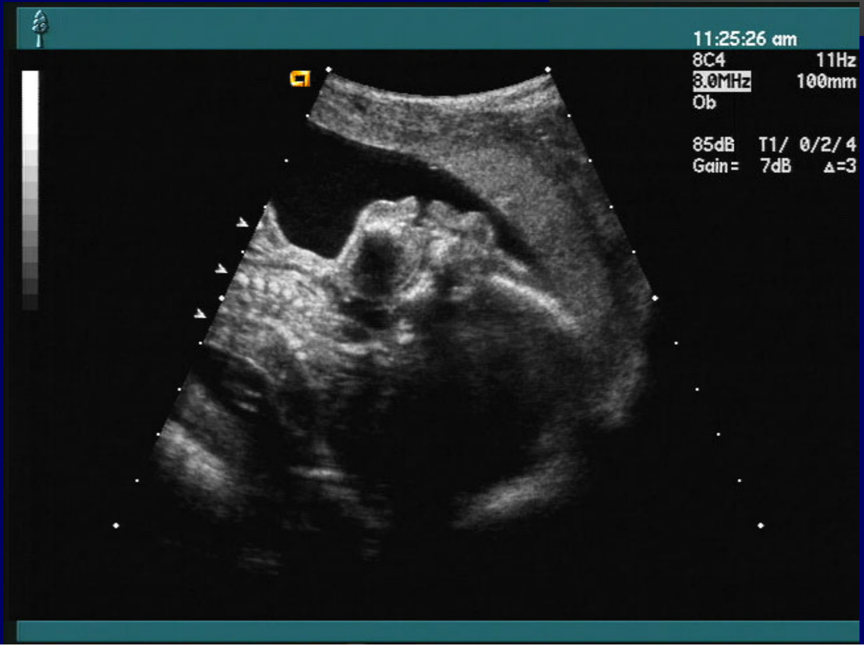


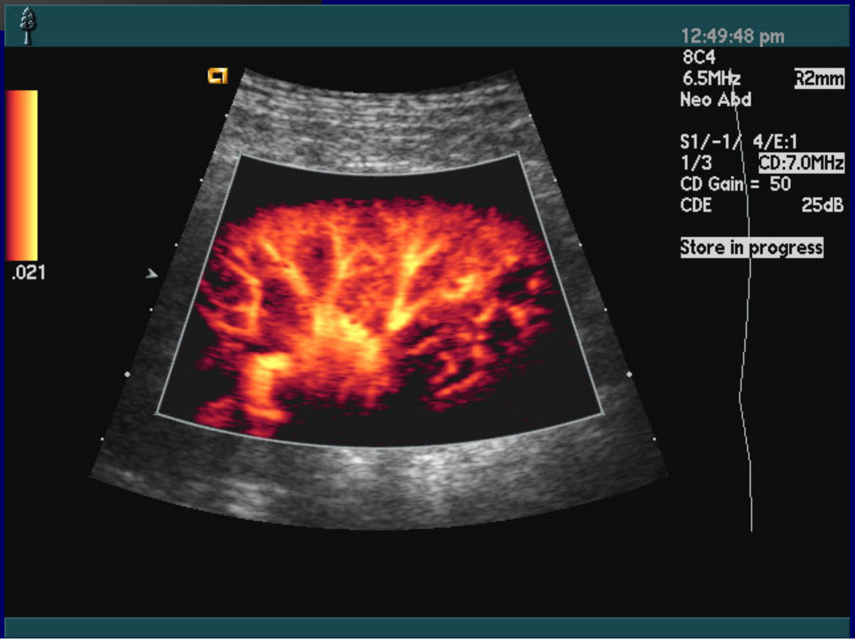
Beam Formation Using Arrays

Focusing:

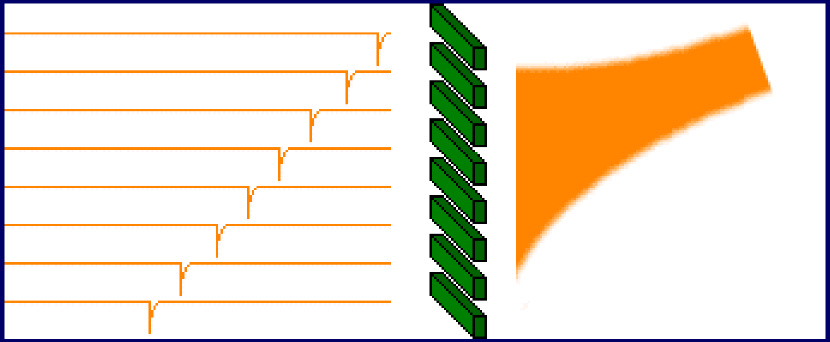


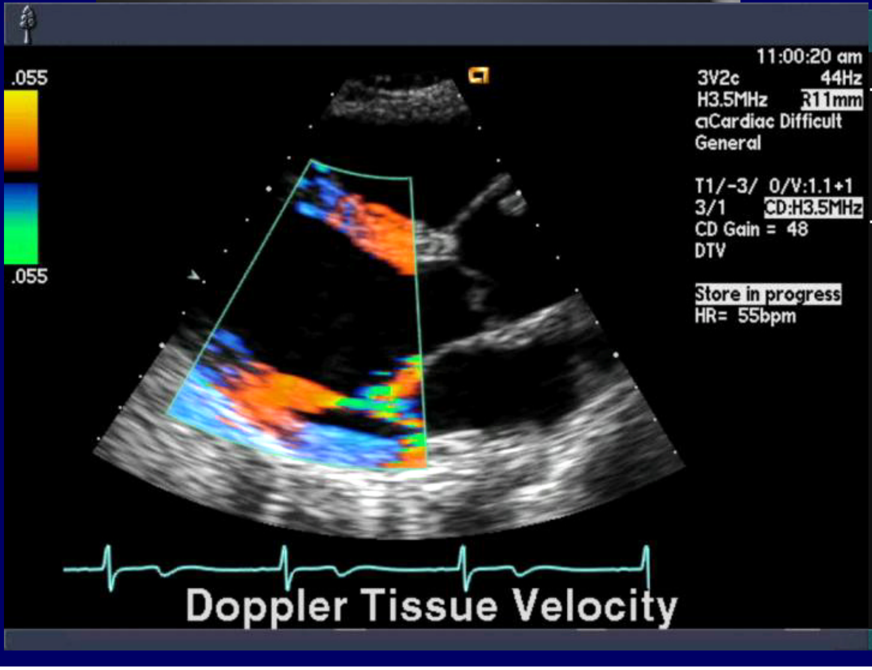
Curved Linear Scanning



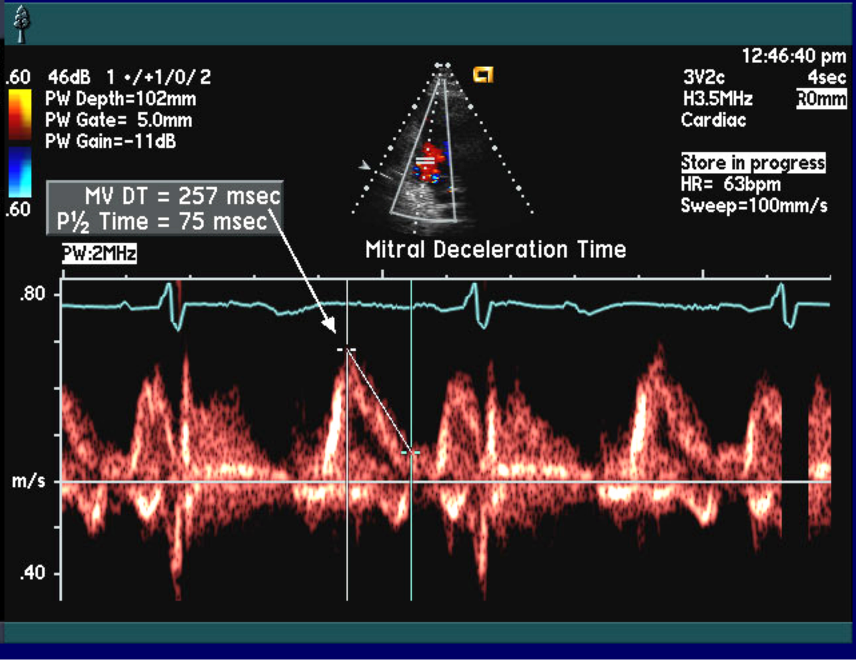


Sector Steering





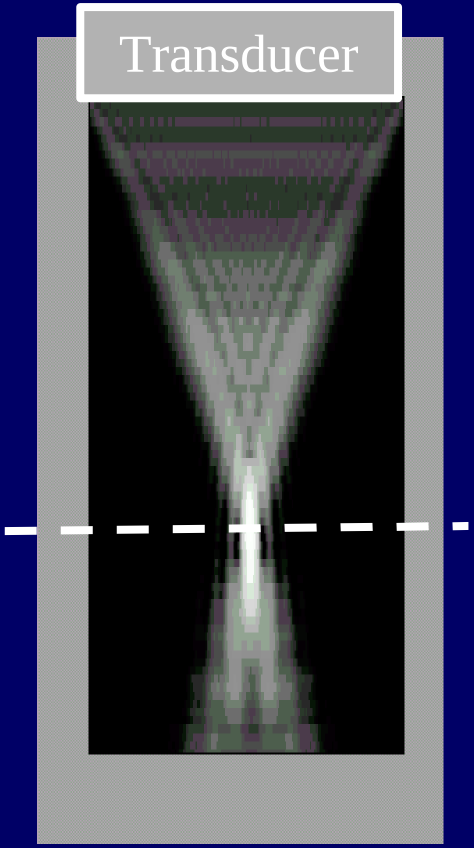
11:00:20 am
3V2c 44Hz
H3.5MHz R11mm
Cardiac Difficult
General
T1/-3/ 0/V:1.1+1
3/1 CD:H3.5MHz
CD Gain = 48
DTV
Store in progress
HR= 55bpm



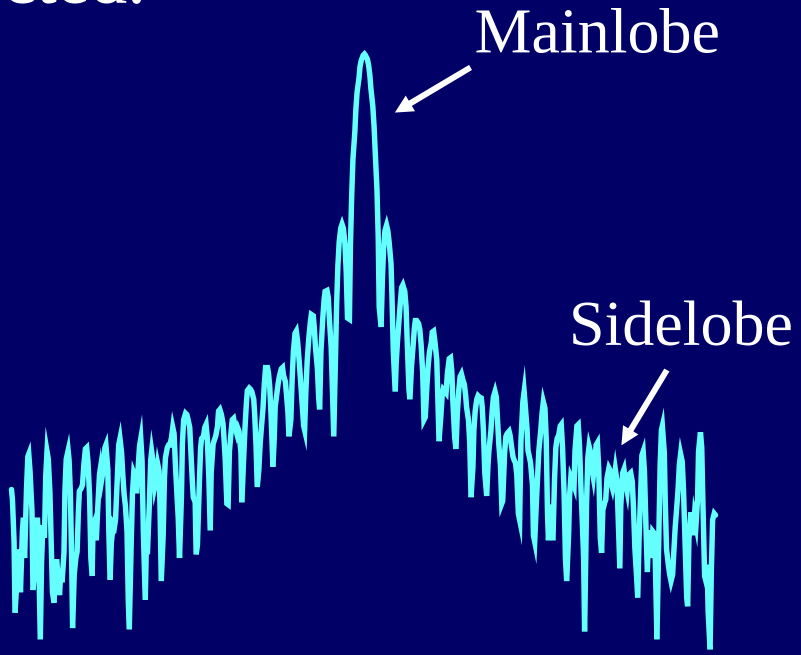
12:46:40 pm
46dB 1 •/+1/0/ 2
PW Depth=102mm
PW Gate= 5.0mm
PW Gain=-11dB
MV DT = 257 msec
P½ Time = 75 msec
PW:2MHz
3V2c 4sec
H3.5MHz R0mm
Cardiac
Store in progress
HR= 63bpm
Sweep=100mm/s

How is the resolution determined?

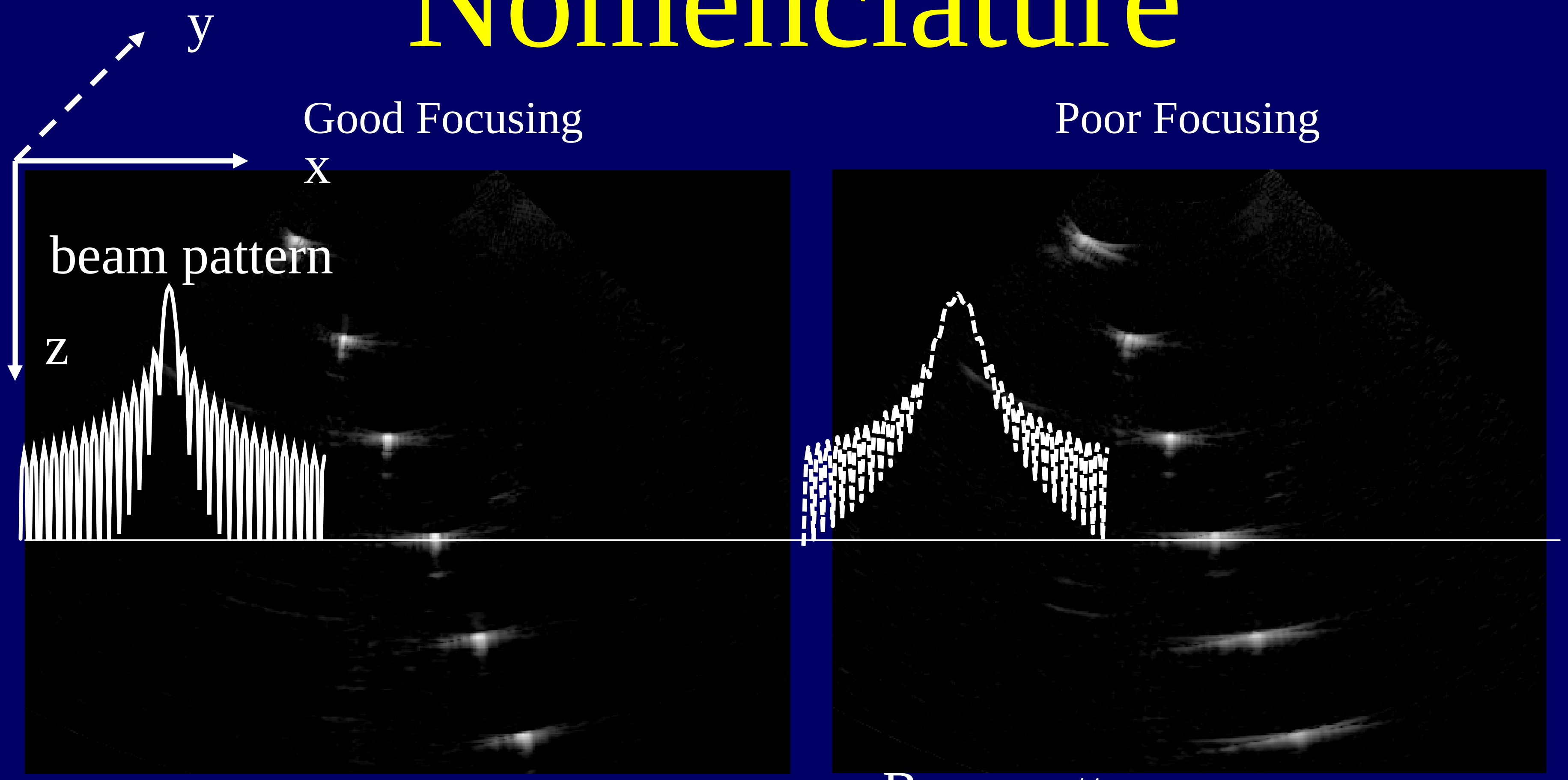
Focusing ←→ Beam Formation



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



Nomenclature



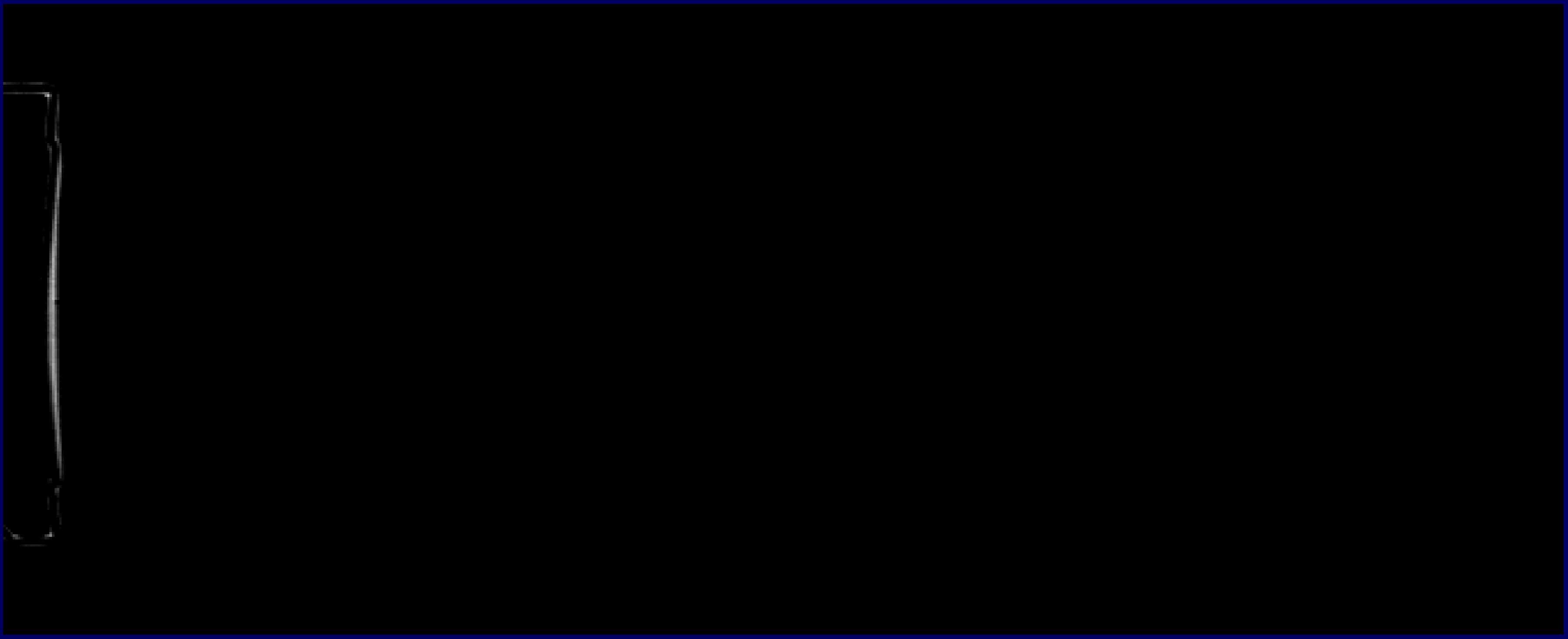
Good Focusing

Poor Focusing

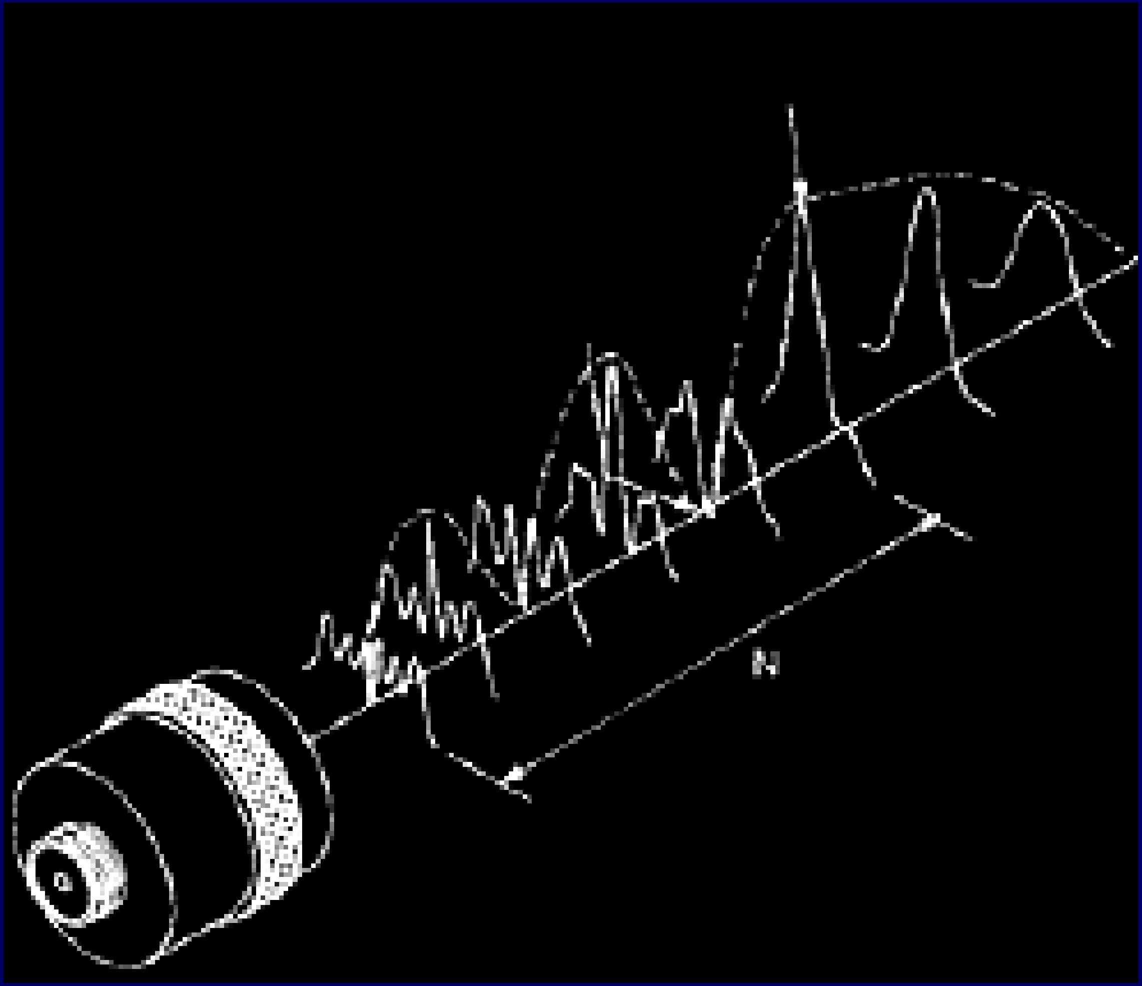
x: Lateral, azimuthal, scan
y: Elevational, non-scan
z: Axial, range, depth

Beam pattern
Radiation pattern
Diffraction pattern
Focusing pattern

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



Radiation Pattern

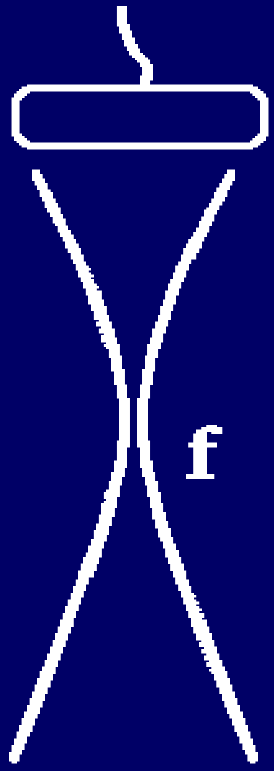


How to focus?

