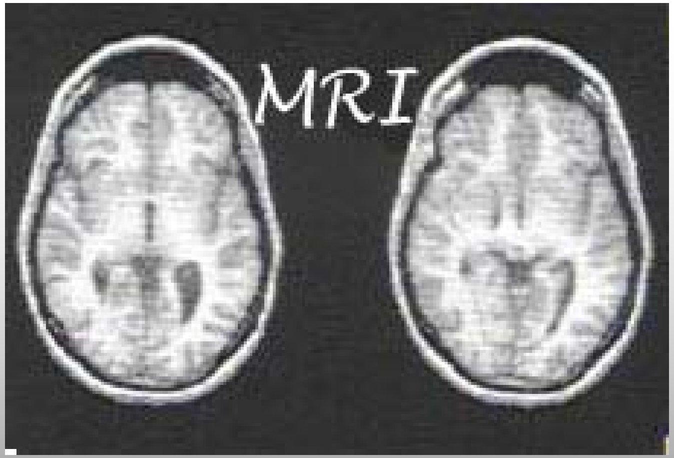
Physics, Instrumentation and New Trends in Techniques of Ultrasound Medical Imaging

Imaging: after **energy** (light, radio waves, Ultrasound and more) is interacting with a target object, an image could be produced, carrying information about the target and suitable to be interpreted by a human observer



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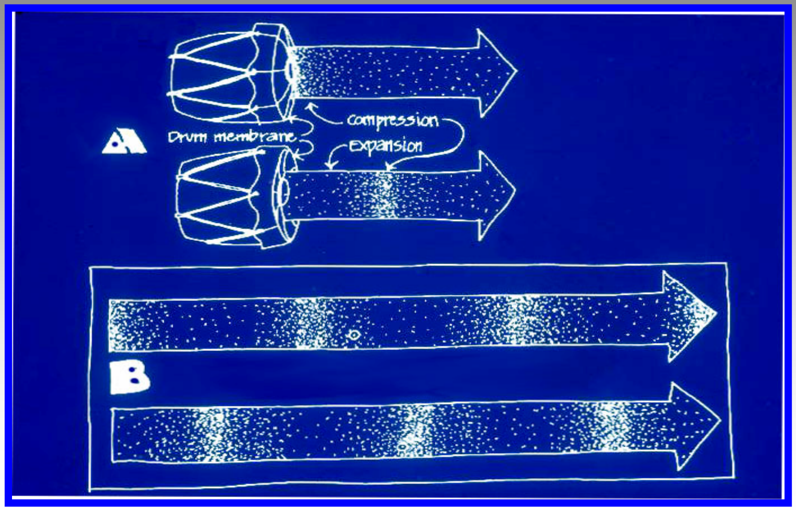
Ultrasonic energy can, as X-rays do, penetrate tissues and is suitable of making medical images of vital organs inner in the body.

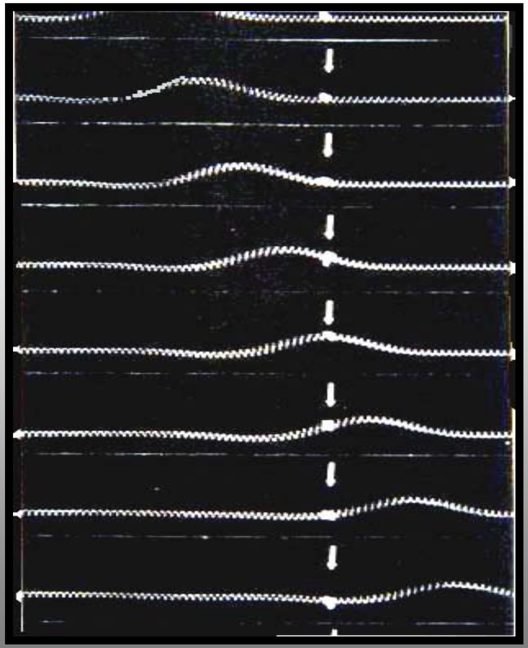
Main differences between Ultrasound and X-rays