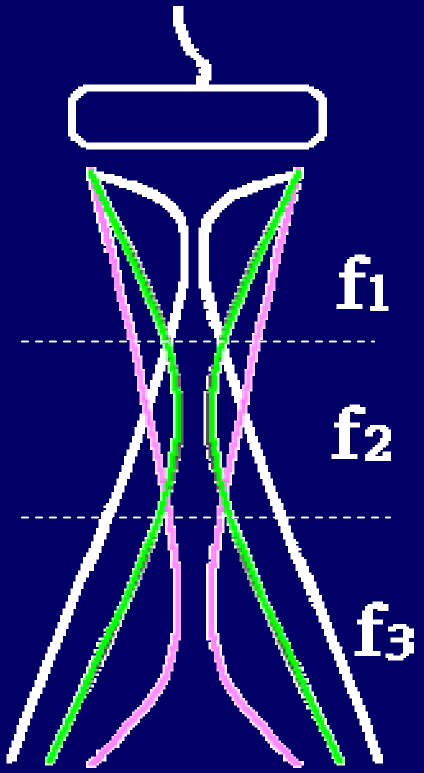
Beamforming

- 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.

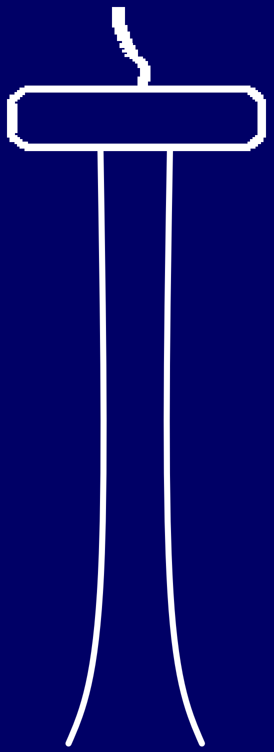
Focusing



Single Zone Focusing

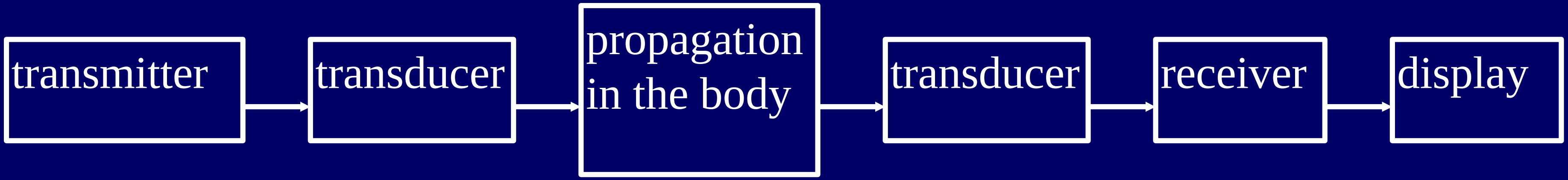


Multi-Zone Focusing



Dynamic Focusing

Imaging Model


transmitter

transducer

propagation in the body

transducer

receiver

display

A-scan:

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

B-scan:

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

Scanning → Convolution

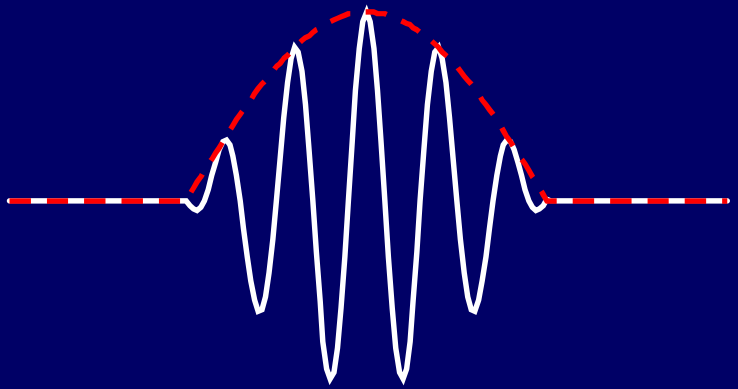
(Correlation vs. Convolution)

Imaging Model

$$p(t-\frac{2z'}{c}) = A(t-\frac{2z'}{c})\cos(2pf_0(t-\frac{2z'}{c}))$$

Ideally,

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



In practice,

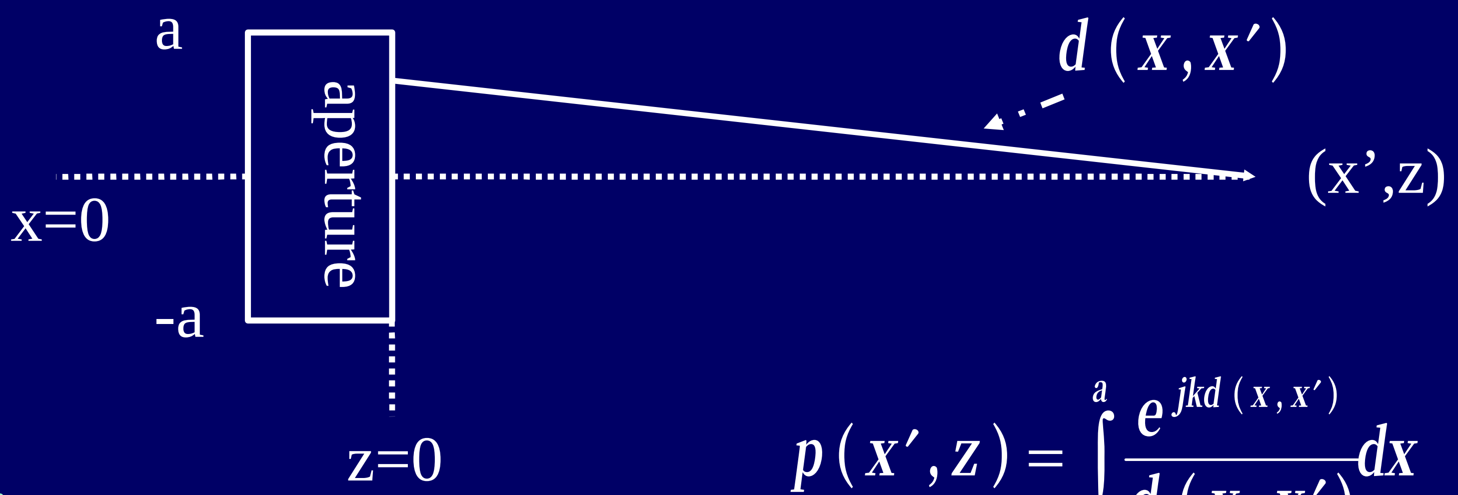
$B(\cdot)$: determined by diffraction

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

Diffraction from 1D Apertures

- Free space Green's function:

$$p(R) = A_0 \frac{e^{jkR}}{R}$$



$$p(x',z) = \int_{-a}^{a} \frac{e^{jkd(x,x')}}{d(x,x')} dx$$

Continuous wave
(CW, single frequency)

Focusing in the Far Field

$$ka^2 / 2z << 1$$

$$p(x', z) \approx \frac{e^{jkz} e^{jkx'^2/2z}}{z} \int_{-a}^{a} C(x) e^{-jkxx'/z} dx = \frac{e^{jkz} e^{jkx'^2/2z}}{z} F.T.[C(x)]$$

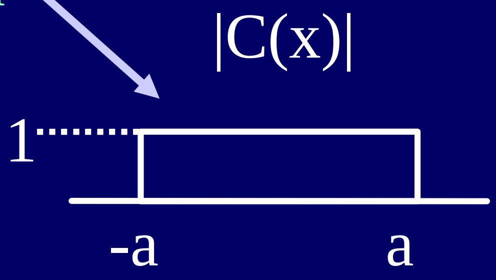
Aperture ←($F.T.$)→ Radiation Pattern

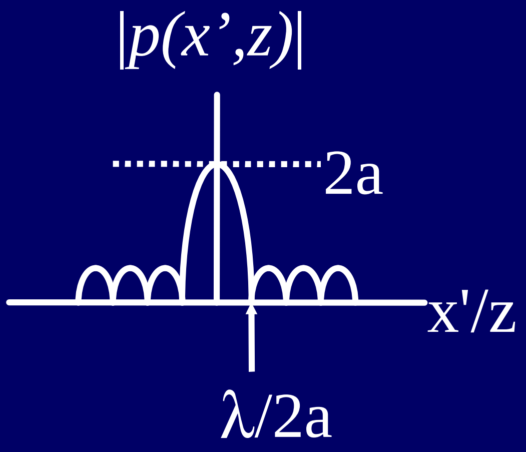
When not in the far field → effective aperture function

$$C(x) = |C(x)| e^{-jkx^2/2z}$$

Radiation Pattern of a Rectangular Aperture

Spatial frequency spectrum



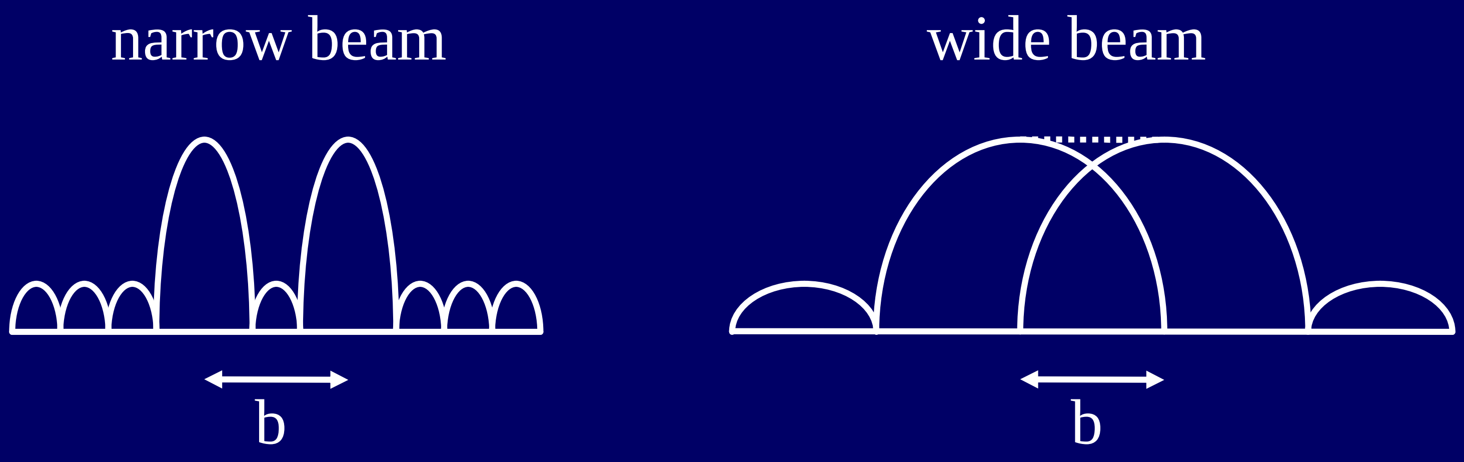


Beam width vs. Aperture size and frequency

$$\left|p(x',z)\right| = \left|\int_{-a}^{a} e^{-jkxx'/z}\,dx\right| = \left|\frac{1}{jkx'/z}\left[e^{jkx'a/z} - e^{-jkx'a/z}\right]\right| = \left|2a\,\frac{\sin kx'a/z}{kx'a/z}\right| = \left|2a\,\mathrm{sin}\,c\!\left(\frac{kx'a}{z}\right)\right|$$

Lateral Resolution

- Frequency ↑
- Aperture size ↑
- -3 dB, -6 dB, -10 dB, -20 dB,…etc.



Focusing in the Fresnel Region

$$z^2 >> (x - x')^2$$

$$d(x, x') = z(1 + \frac{(x - x')^2}{z^2})^{1/2} \approx z + \frac{(x - x')^2}{2z}$$

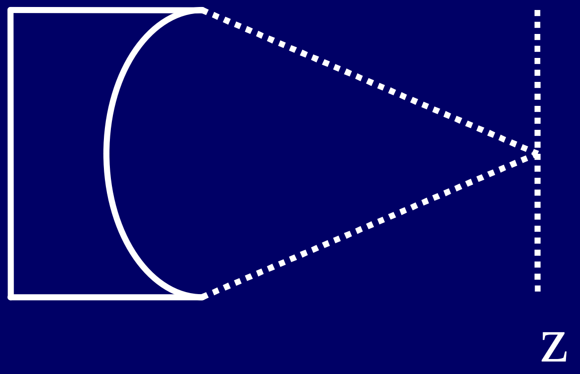
$$p(x', z) \approx \frac{1}{z} \int_{-a}^{a} e^{jkz} e^{jk(x-x')^2/2z} dx = \frac{e^{jkz} e^{jkx'^2/2z}}{z} \int_{-a}^{a} e^{-jkxx'/z} e^{jkx^2/2z} dx$$

$$C(x) = |C(x)| e^{jq(x)}$$

$$p(x', z) \approx \frac{e^{jkz} e^{jkx'^2/2z}}{z} \int_{-a}^{a} C(x) e^{-jkxx'/z} e^{jkx^2/2z} dx$$

Focusing: An Acoustic Lens

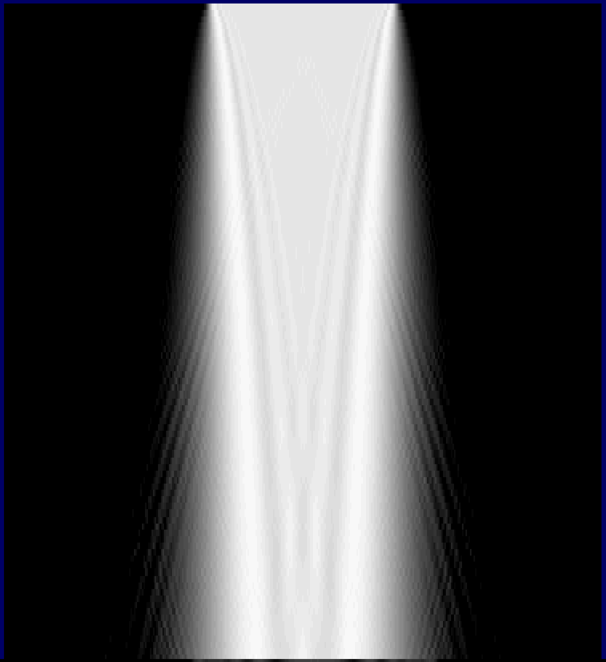
$$C(x) = |C(x)|e^{-jkx^2/2z}$$



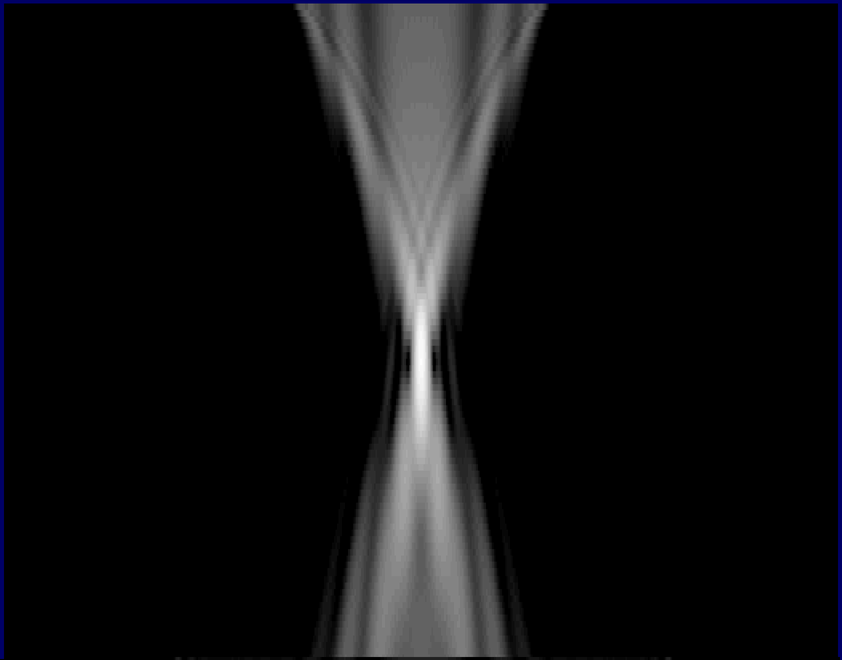
When out of the fixed focal point:

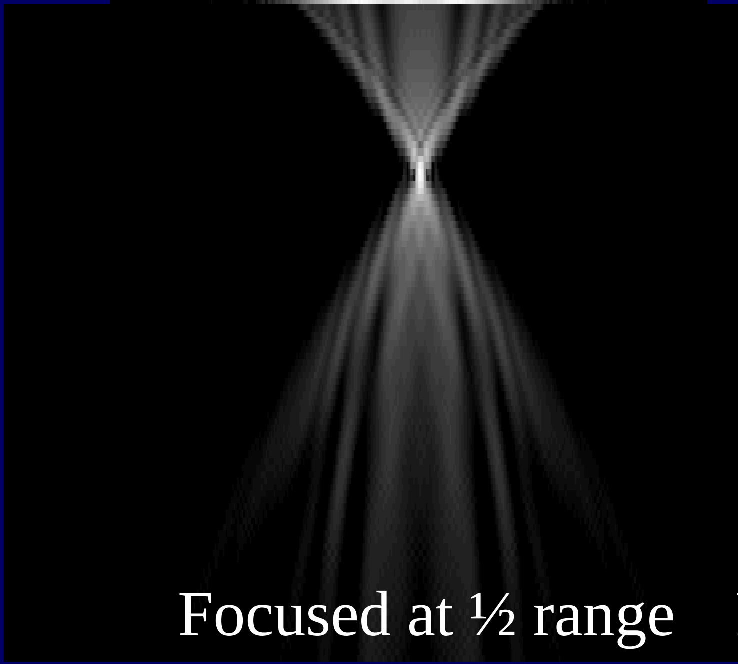
$$C'(x) = |C(x)|e^{\frac{jkx^2}{2}\left(\frac{1}{z}-\frac{1}{z_0}\right)}$$

Unfocused

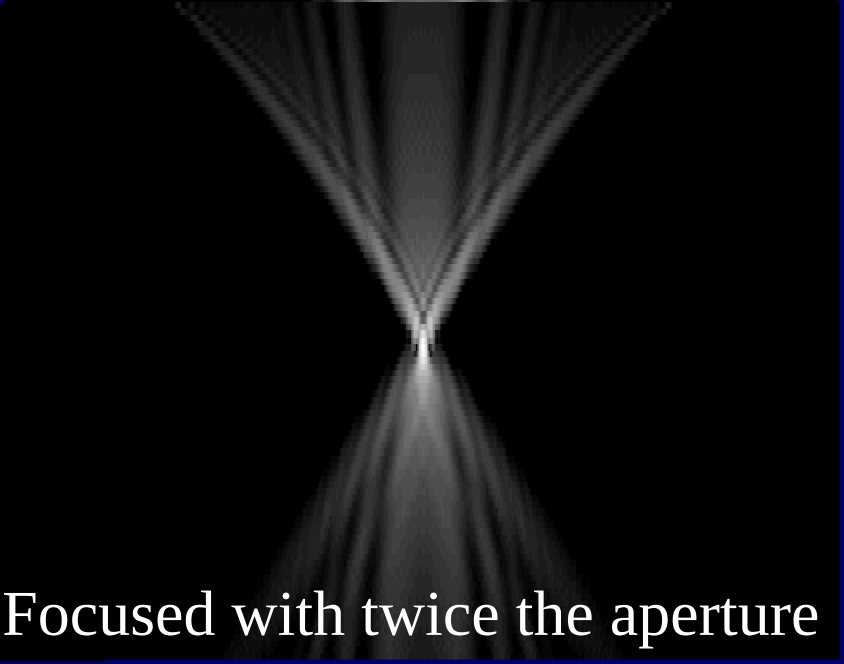


Focused



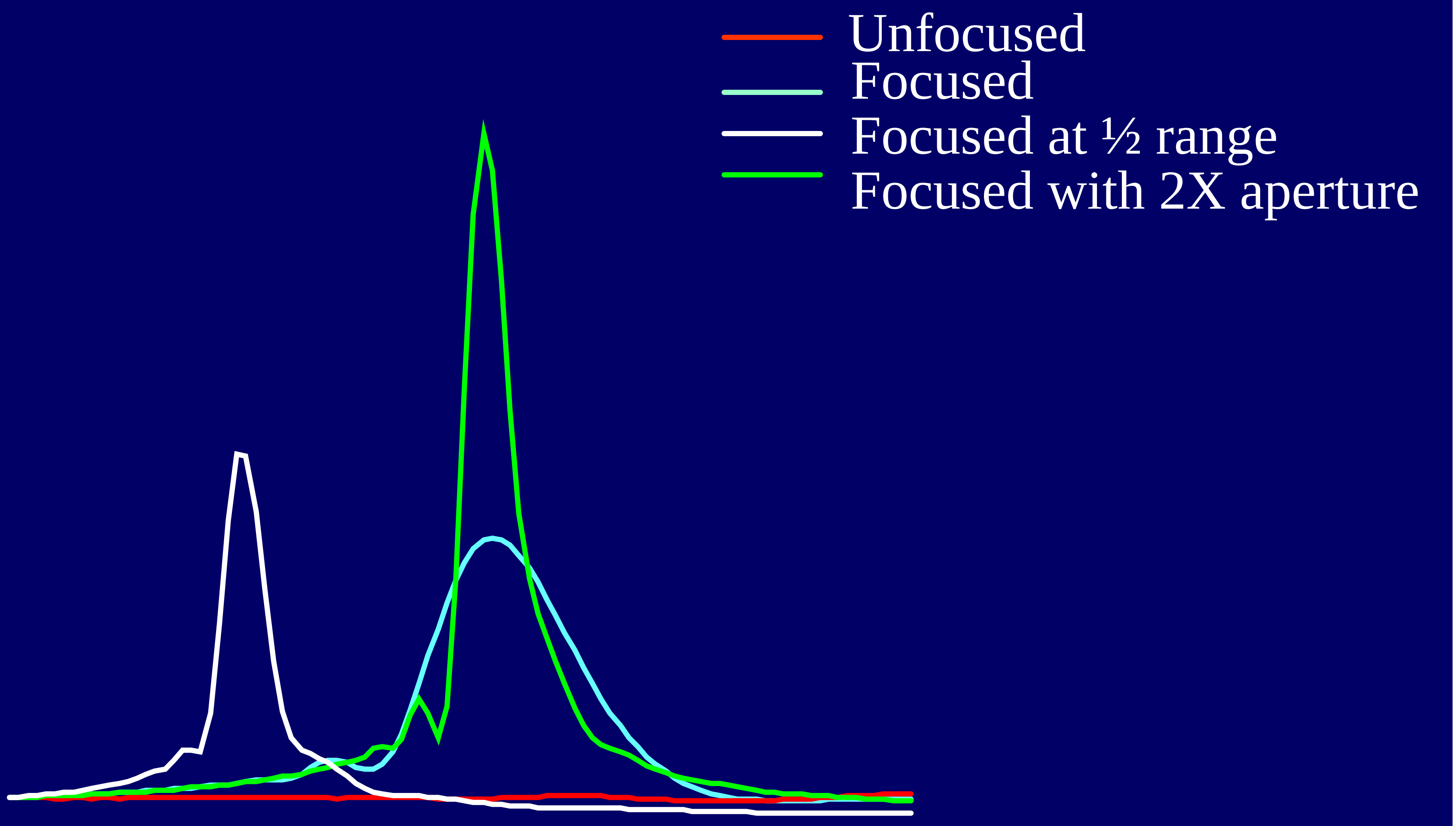


Focused at ½ range



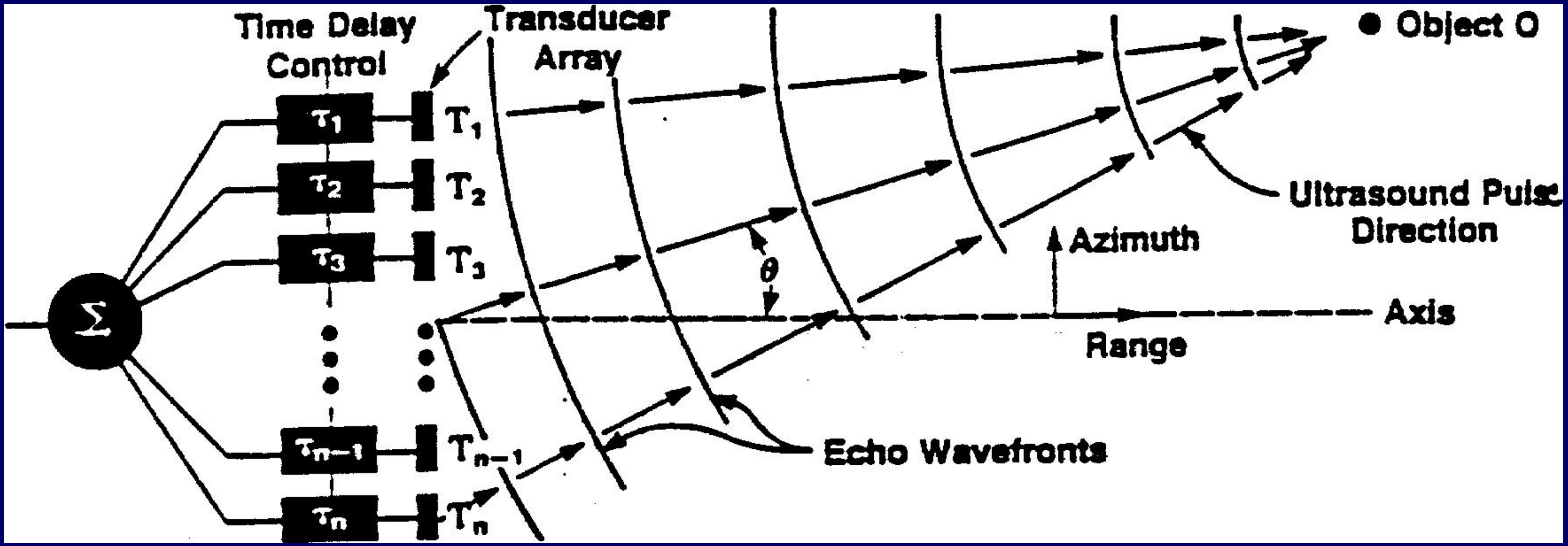
Focused with twice the aperture

Axial Intensity



Implementation of Focusing Using Arrays (Section IV)

Beam Formation Using Arrays



$$O(t) = \sum_{i=1}^{N} S_i \left(t - t\left(x_i, R, q\right)\right)$$

← Delay and Sum

Propagating Delays

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

In Fresnel region

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

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

Effective aperture size: $2a\rightarrow 2a\cos q$

Propagating Delays

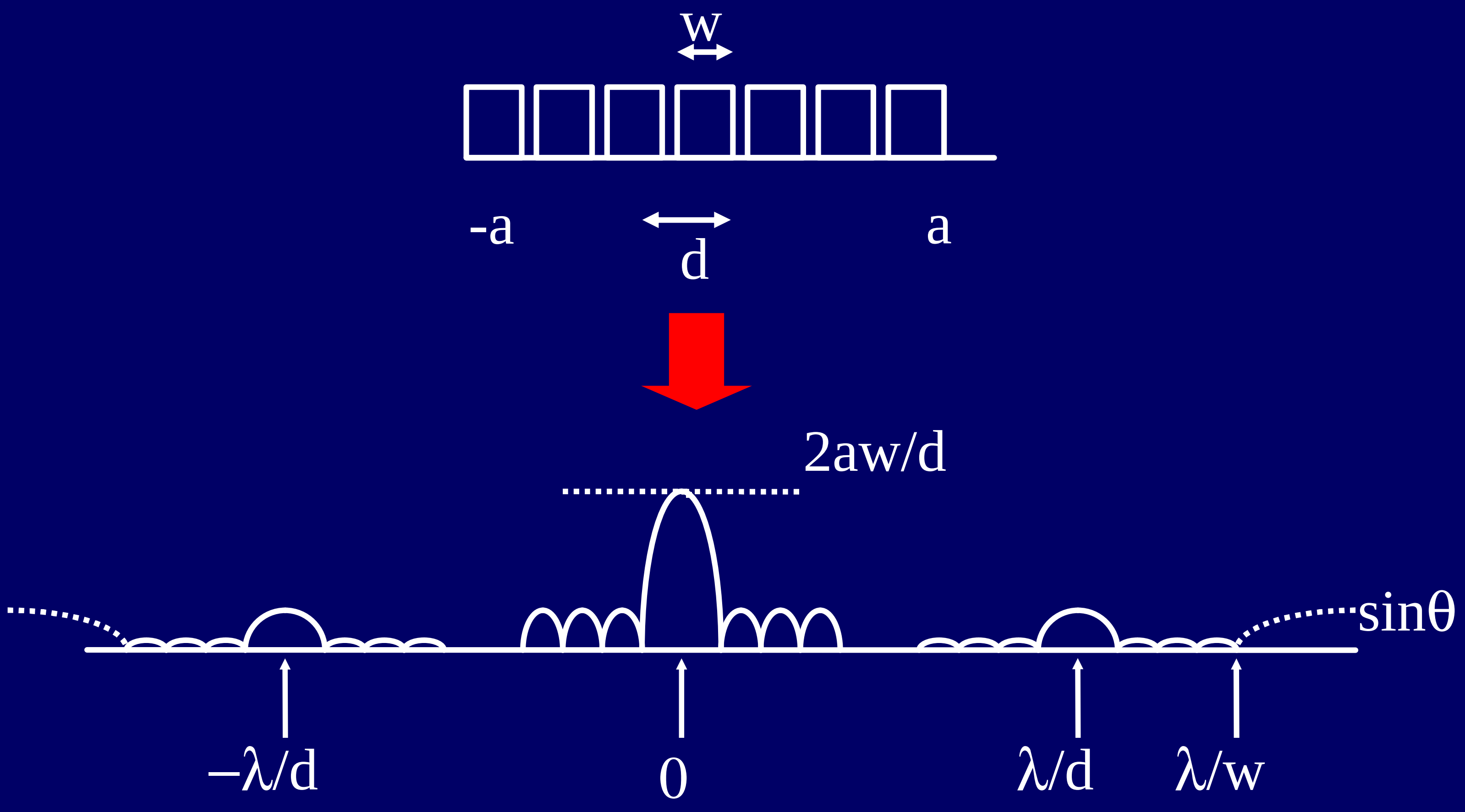
Transmit:

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

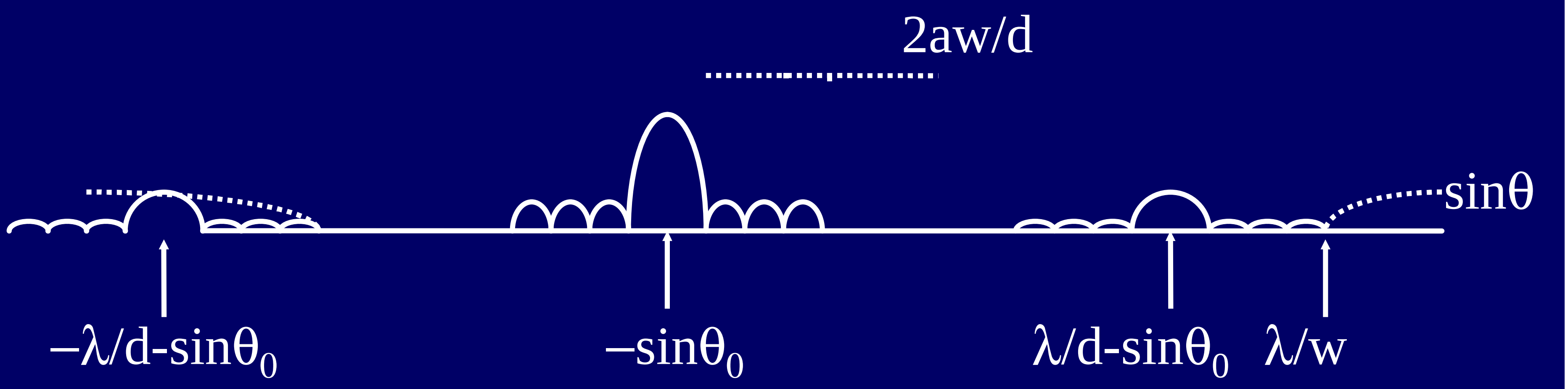
Receive:

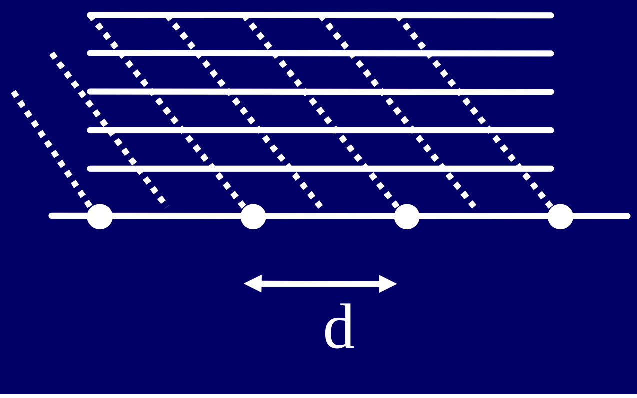
$$t^{R}(x_i, R, q) = \frac{2R}{c} - \frac{x_i \sin q}{c} + \frac{x_i^2 \cos^2 q}{2Rc}$$

Array → Sampled Aperture



Array Steering and Grating Lobes





—— primary beam

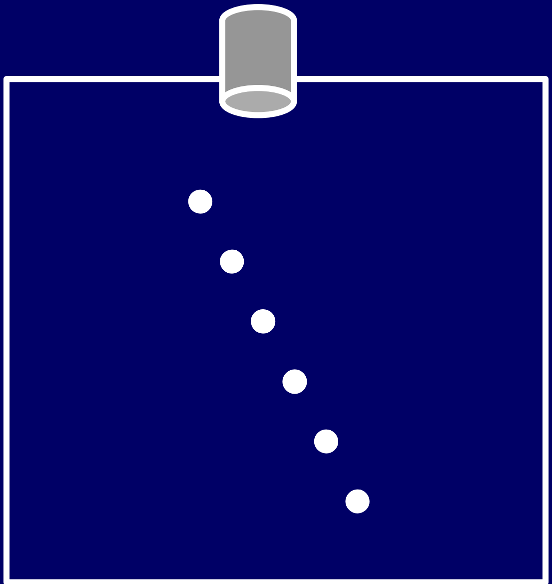
······ secondary beam

$2 \leq l / d$

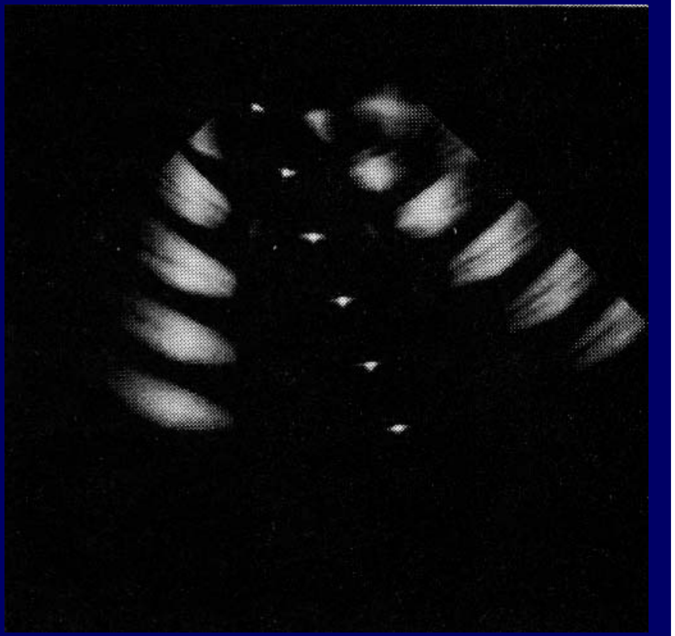
$d \leq l / 2$

Grating Lobes

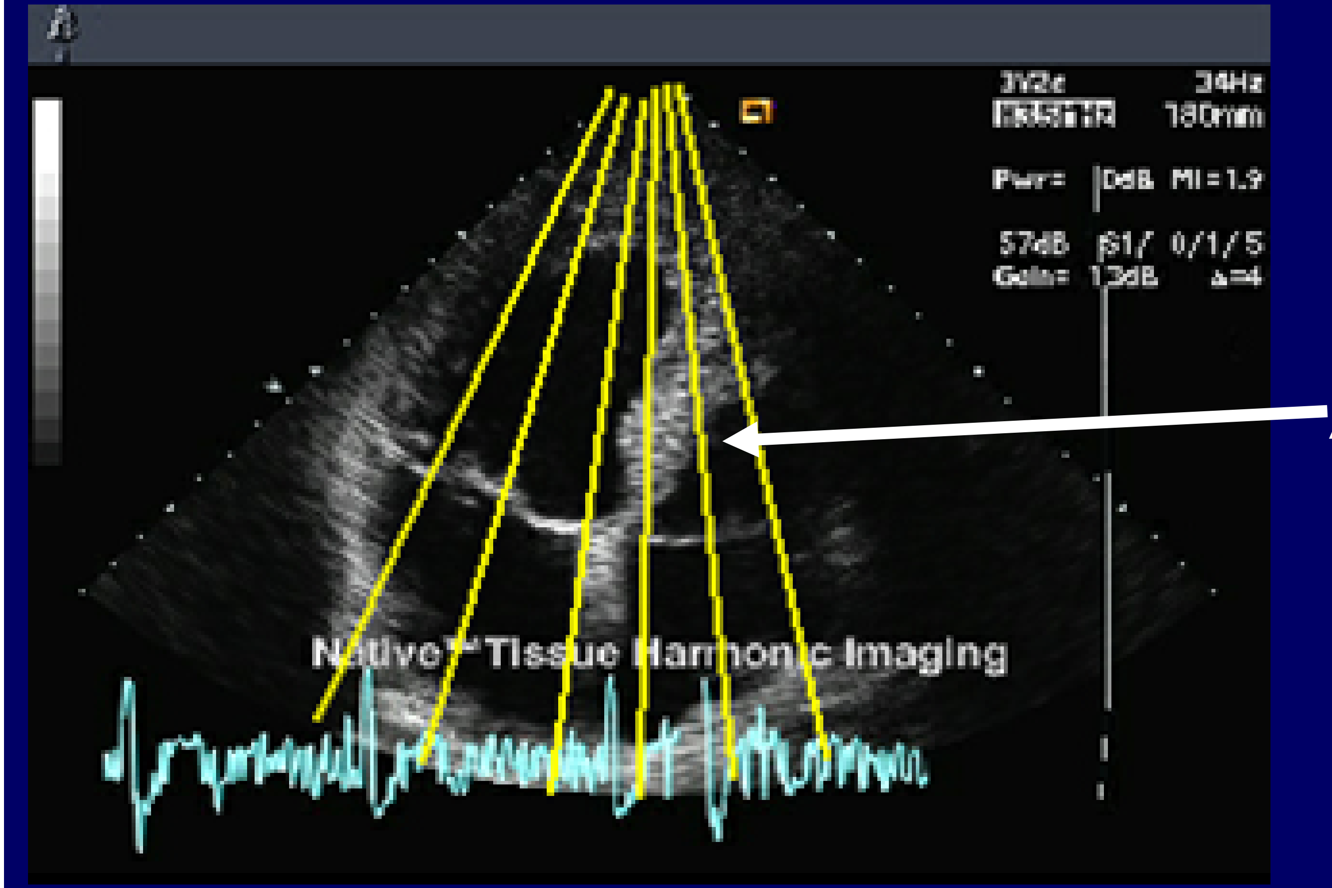
No Grating Lobes



With Grating Lobes



Beam Sampling

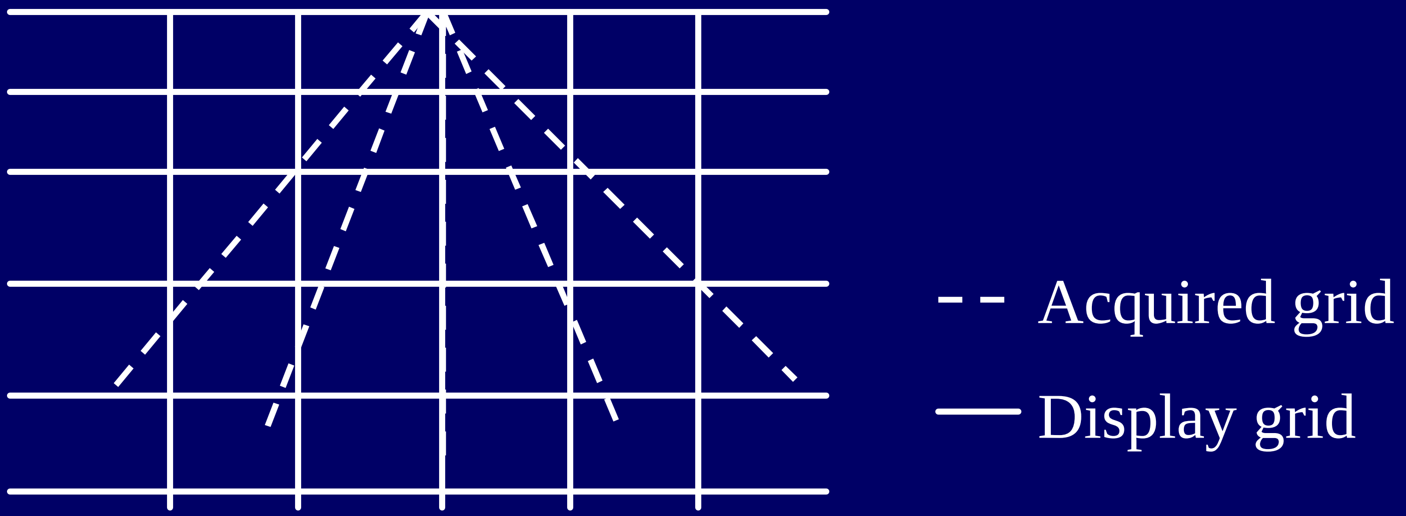


$$\Delta \sin q \le \frac{l}{4a}$$

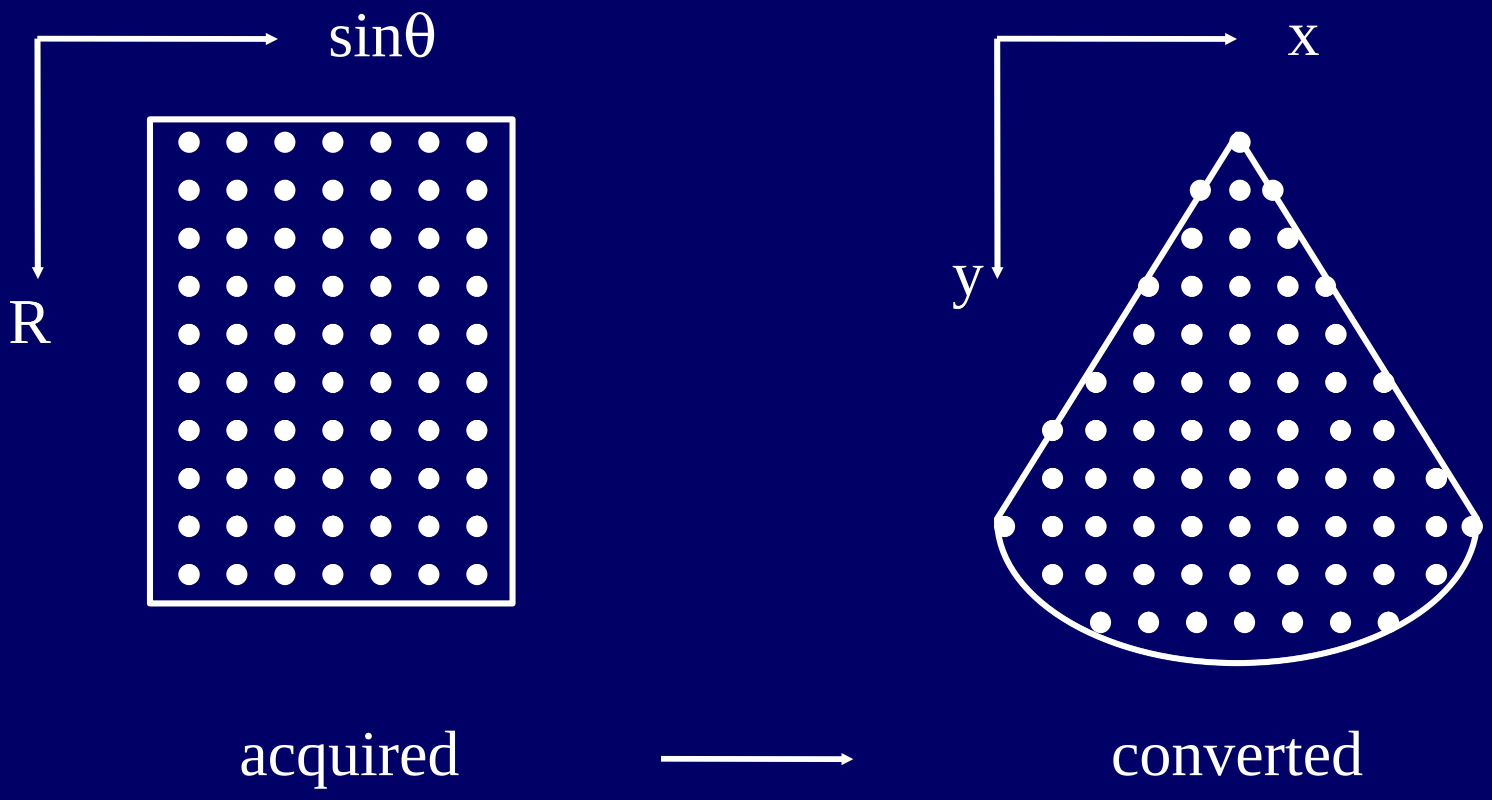
Real-Time Image Formation
(Section V)