	Diagnostic Ultrasound	**X-rays** (Radiology)
wave type	longitudinal mechanical waves	electromagnetic waves
transmission	elastic medium	No medium
generation	stressing the medium	accelerating electric charges
velocity	depends on the medium through which it propagates	constant: ~300,000 m/s
Similar waves	seismic, acoustic	radio, light

Sound is the perception of vibrations stimulating the ear



Sound is a periodic disturbance (vibrations) that in fluids density, propagates as longitudinal waves

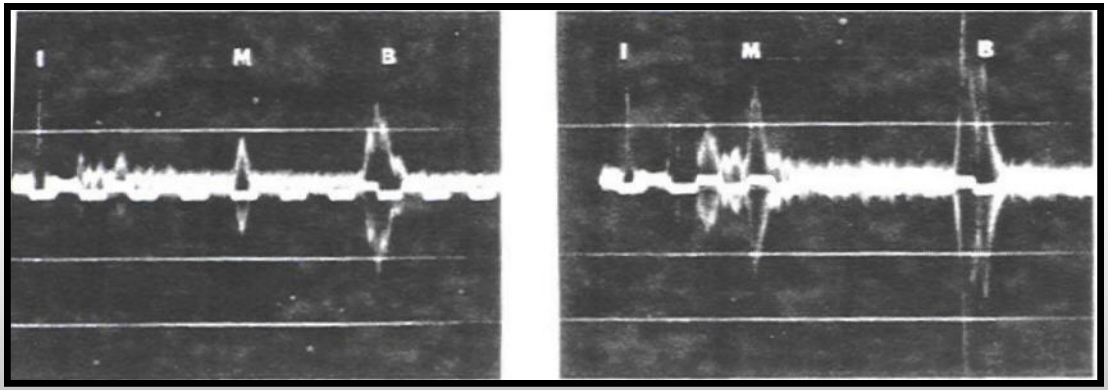


Ultrasound is sound with a frequency over 20,000 Hz, which is about the upper limit of human hearing. Human beings cannot hear ultrasound

First use of diagnostic ultrasound

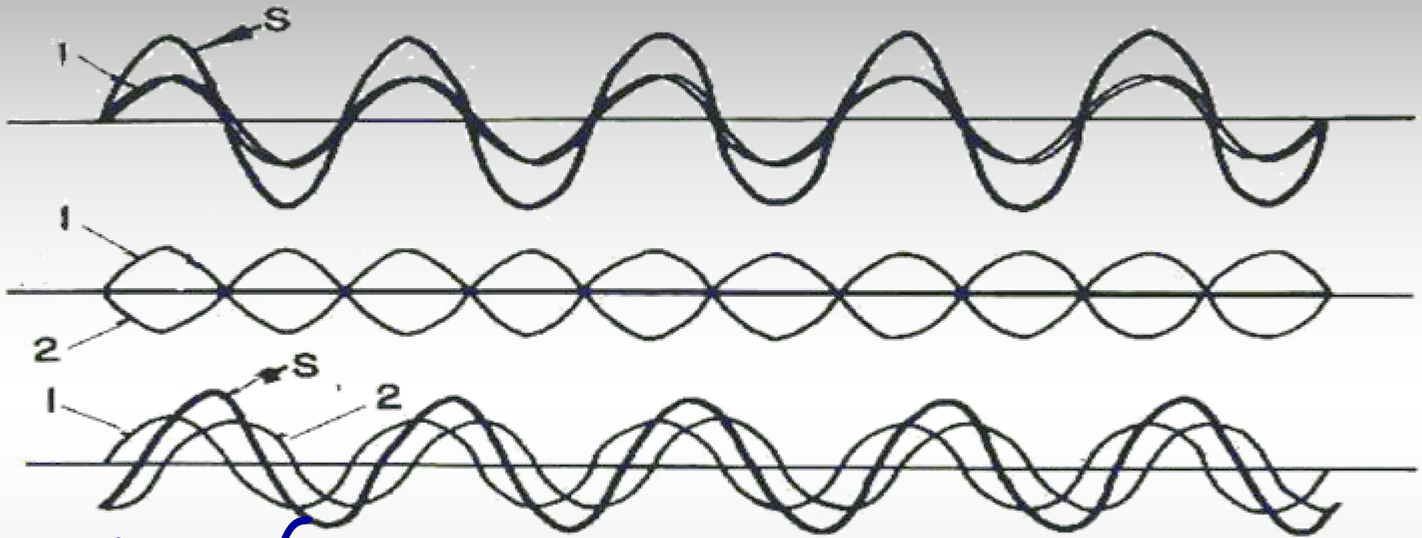
Dr. Karl Dussik, a psychiatrist, in Austria, was the first person publishing, in 1942, a medical use of diagnostic ultrasound (Transmission technique), named "hyperphonography of the Brain".