Scan Conversion

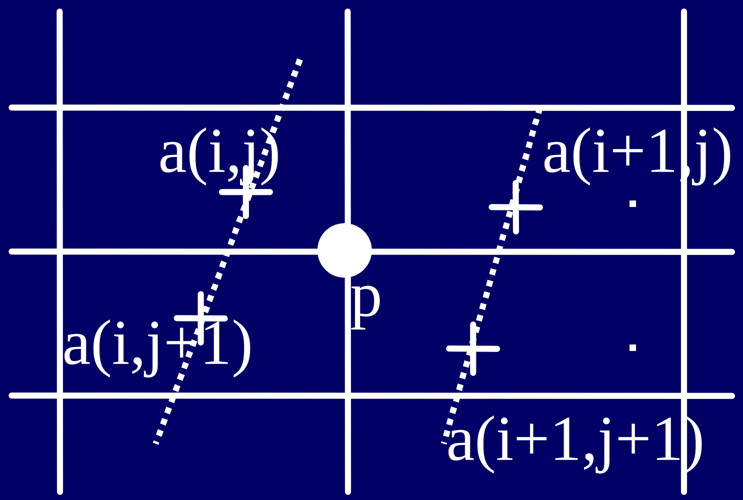
- Acquired data may not be on the display grid.



Scan Conversion



Scan Conversion



…… original grid

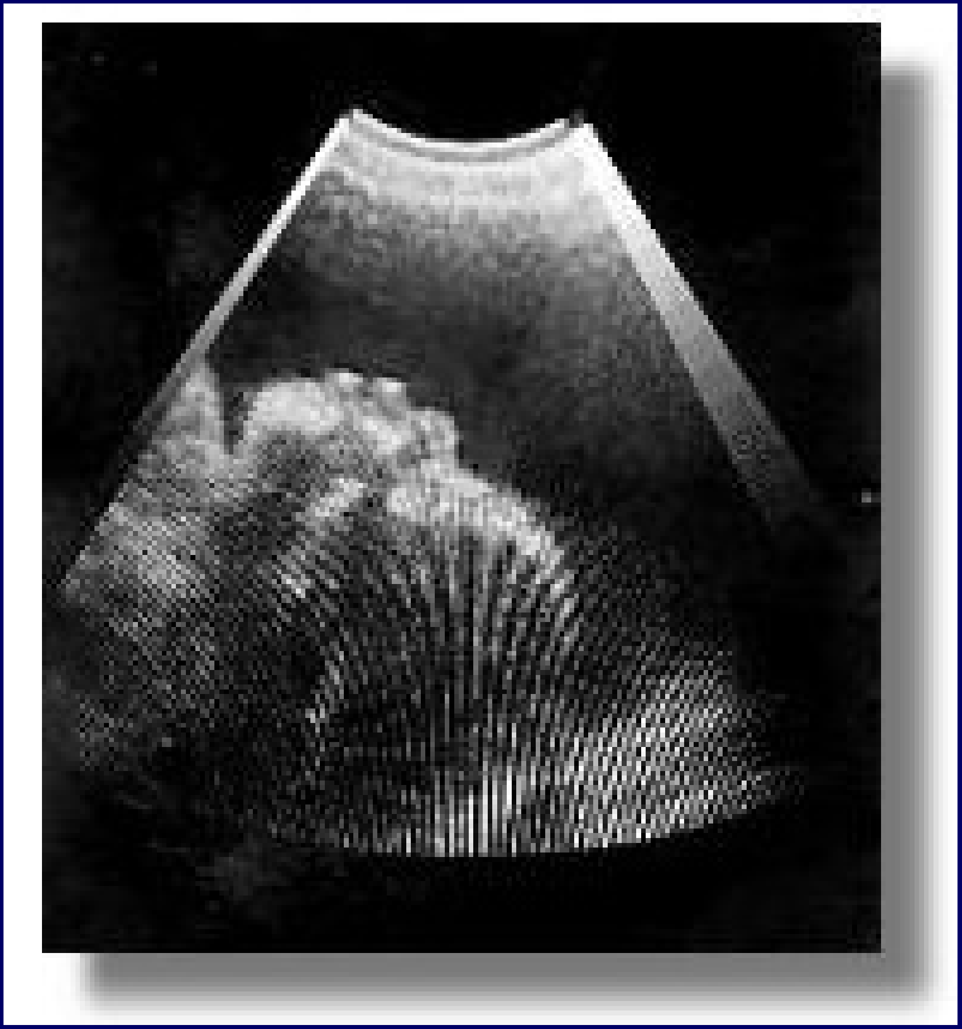
— raster grid

\+ acquired data

● display pixel

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

Moiré Pattern



Temporal Resolution (Section VI)

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.

Contrast Resolution
(Section VII)

Contrast Resolution

- Contrast resolution is determined by both spatial resolution and speckle noise variations.
- Speckle comes from coherent interference of diffuse scatterers. In-coherent processing must be used to reduce speckle noise.
- There exists a tradeoff between contrast and spatial resolutions.

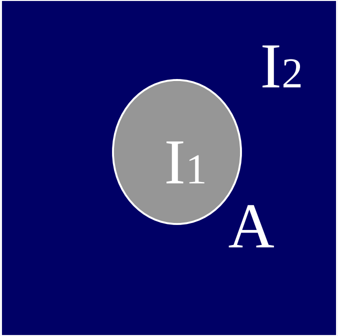
Contrast Resolution

- Contrast-to-Noise Ratio (CNR):

$$CNR = \frac{\langle I_1 - I_2 \rangle}{s_{I_A}} = \frac{\langle \Delta I \rangle}{s_I}\sqrt{N}$$

- On a log display

$$CNR = \frac{10\log\left(\frac{I_1}{I_2}\right)}{s_D}\sqrt{N}$$



Contrast Resolution

- Contrast resolution is primarily limited by speckle noise.
- Speckle is a multiplicative noise.
- On a logarithmic display,

$$s_D \approx 4.34dB.$$

Spatial vs. Contrast

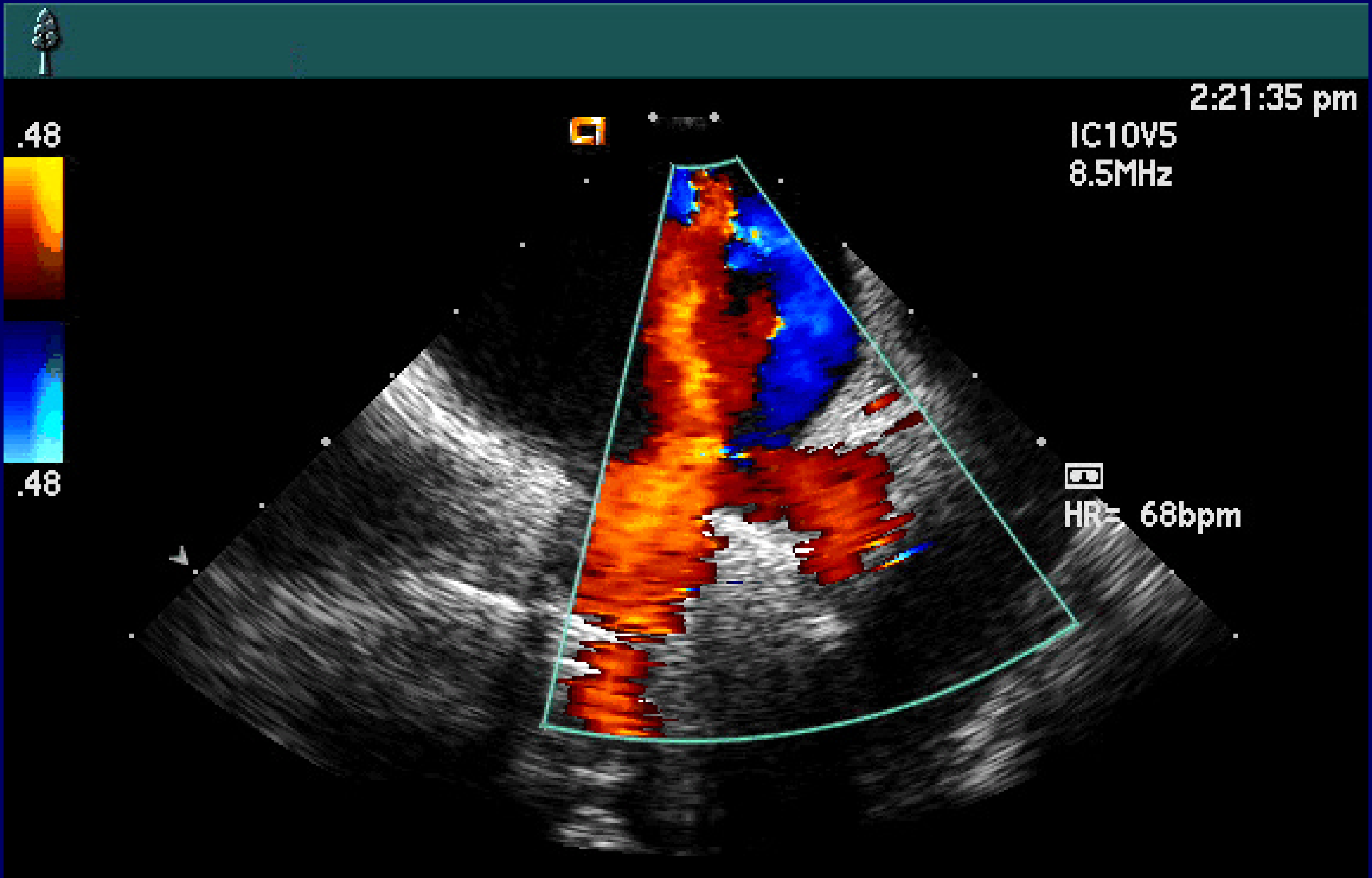
$$CNR = \frac{10\log\left(\frac{I_1}{I_2}\right)}{4.34}\sqrt{N}$$

- Speckle noise is 4.34dB for true speckle, a figure of merit for detectability.
- CNR increases as speckle noise decreases, generally resulting in loss in spatial resolution.
- Both CNR and spatial resolution can be improved by reducing sample volume.

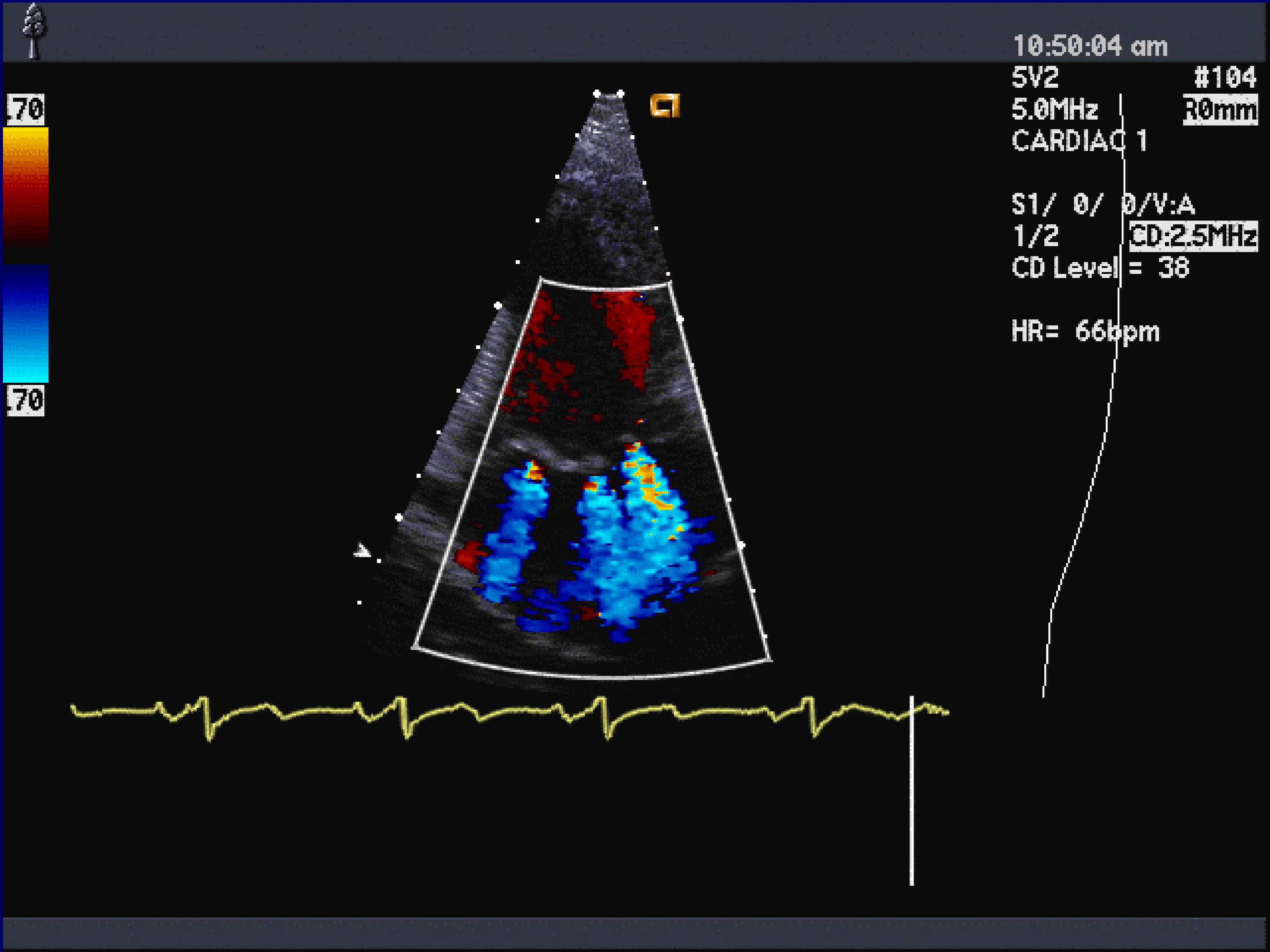
Doppler Techniques for Motion Estimation

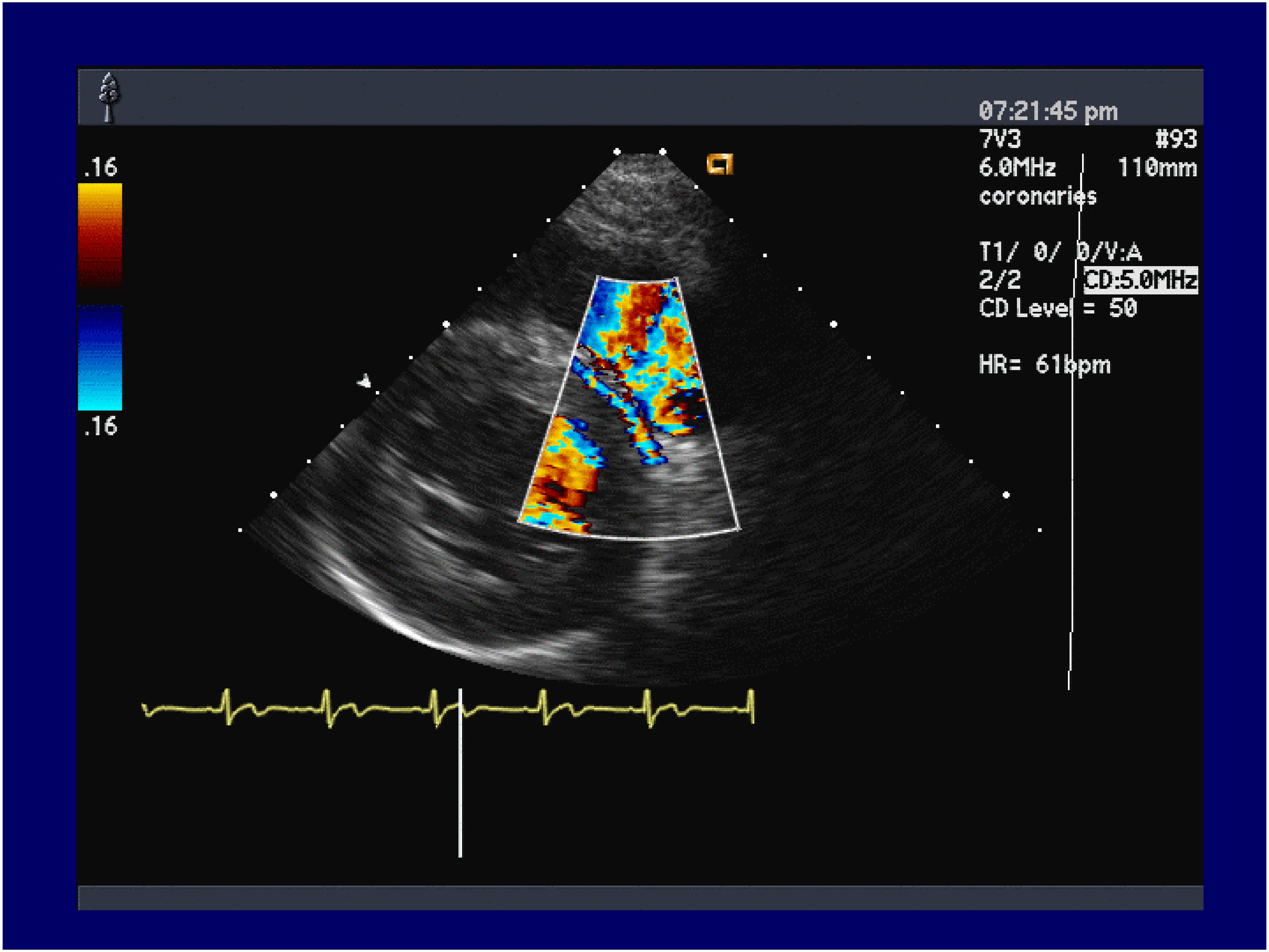
(Section VIII)

Color Doppler Mode

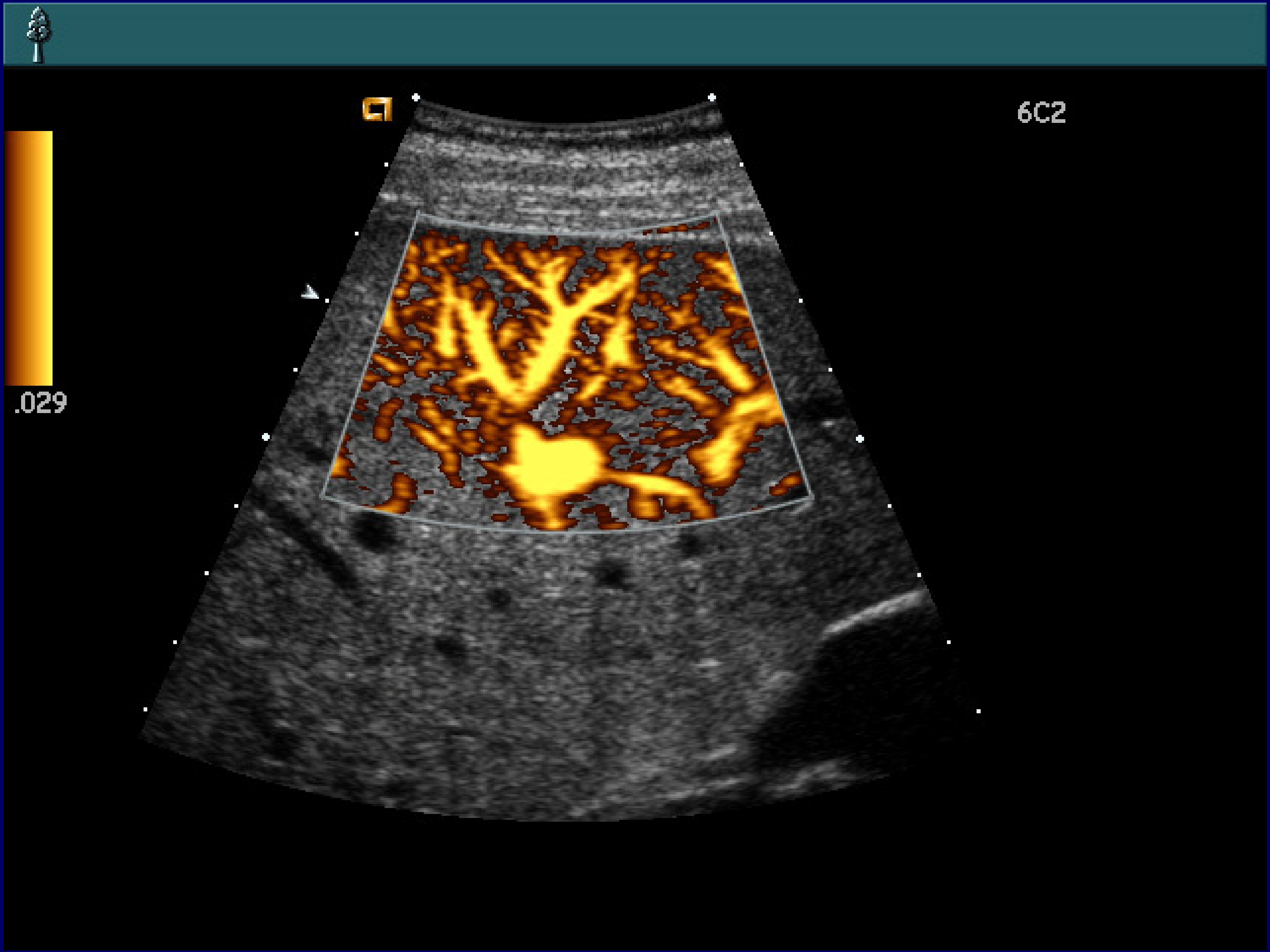


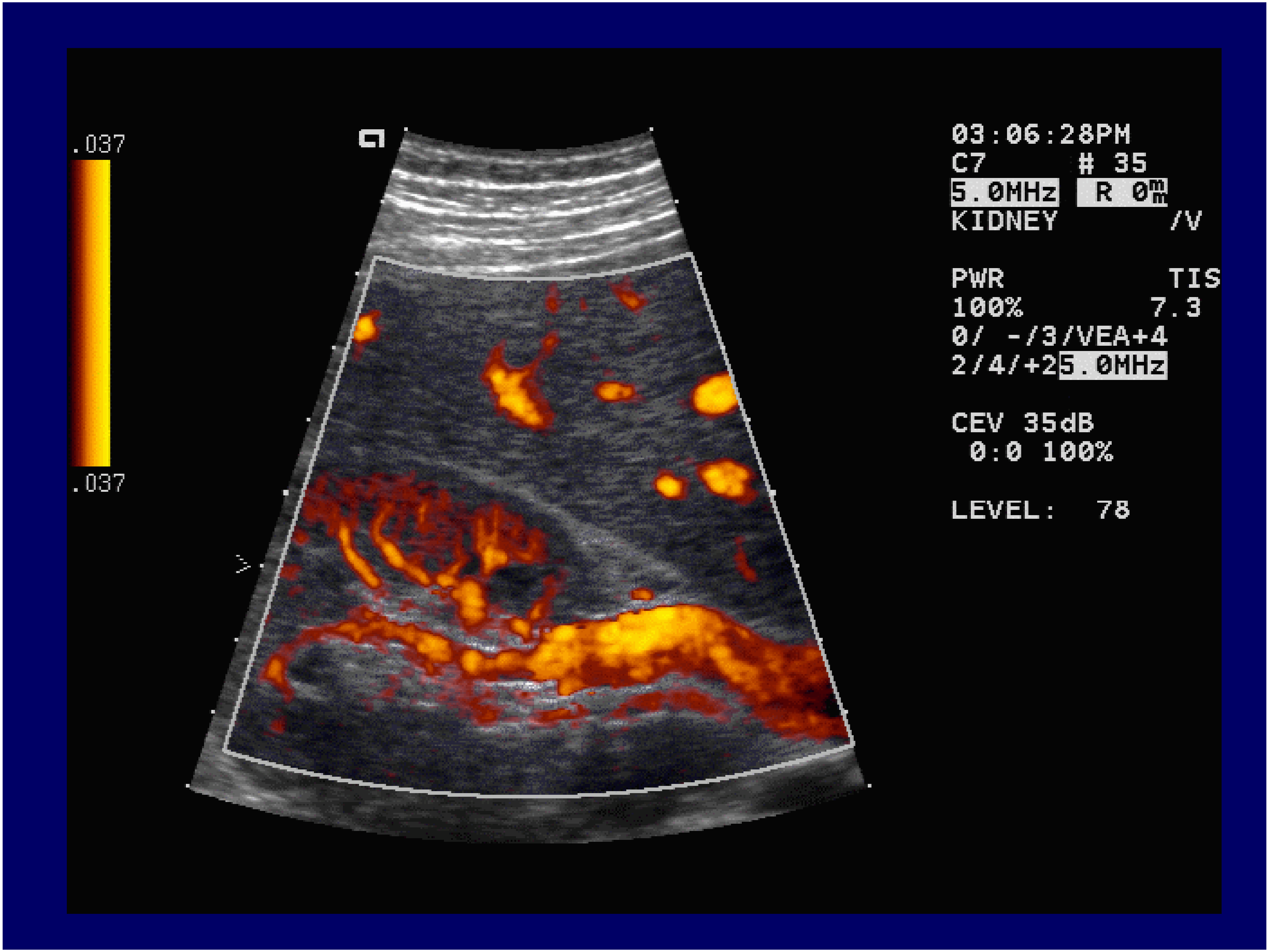
Color Doppler
Left Pulmonary Veins


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

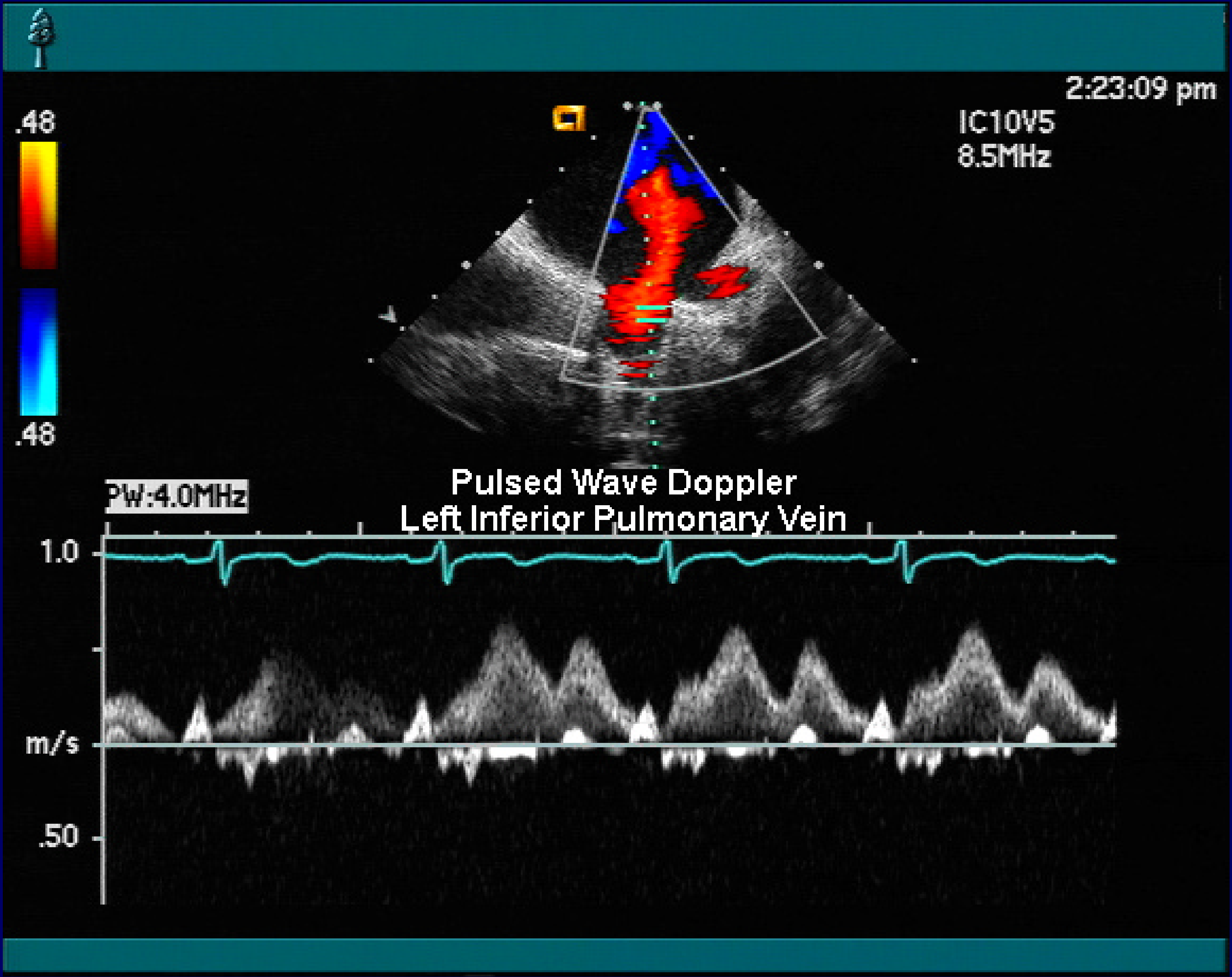

.16
.16
07:21:45 pm
7V3 #93
6.0MHz 110mm
coronaries
T1/ 0/ 0/V:A
2/2 CD:5.0MHz
CD Level = 50
HR= 61bpm

Power Doppler


6C2
.029

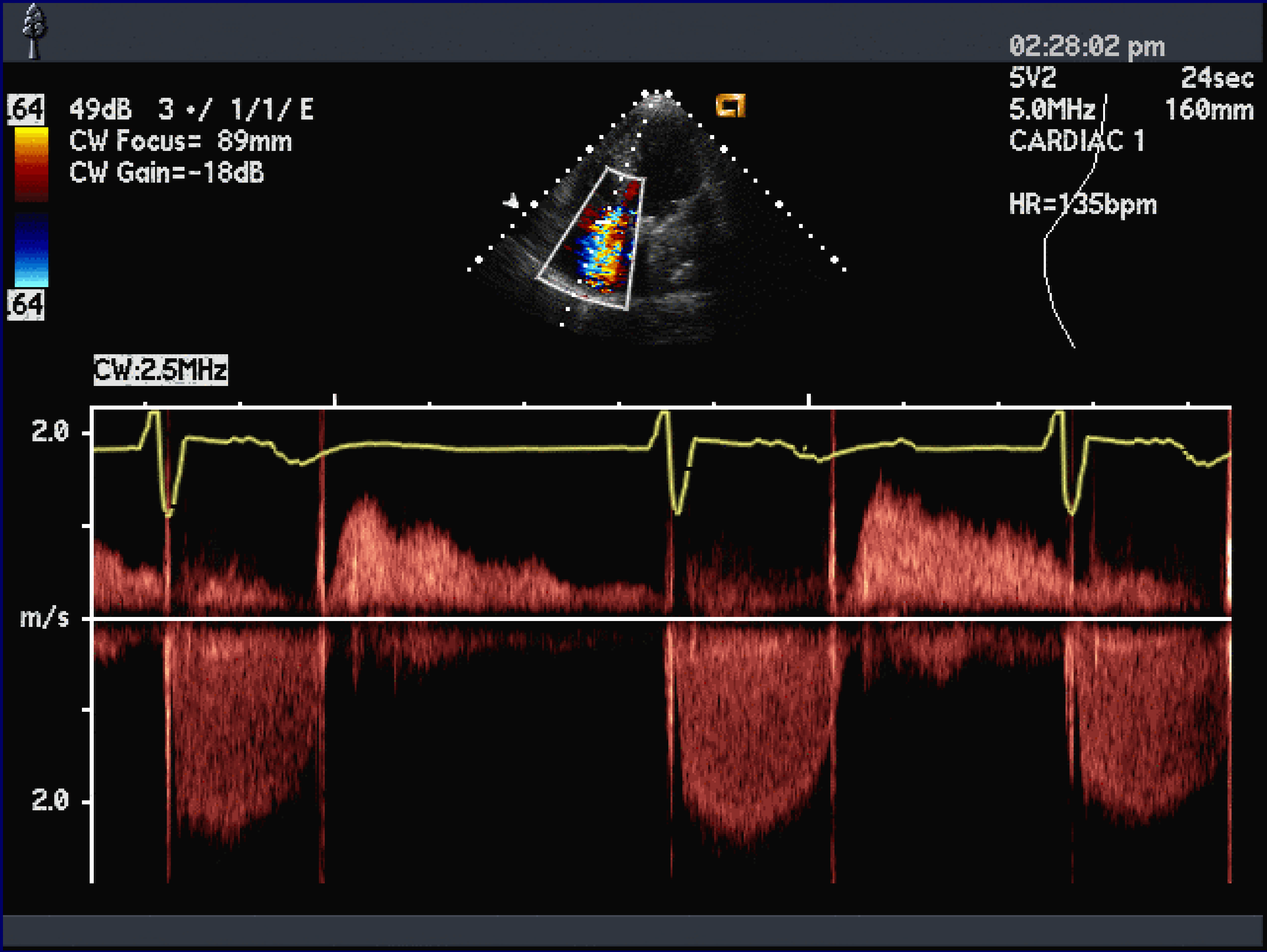

.037
.037
03:06:28PM
C7 # 35
5.0MHz R 0mm
KIDNEY /V
PWR TIS
100% 7.3
0/ -/3/VEA+4
2/4/+25.0MHz
CEV 35dB
0:0 100%
LEVEL: 78

PW Doppler (Spectral Doppler)

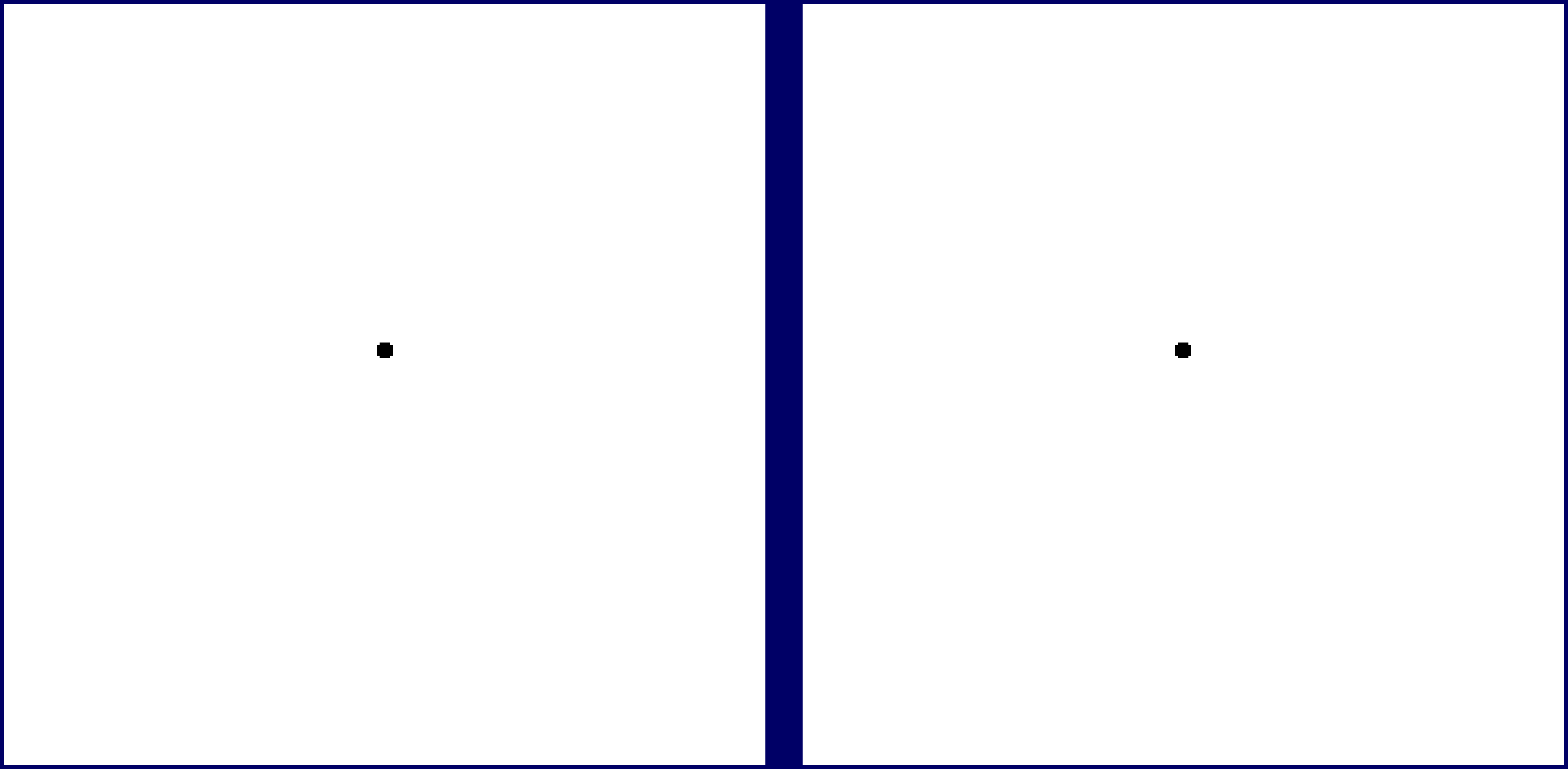


Pulsed Wave Doppler
Left Inferior Pulmonary Vein

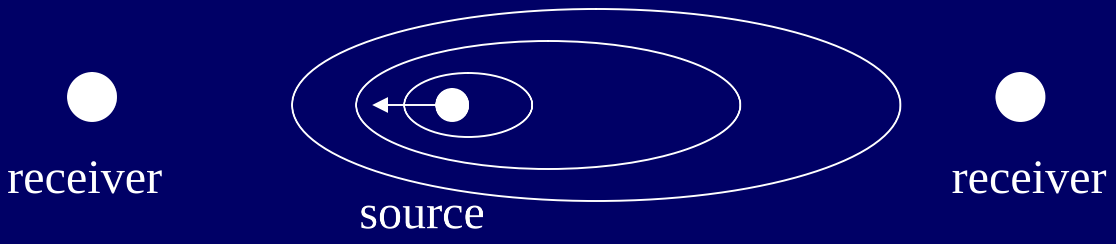
CW Doppler (Spectral Doppler)


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,

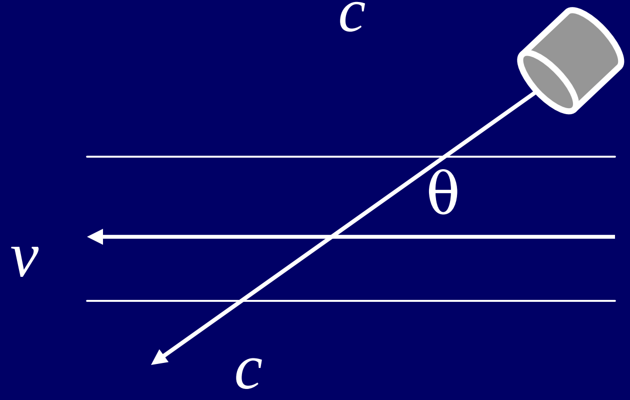
v_s and v_r are source and receiver velocities.

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.

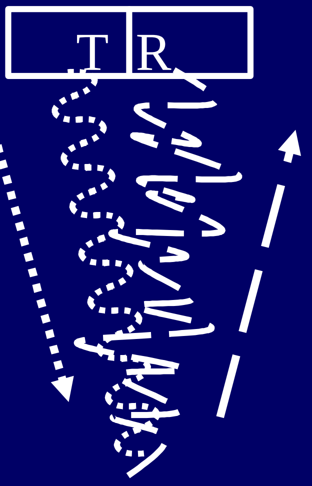
Doppler Equations

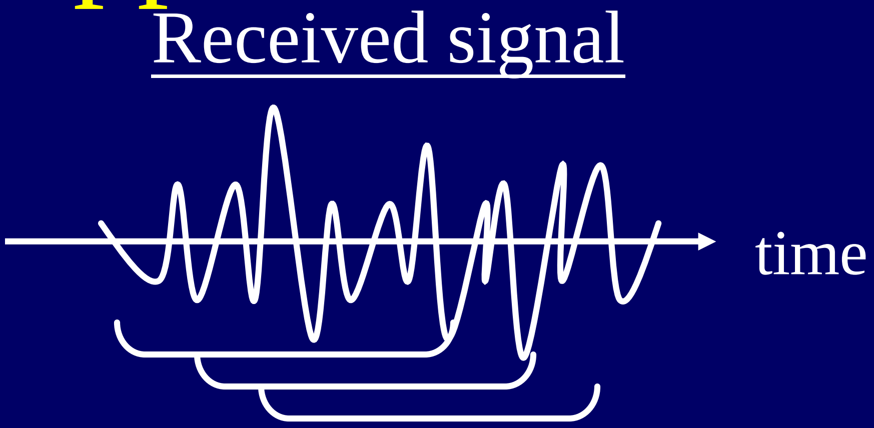
$$f_d = \frac{2vf_s}{c}\cos\theta$$

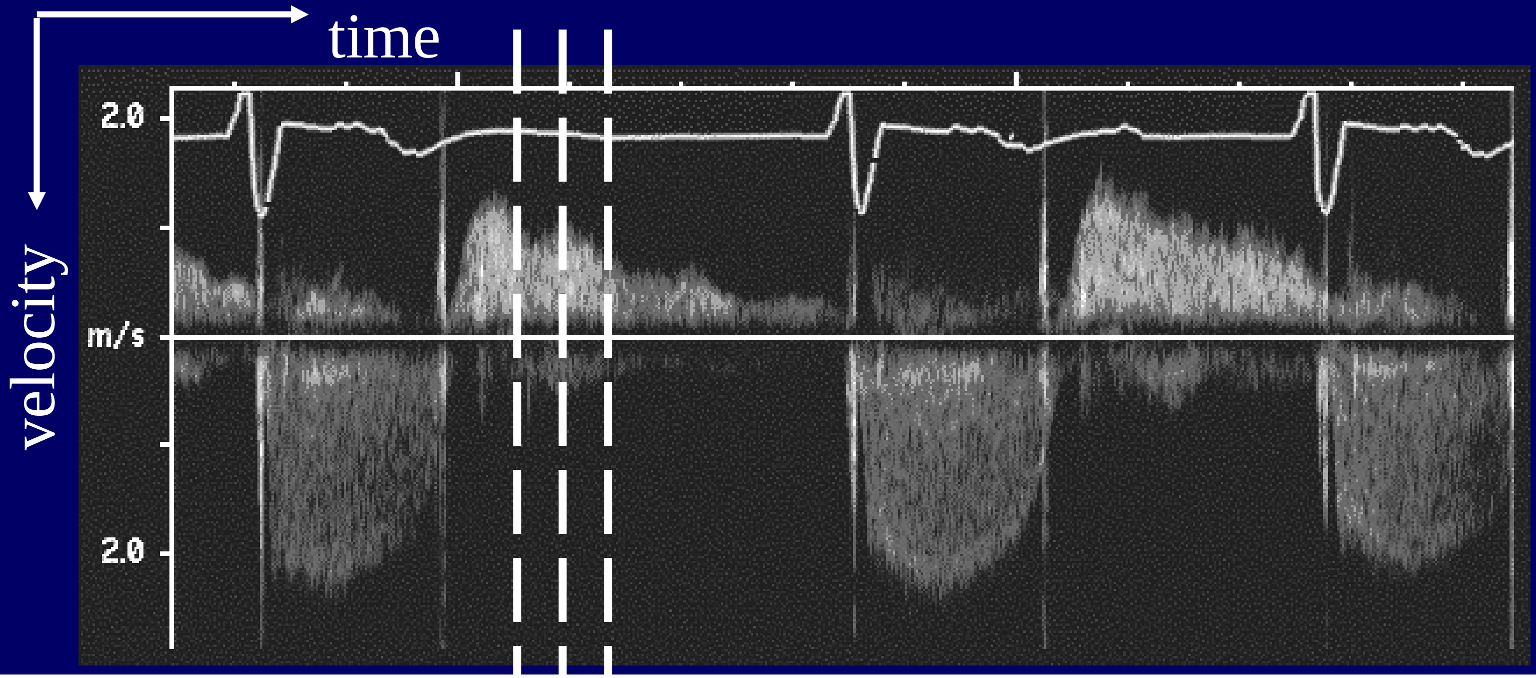


- Typical physiological flows (5-10m/sec at most) are much slower than sound velocity in the body (~1500m/sec).
- Doppler shift is doubled due to round-trip propagation.
- Only parallel flows can be detected.