He was trying to locate brain tumours with a method consisting of an ultrasound emitter at one end and an ultrasound receiver at the other.



The enchephalogram made by Leksell, 1953, showing a displaced M-echo, by reflection technique

Sound Characteristics



- *Frequency f*
- *Period T*
- *Wavelength λ*
- *Speed C*
- *Acoustic Impedance Z*

$T=1/f$

$\lambda=c/f$

$C=[B/\rho]^{1/2}$

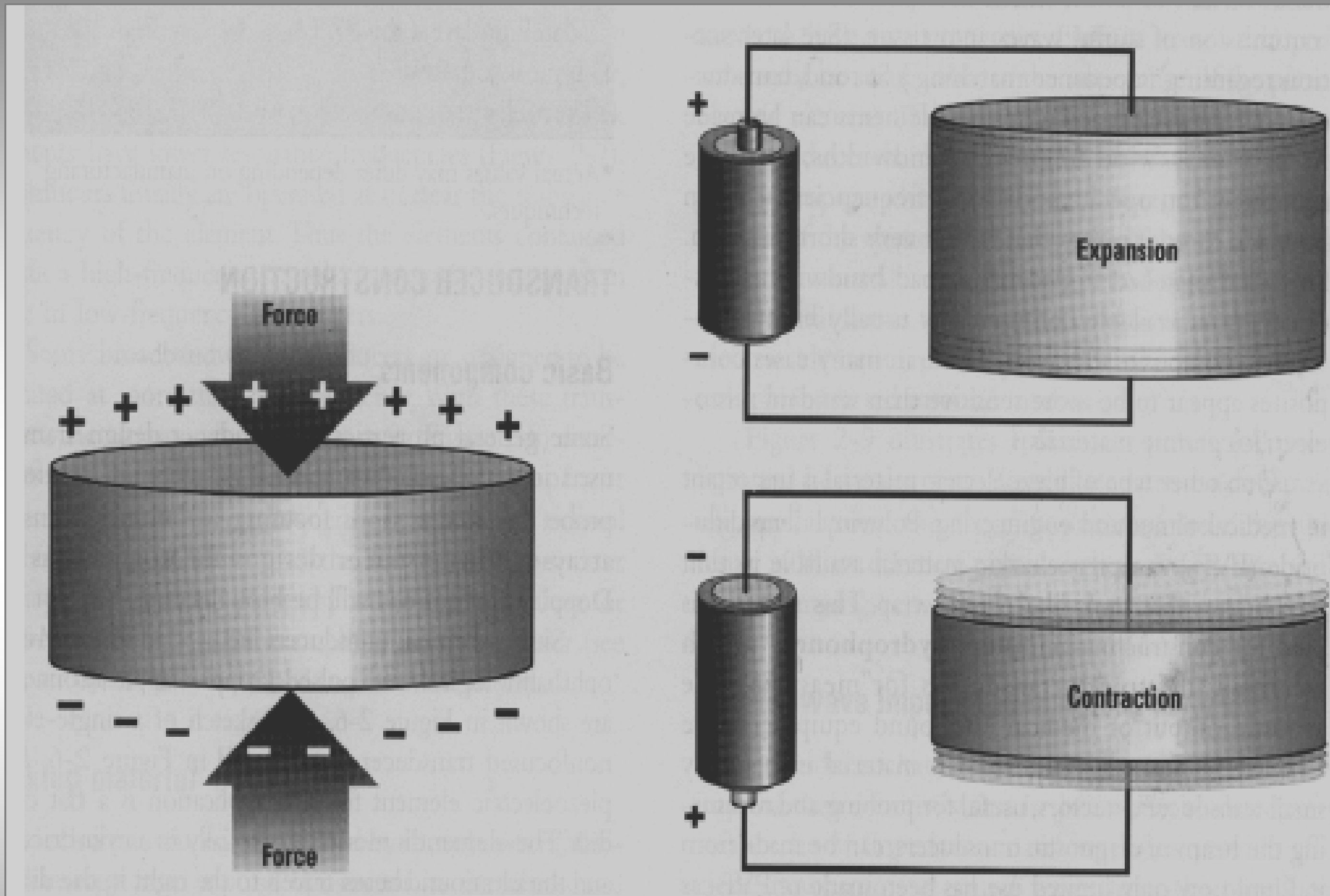
$Z=\rho.C$

ρ= density of the medium, B=bulk modulus

Velocity of sound in some Biological Materials

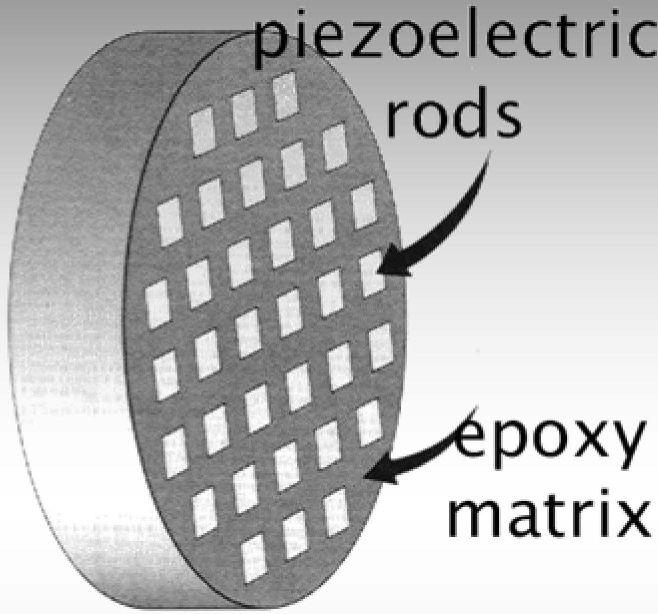
Material	**Sound Velocity (m/s)**	**Impedance (Rayl x10^{-6})**
Air	**330**	**0.0004**
Fat	1450	1.38
Water	1480	1.48
Average Soft Tissue	1540	1.63
Liver	1550	1.65
Kidney	1560	1.62
Blood	1570	1.61
Muscle	1580	1.7
Skull Bone	**4080**	**7.8**