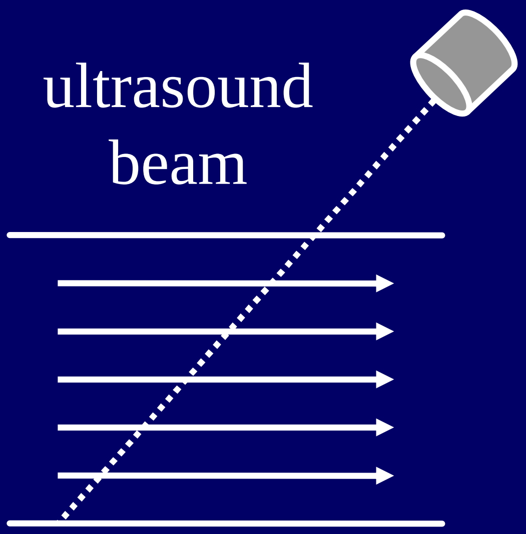
Continuous Wave (CW) Doppler

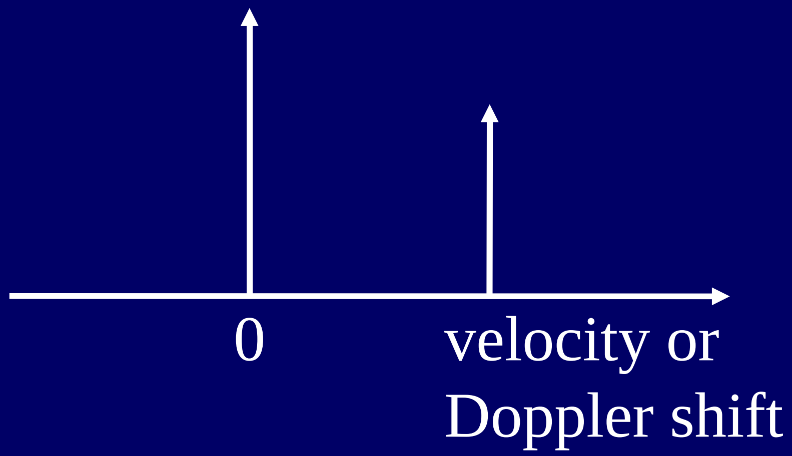




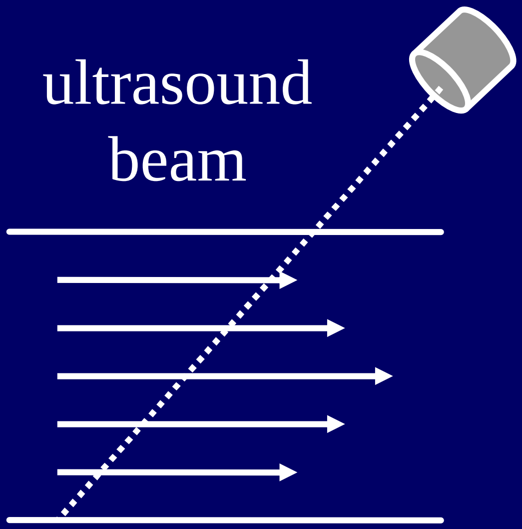


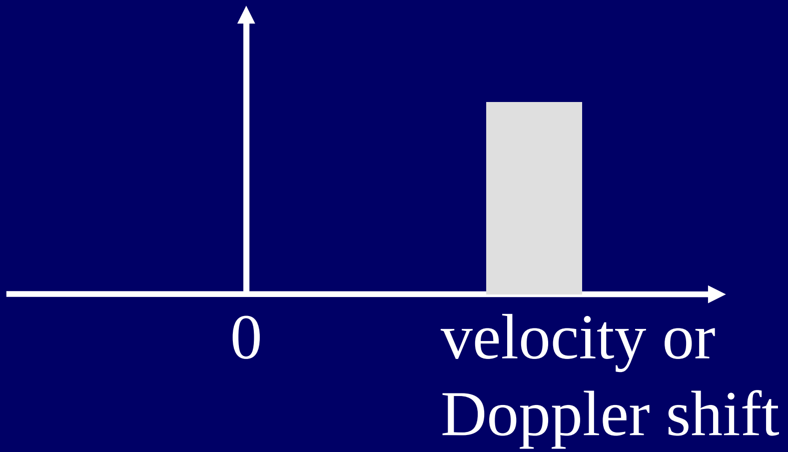
Flow Pattern v. Velocity Profile



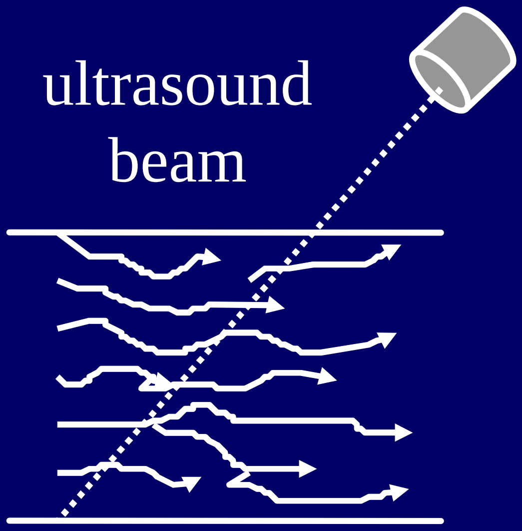


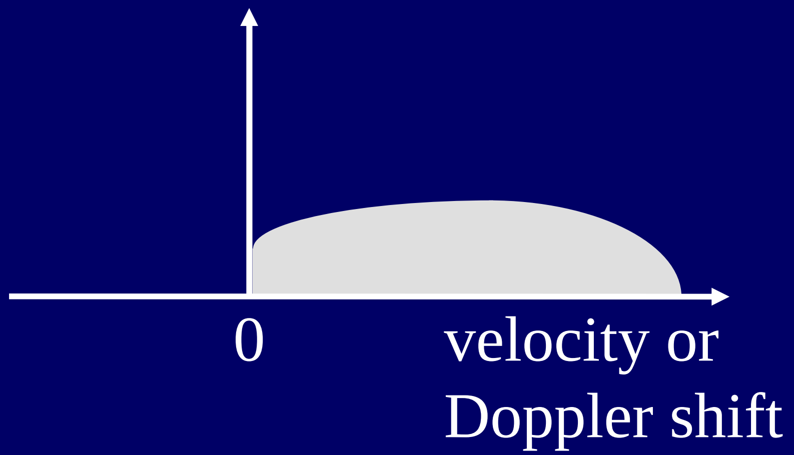
Flow Pattern v. Velocity Profile



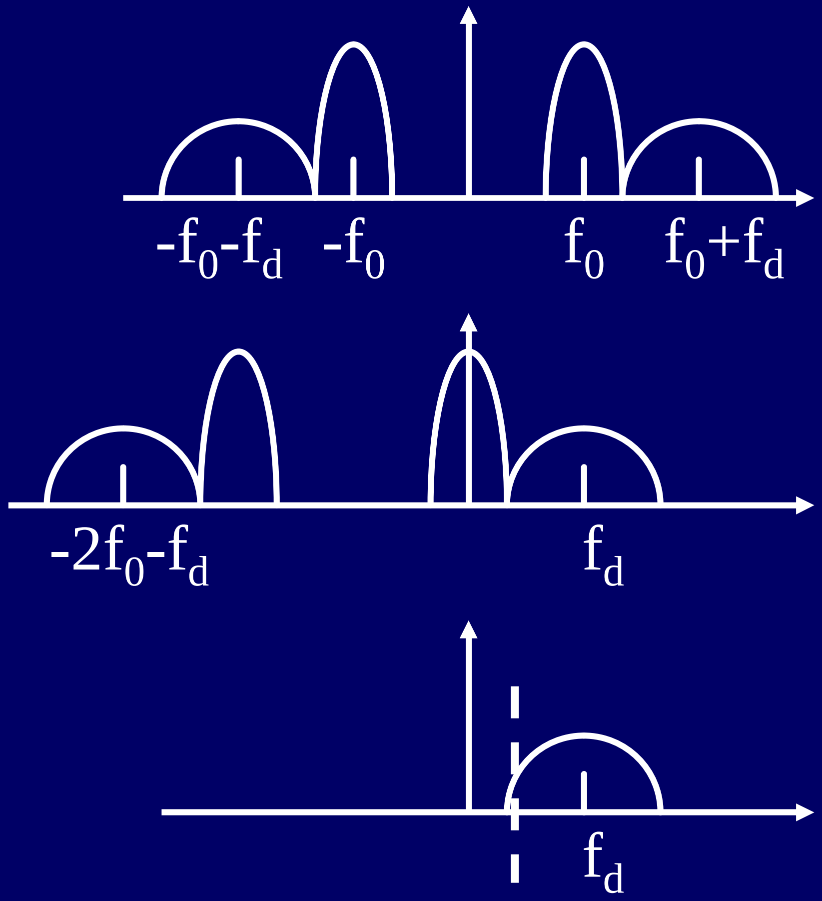


Flow Pattern v. Velocity Profile





CW Doppler Processing

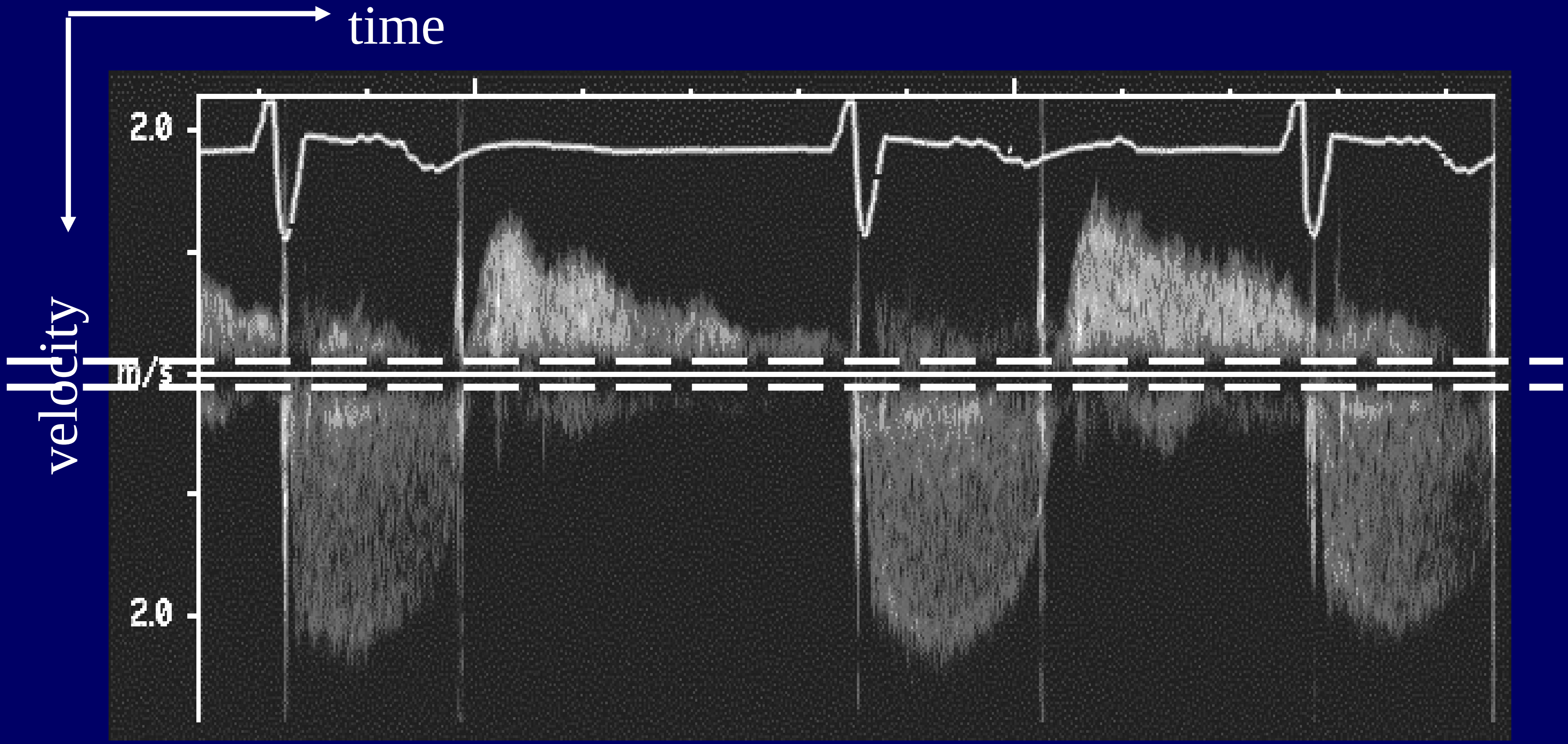


original spectrum

demodulated

demodulated and filtered

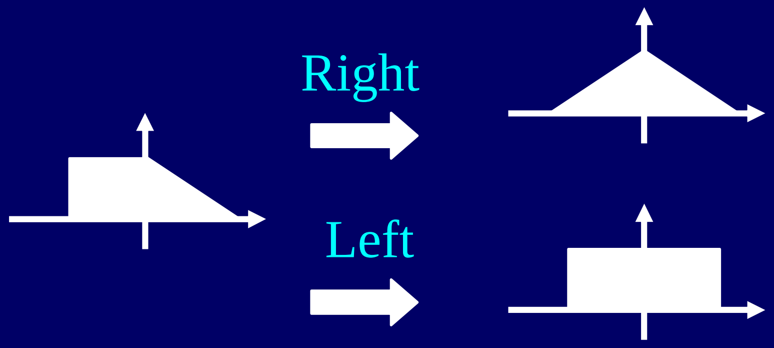
Wall Filter (Clutter Filter)



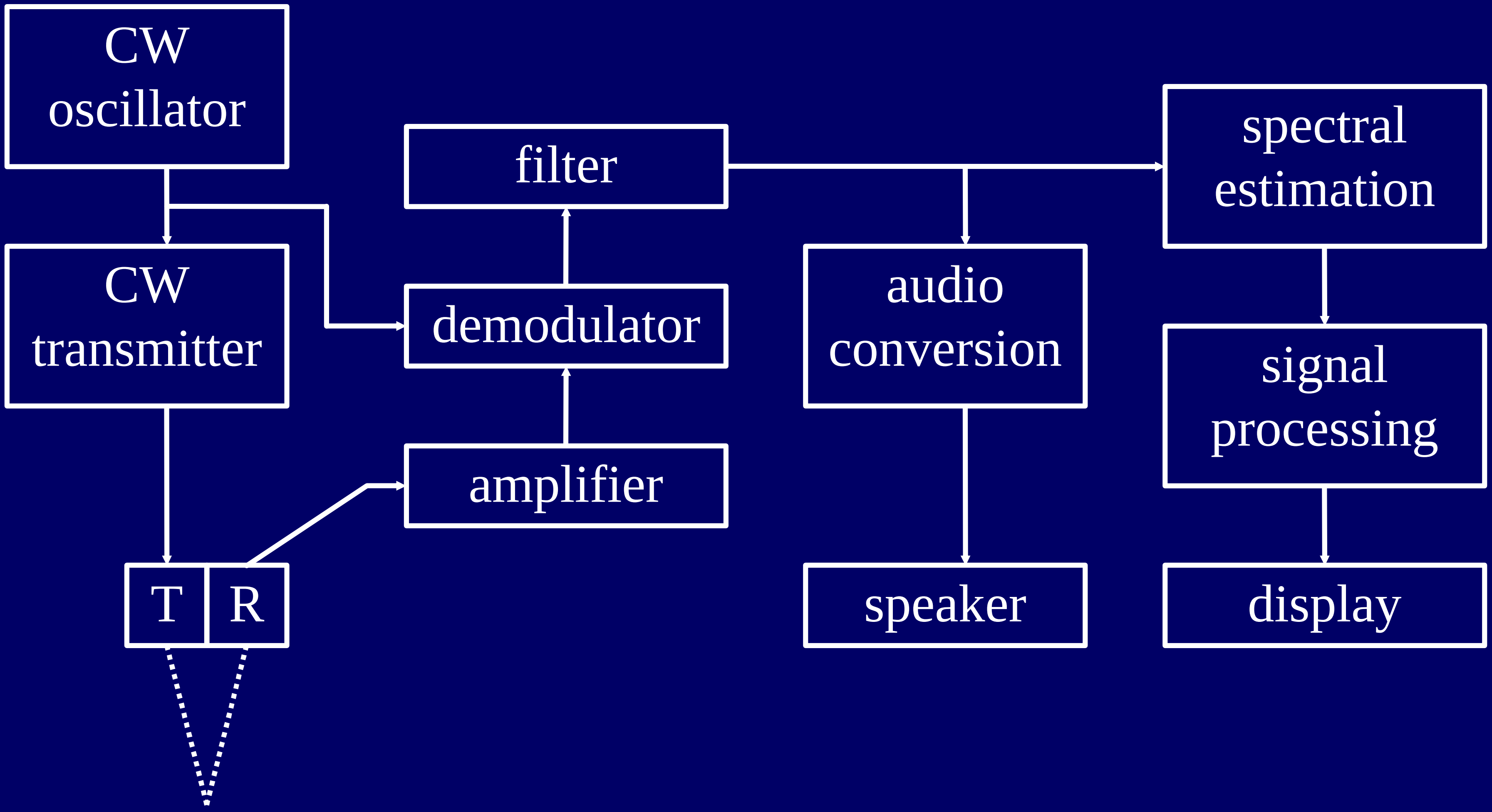
Audio Doppler

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

- 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 Doppler



CW oscillator

CW transmitter

T

R

filter

demodulator

amplifier

audio conversion

speaker

spectral estimation

signal processing

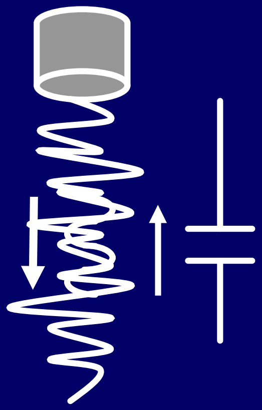
display

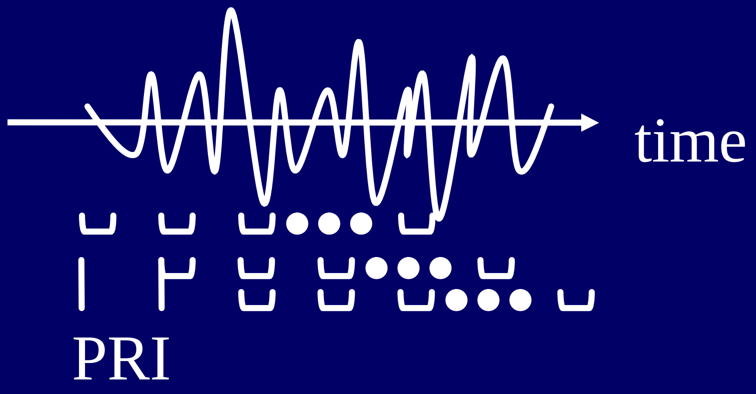
CW → PW

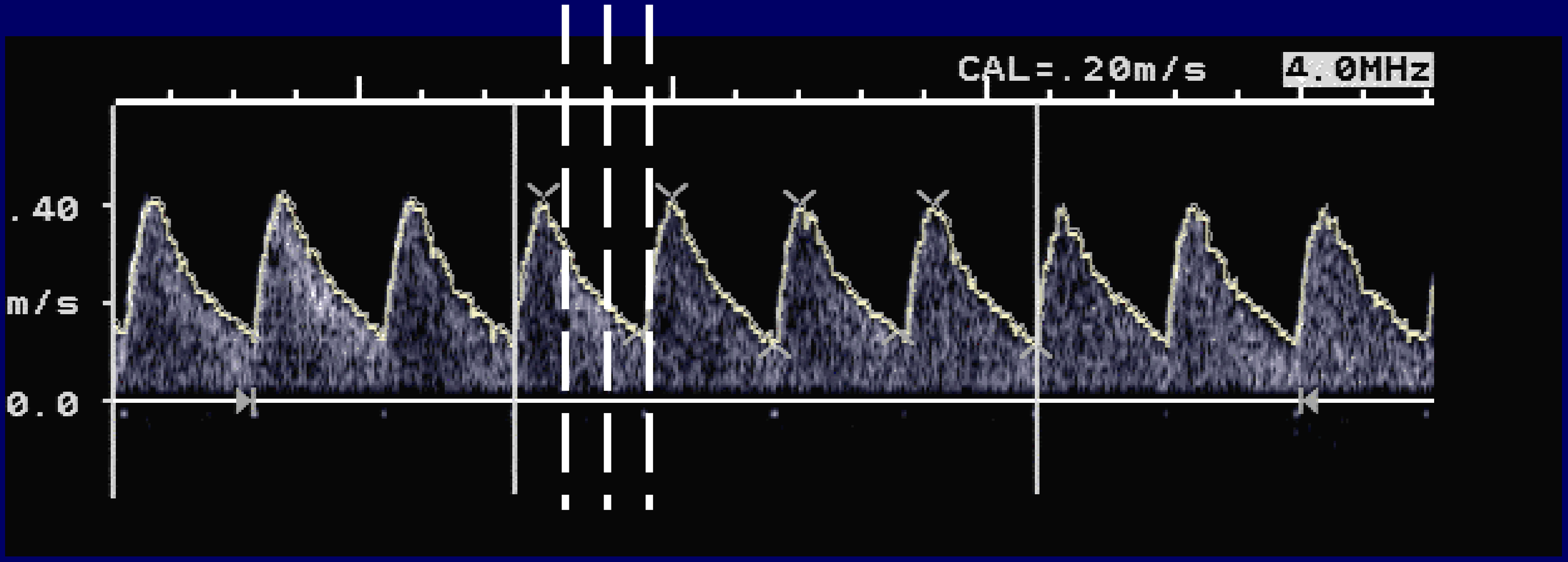
- CW: No range resolution.
- Sampling in time = sampling in range.

→ CW Doppler to PW Doppler.

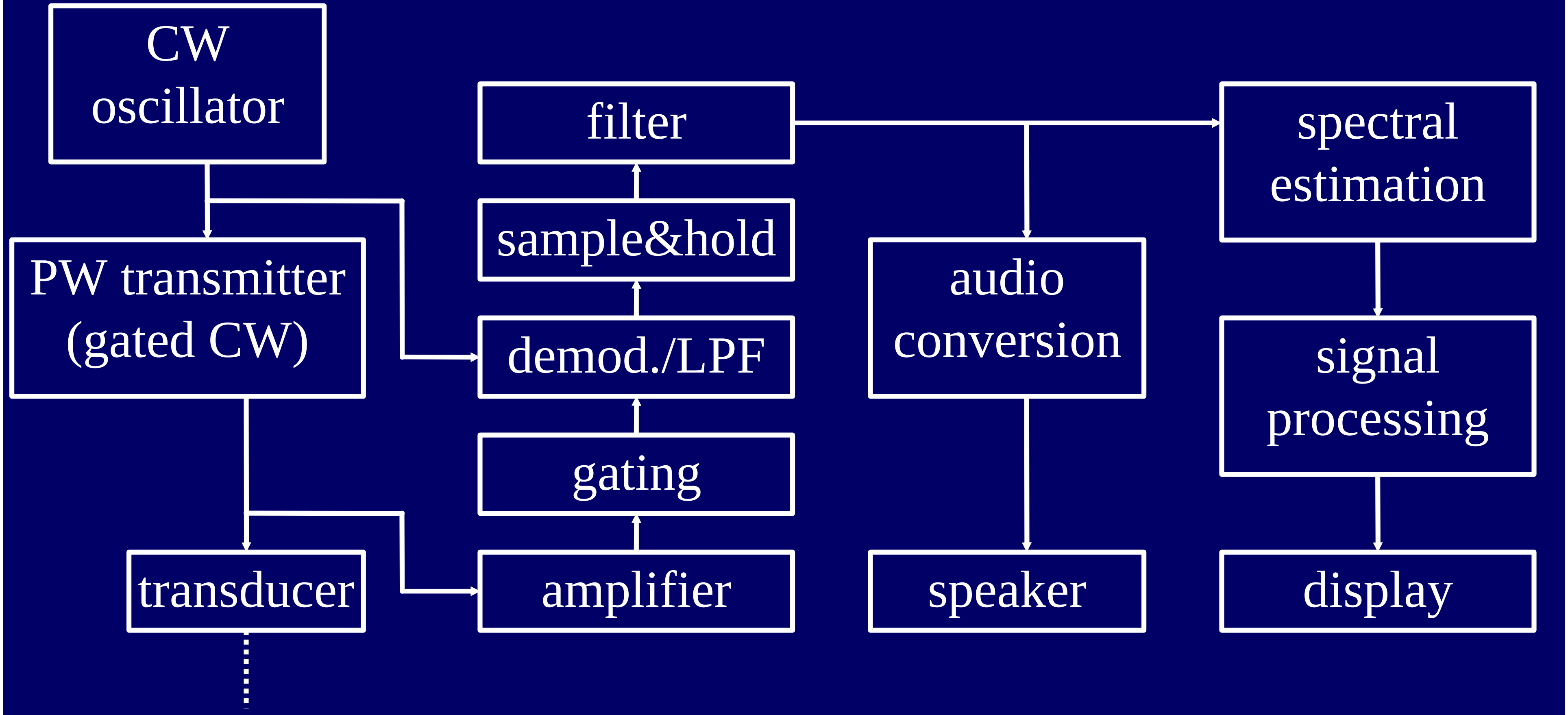
Pulsed Wave (PW) Doppler







PW System Diagram



CW oscillator

PW transmitter (gated CW)

transducer

filter

sample&hold

demod./LPF

gating

amplifier

audio conversion

speaker

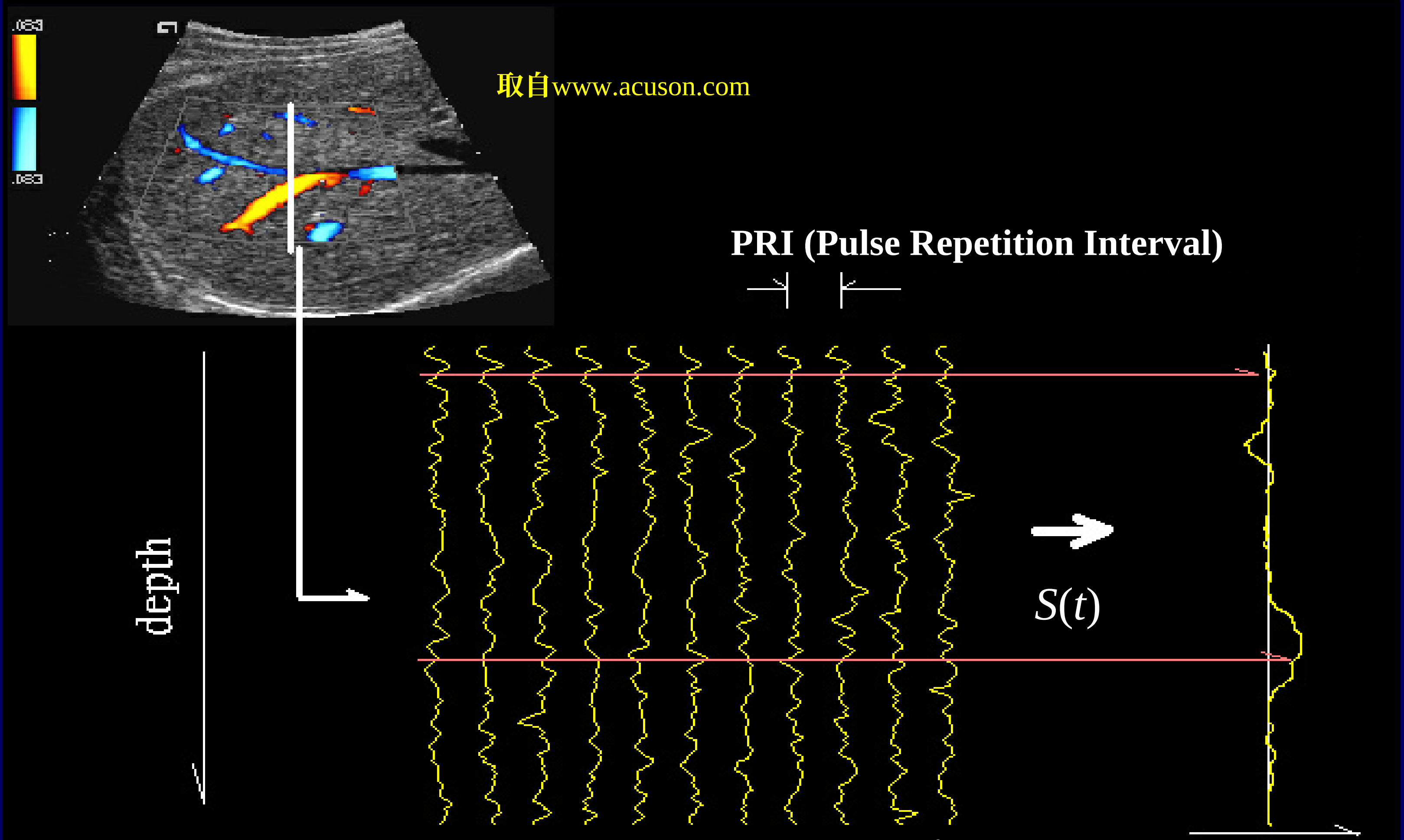
spectral estimation

signal processing

display

Another View for PW Doppler,…

Autocorrelation Processing



取自www.acuson.com

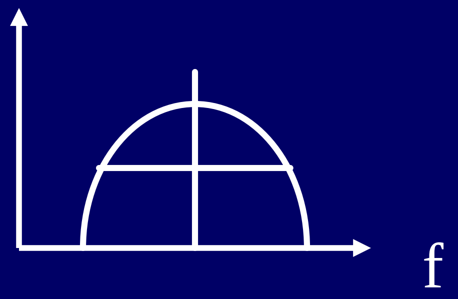
PRI (Pulse Repetition Interval)

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

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 mean velocity (including directionality), variance and energy (power).

Color Doppler Derivation

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

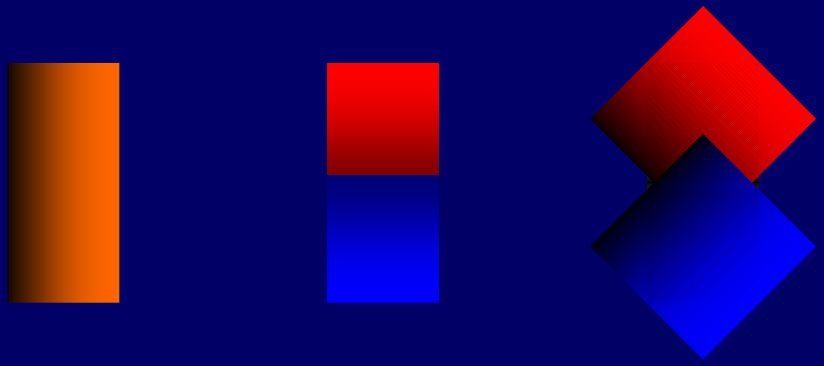
$$R(t) = \left|R(t)\right| e^{jq(t)}$$

$$\overline{w} = q'(0) \approx \frac{q(T)-q(0)}{T} = \frac{q(T)}{T}$$

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

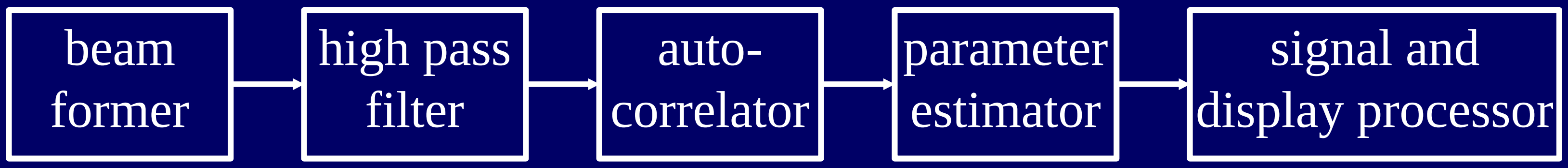
$$E = \int_{-\infty}^{\infty} P(w)\,dw = R(0)$$

Color Doppler

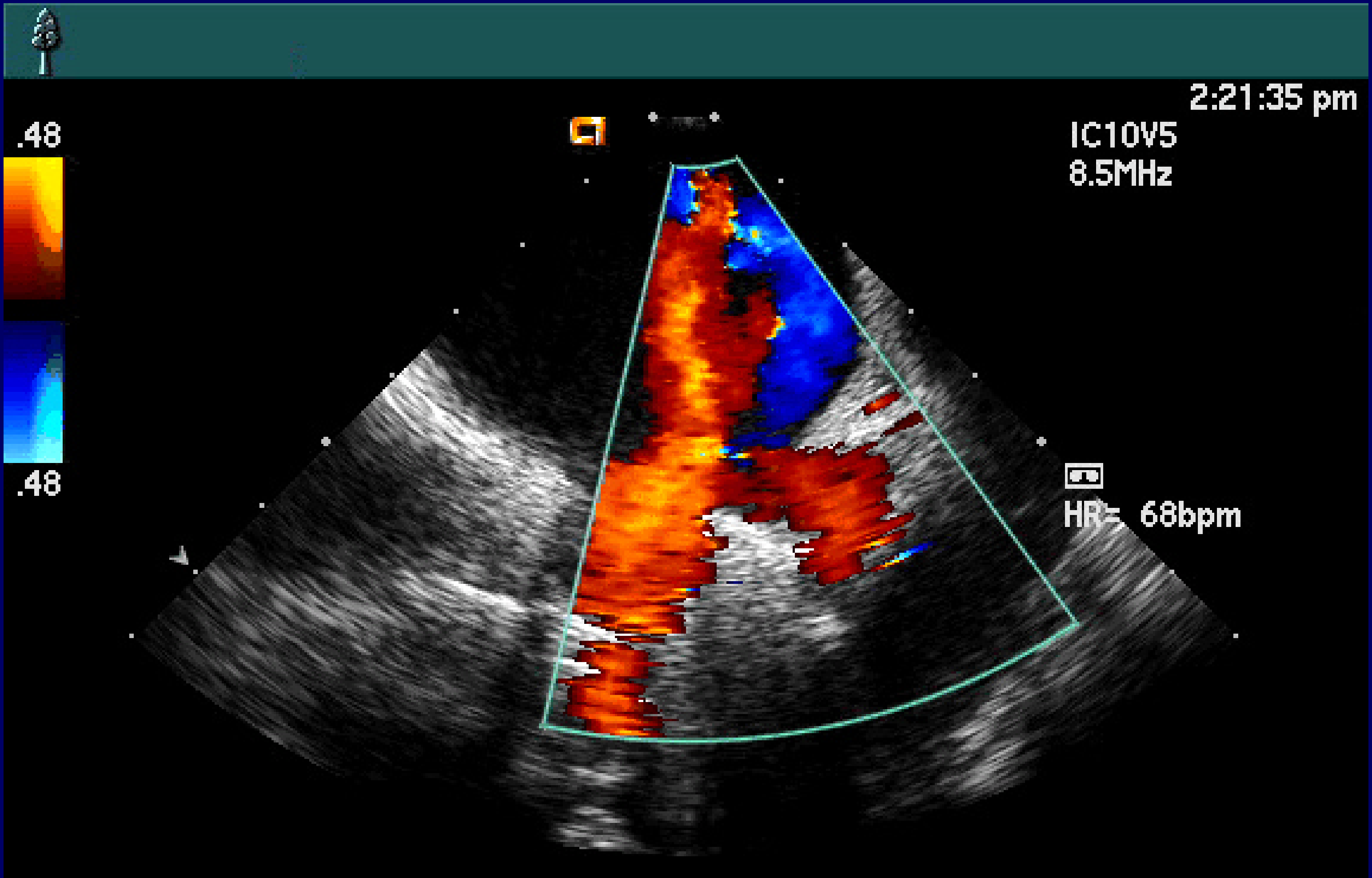


- Flow parameters are mapped into colors for display (1D or 2D).
- Choice of map affects the presentation of Color Doppler images.

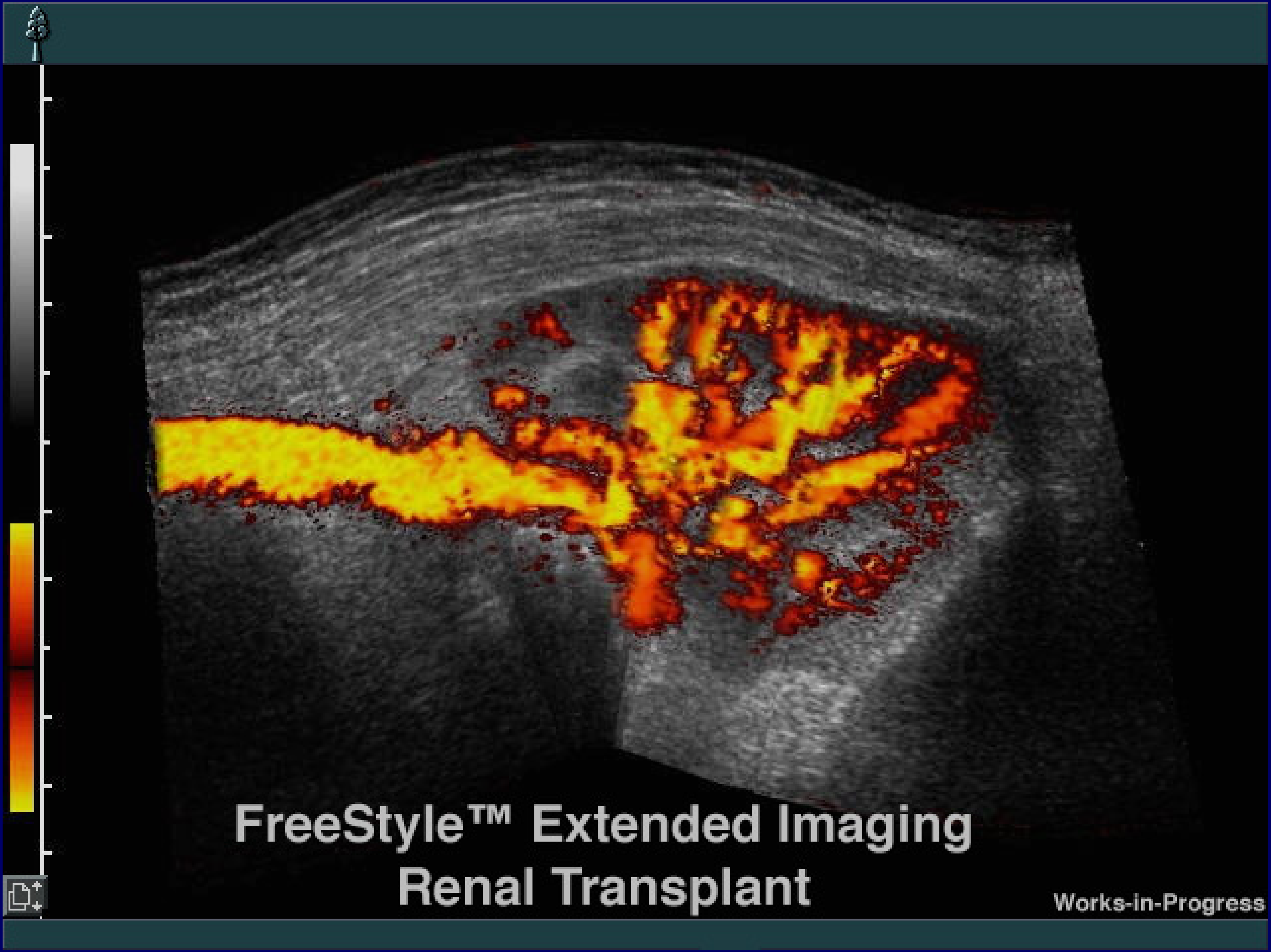
Color Doppler: Signal Processing


beam former → high pass filter → auto-correlator → parameter estimator → signal and display processor

- 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.