Piezoelectric Phenomenon

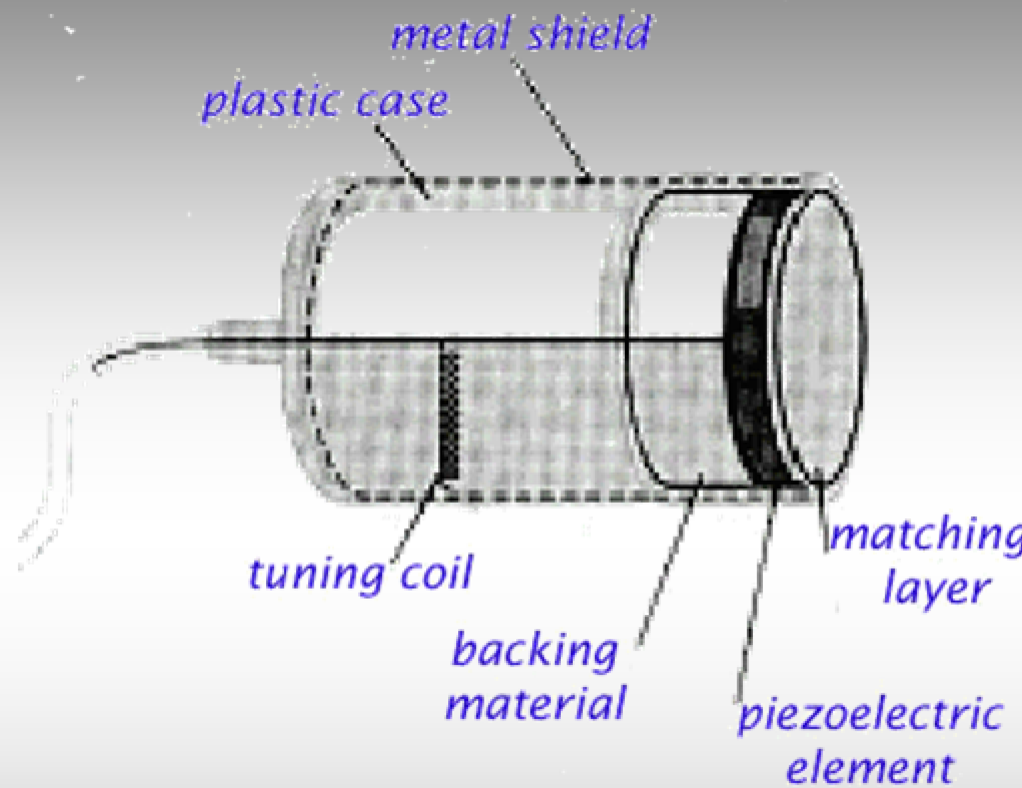


Transducer: A device that converts energy from one form to another. Its major component is a crystal of **piezo-electric** material (Quartz or Lead Zirconate Titanate).

Ultrasound Transducers

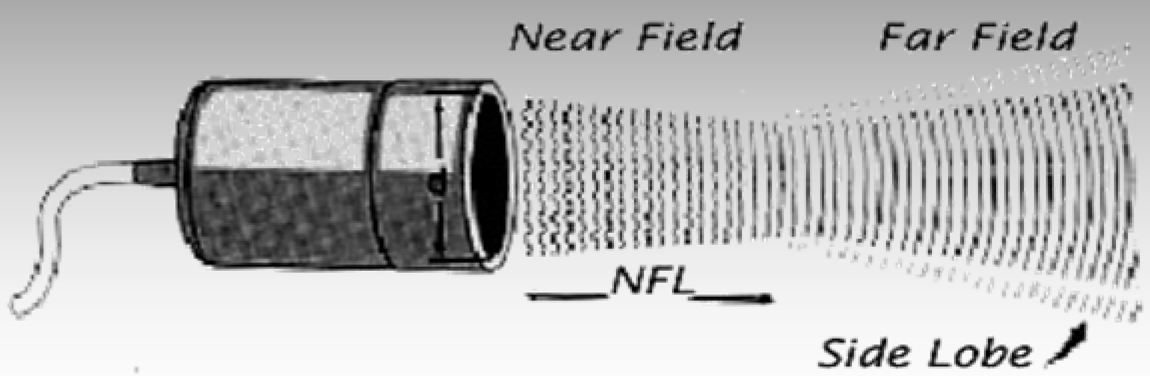


Composite piezoelectric element, consisting of grooves cut into the face of a PZT ceramic, leaving piezoelectric rods.
Epoxy resin fills the space in between.