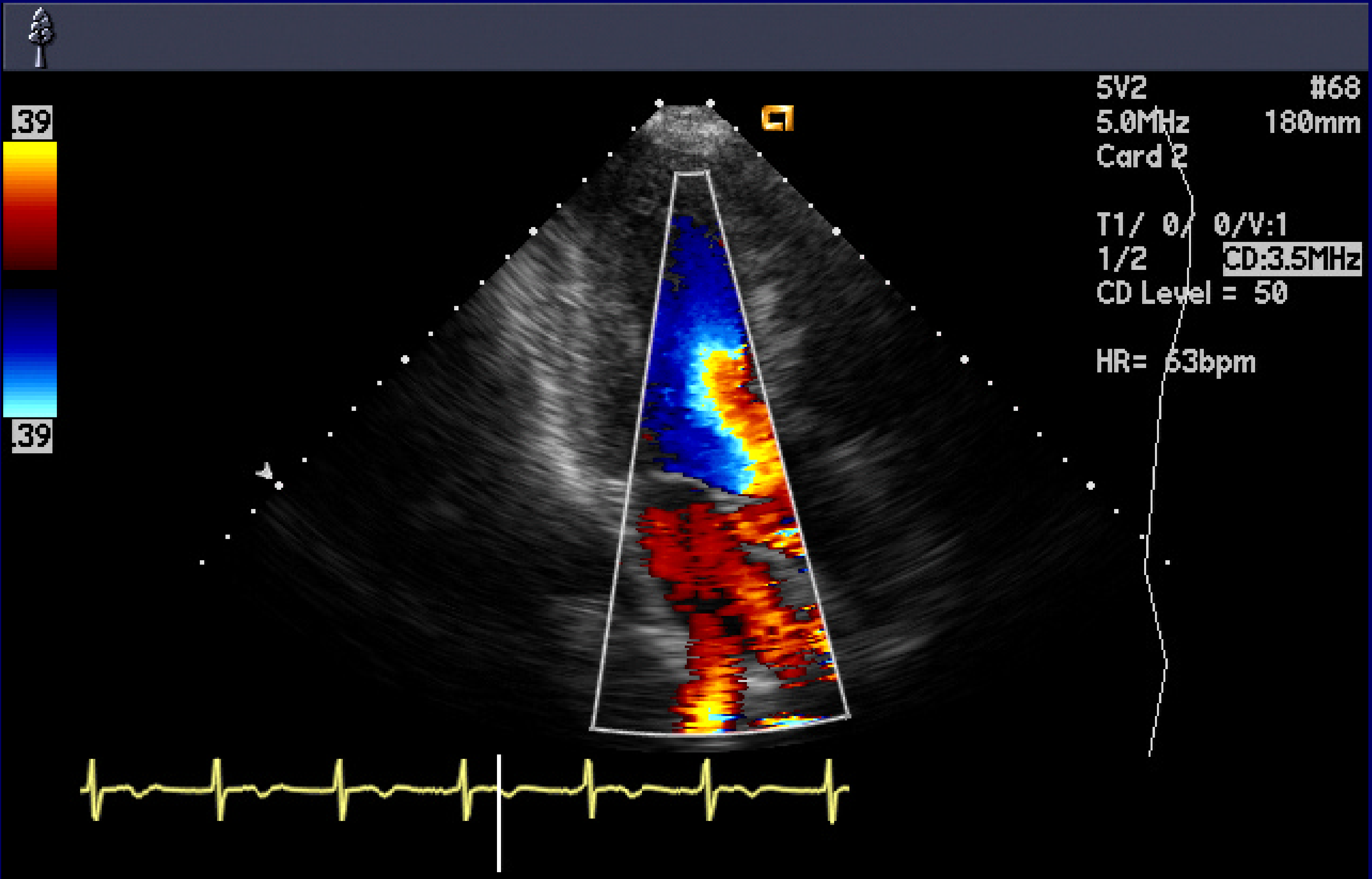
Color Doppler
Left Pulmonary Veins



FreeStyle™ Extended Imaging
Renal Transplant

Works-in-Progress

PW/Color Doppler Limitations



5V2 #68
5.0MHz 180mm
Card 2

T1/ 0/ 0/V:1
1/2 CD:3.5MHz
CD Level = 50

HR= 63bpm

Pulmonary Vein Inflow

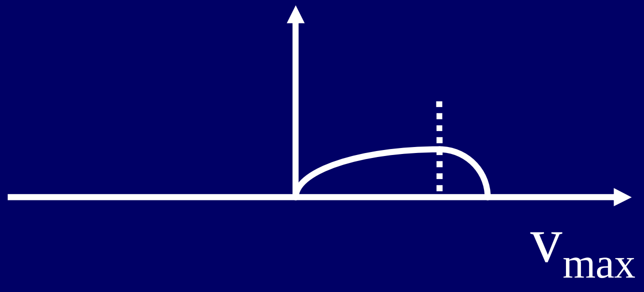
Velocity Ambiguity

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

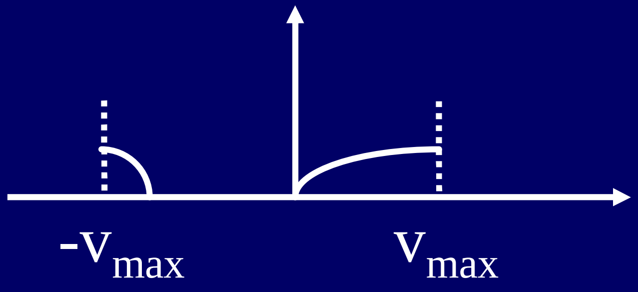
$$2f_{\max} = \frac{4v_{\max} f_s}{c} \leq \frac{1}{PRI}$$

$$v_{\max} \leq \frac{l}{4 \cdot PRI}$$

no aliasing

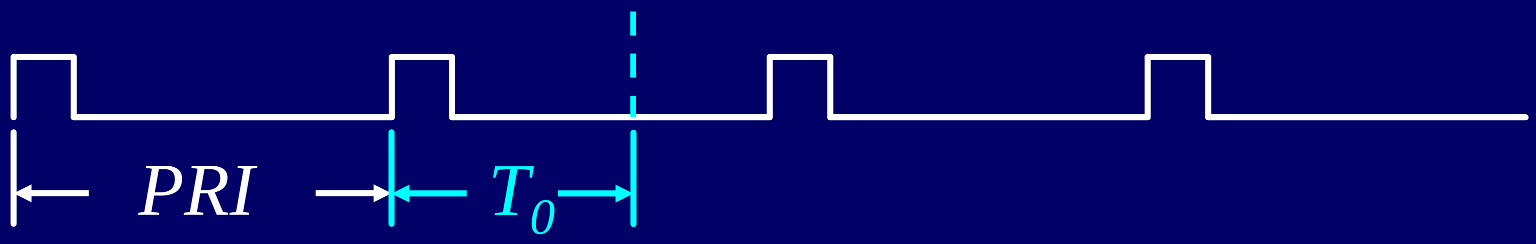


aliasing



Range Ambiguity

$c \cdot PRI / 2$



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

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. $f_d = \frac{2vf_s}{c} \cos q$

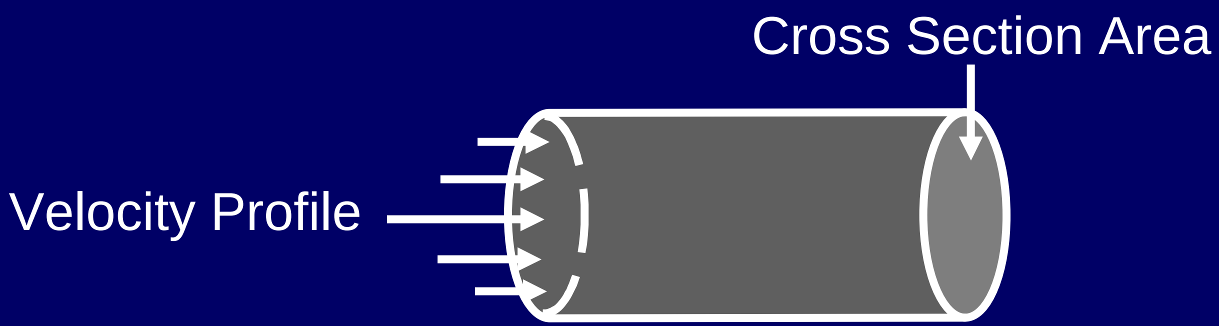
Is Quantitative Volume Flow Estimation Possible?

Ultrasonic Quantitative Blood Flow Estimation

- Blood volume flow rate (*Q*) equals blood flow with velocity (*v*) pasting a blood vessel cross sectional area (*Area*).

$$Q = v \times Area$$

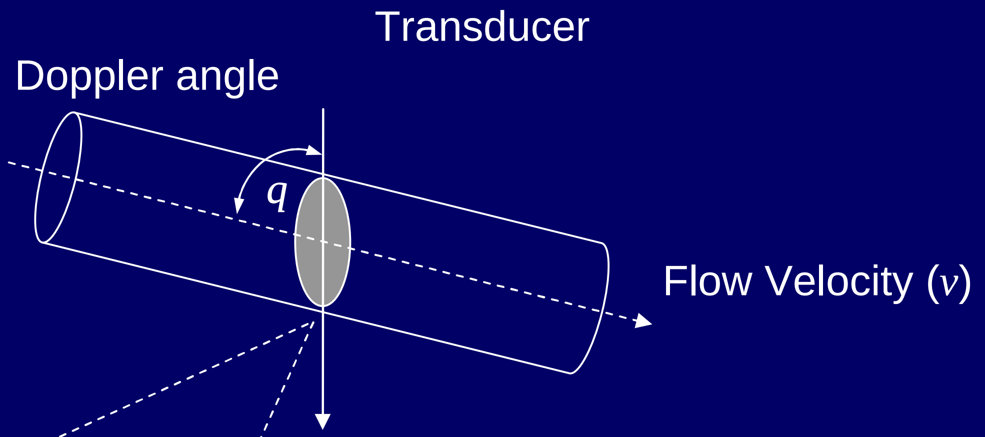
- The size of blood vessel cross section area can be obtained by B-mode scanning.

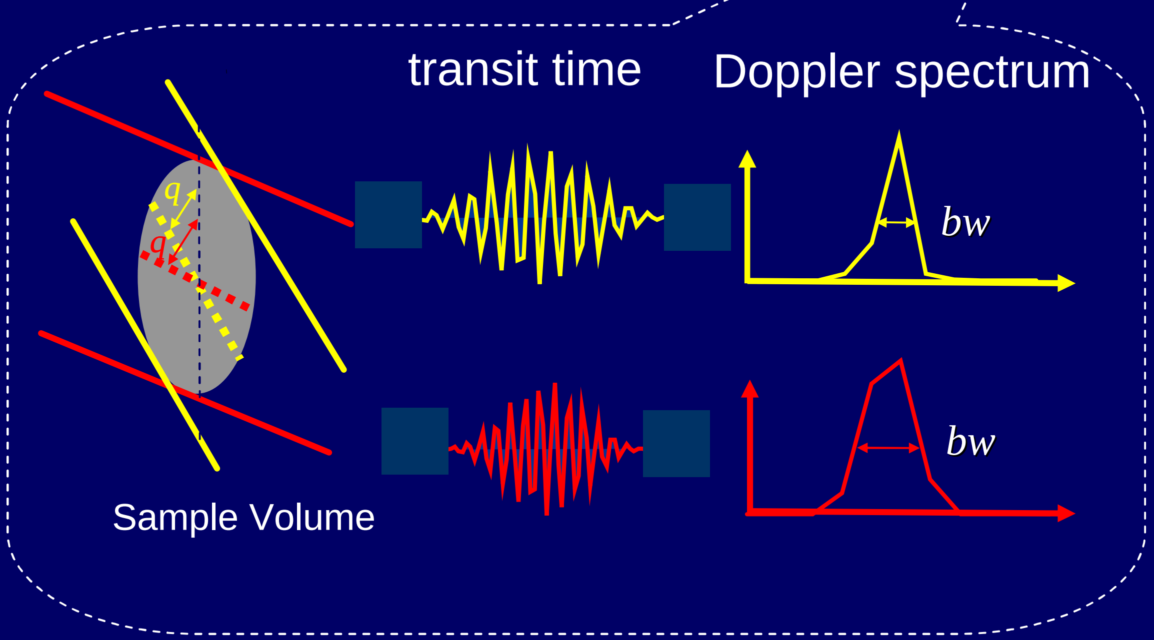


Doppler Angle Must Be Known.

Doppler Angle Estimation

Doppler Spectrum Bandwidth (*bw*) vs. Lateral velocity (*v* sin*q*)





$$bw = k\frac{v\sin q}{w}$$

$$q = \tan^{-1}\left(\frac{w\cdot bw}{k\cdot v\cdot \cos q}\right)$$

w : -6 dB beam width
: scaling factor

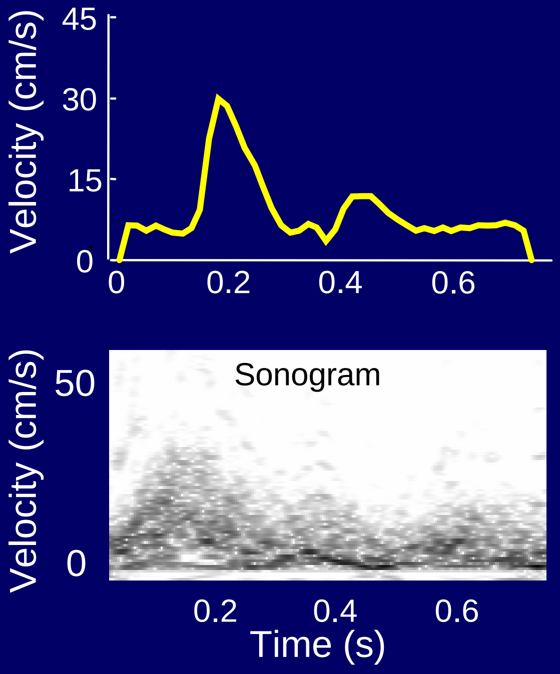
(Newhouse et al, 1980)

Doppler Angle Estimation

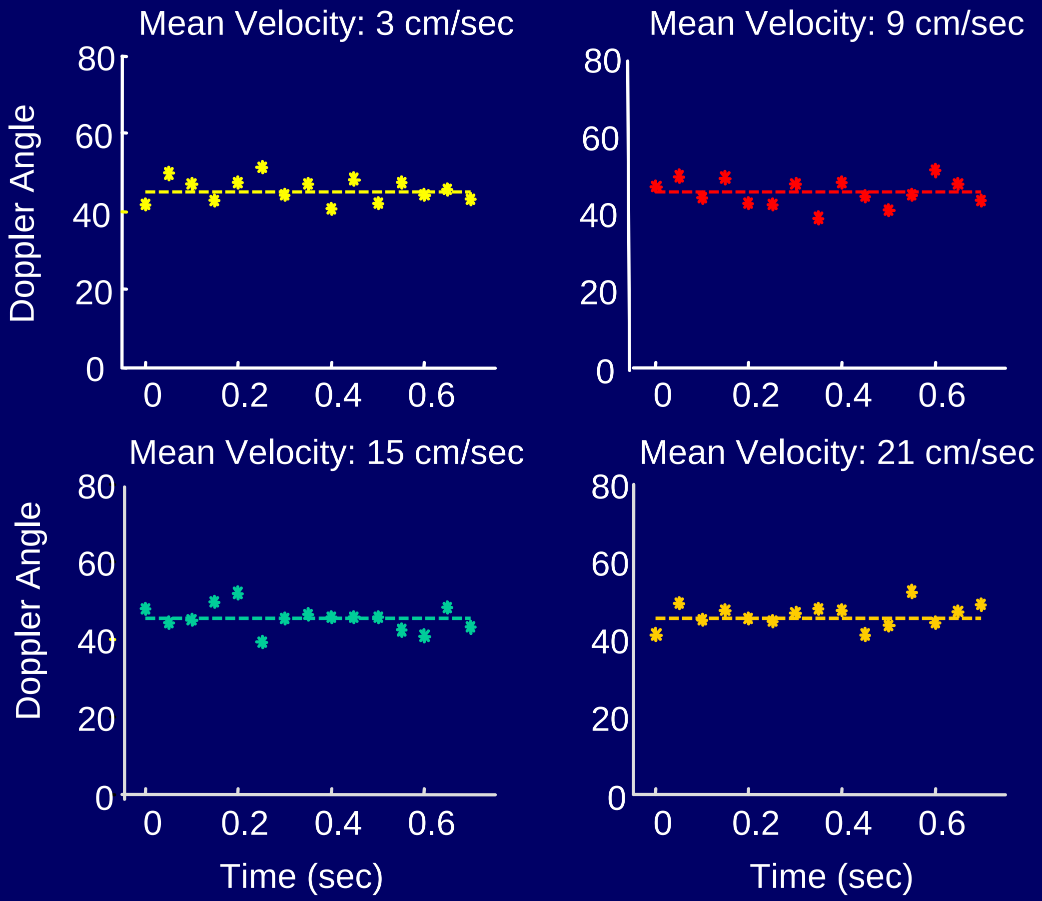
Flow with Spatial and Temporal Velocity Gradients

Carotid Artery

Heart rate = 80 / min
Heat cycle = 752 msec



Doppler angle: 45 degrees (AR method)



Doppler Tissue Imaging

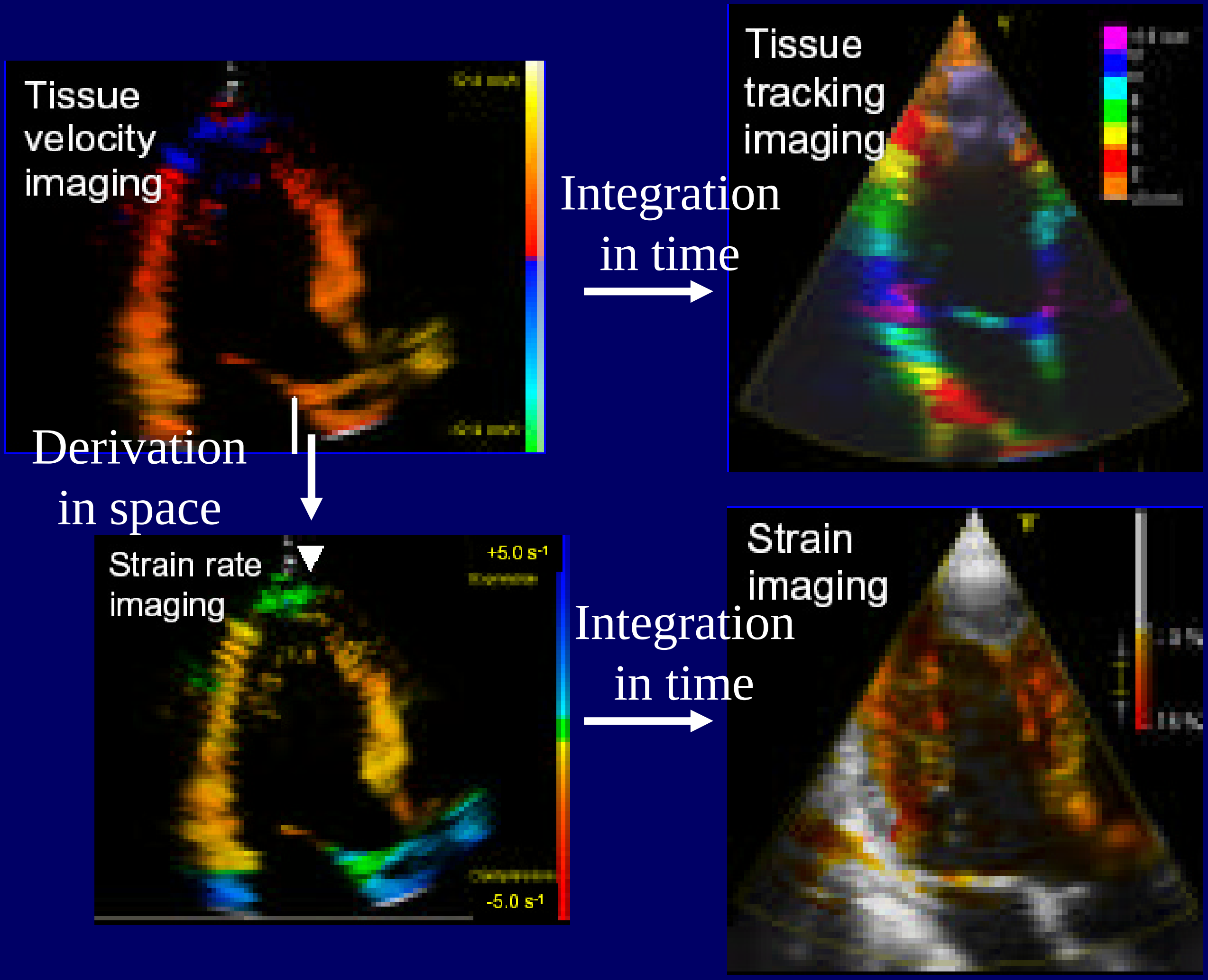
Doppler: Tissue Motion Imaging

- 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



Tissue velocity imaging

Integration in time

Tissue tracking imaging

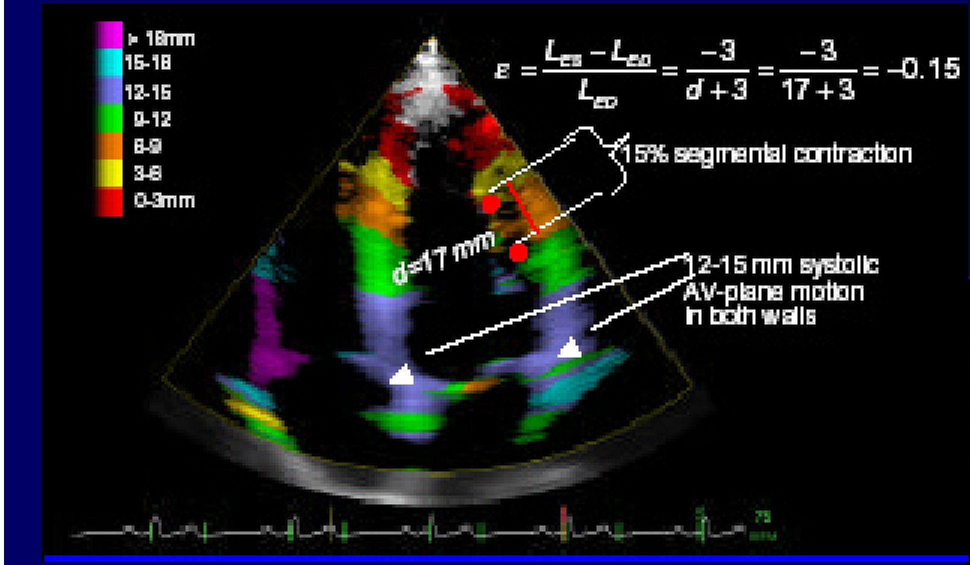
Derivation in space

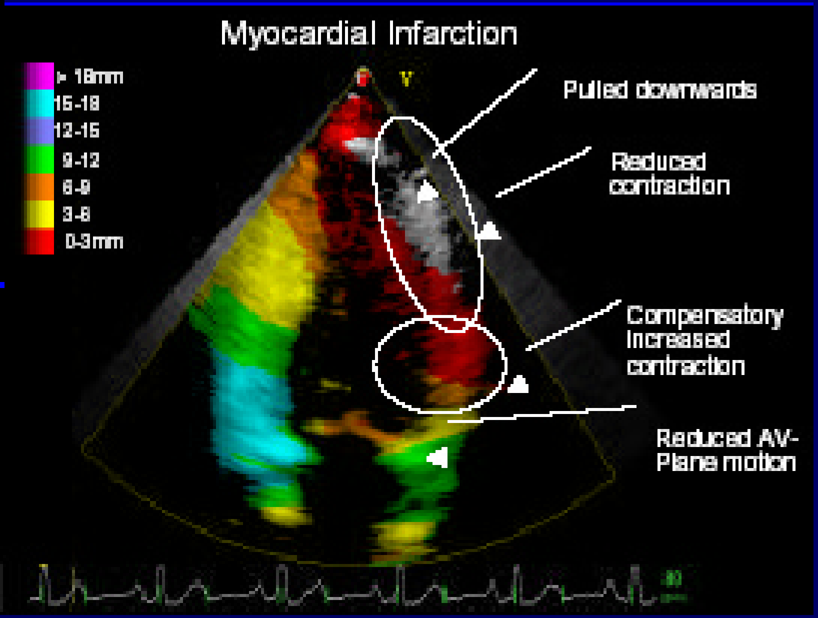
Strain rate imaging

Integration in time

Strain imaging

Doppler Tissue Imaging





Thank you!