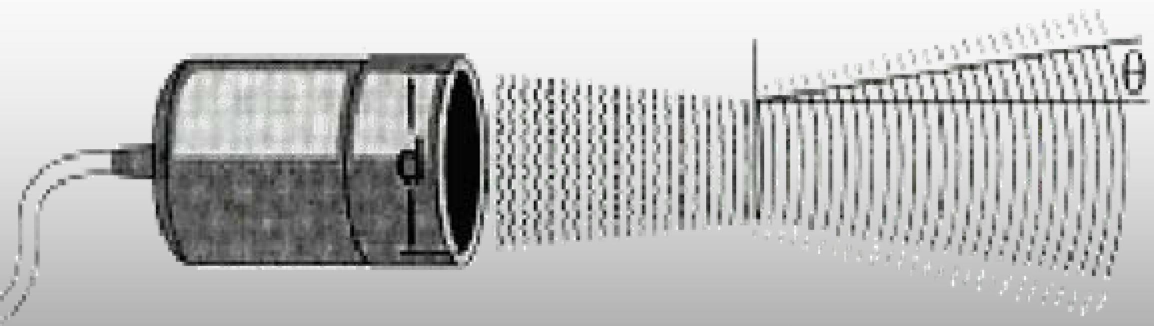
Single element composition

Ultrasound Beam Pattern



NFL:Near Field Length

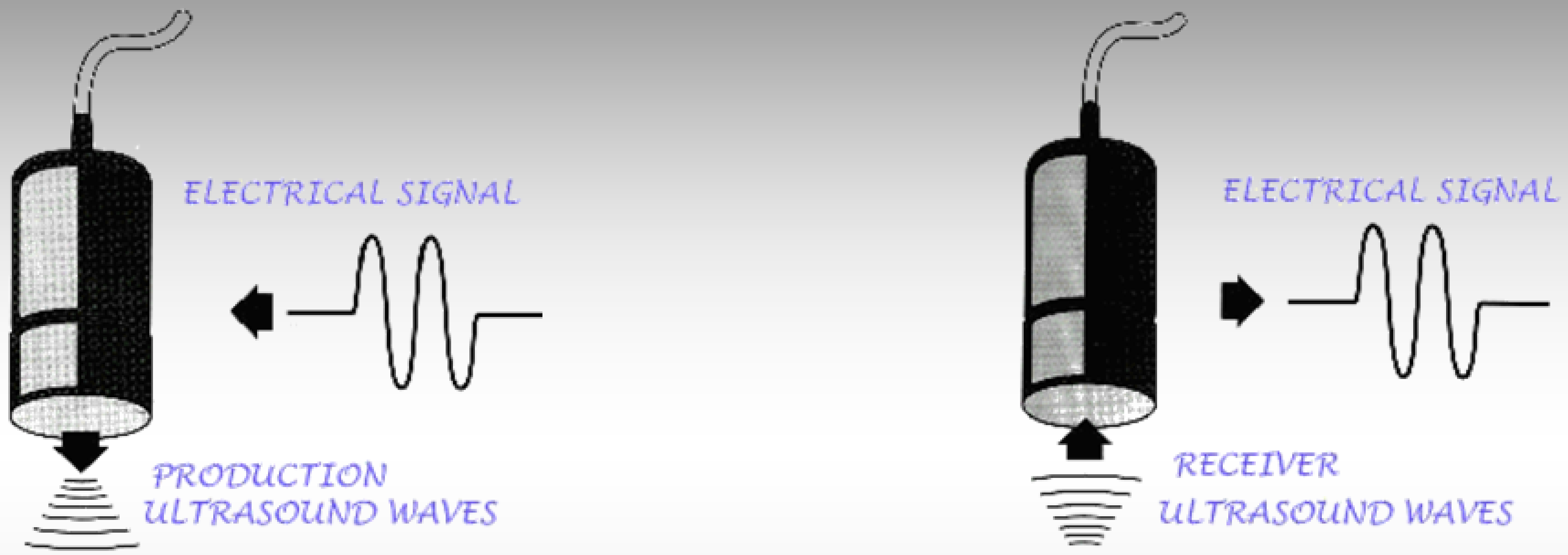
Side lobes :
energy of the sound beam outside the main beam



$$\sin\theta = \frac{1.2 \text{Wavelength}(\lambda)}{\text{Diameter}}$$

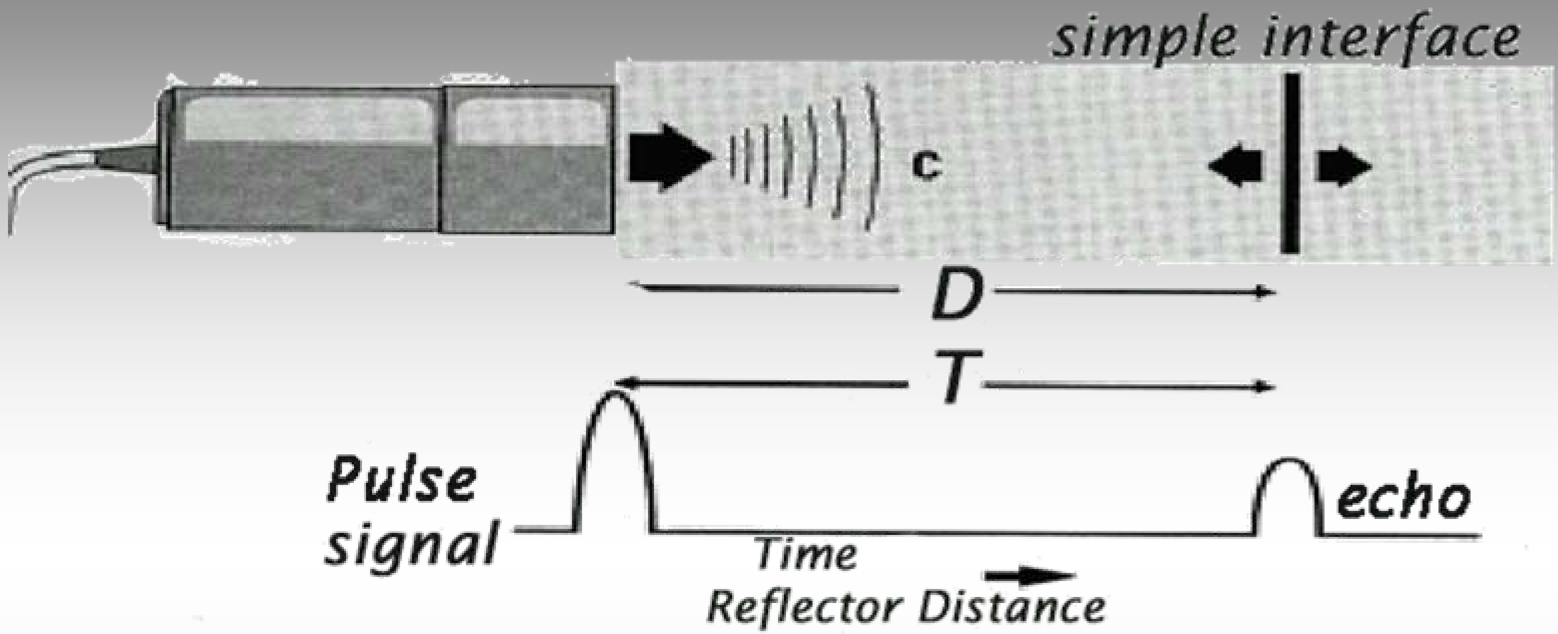
divergence angle **θ**:
Proportional to **λ**
Inversely proportional to **D,f**

Pulse-Echo Technique



Ultrasound diagnosis translates echoes to electric pulses (transducer) and electric pulses to digital representations (Digital Scan Converter)

Medical Ultrasound Propagation

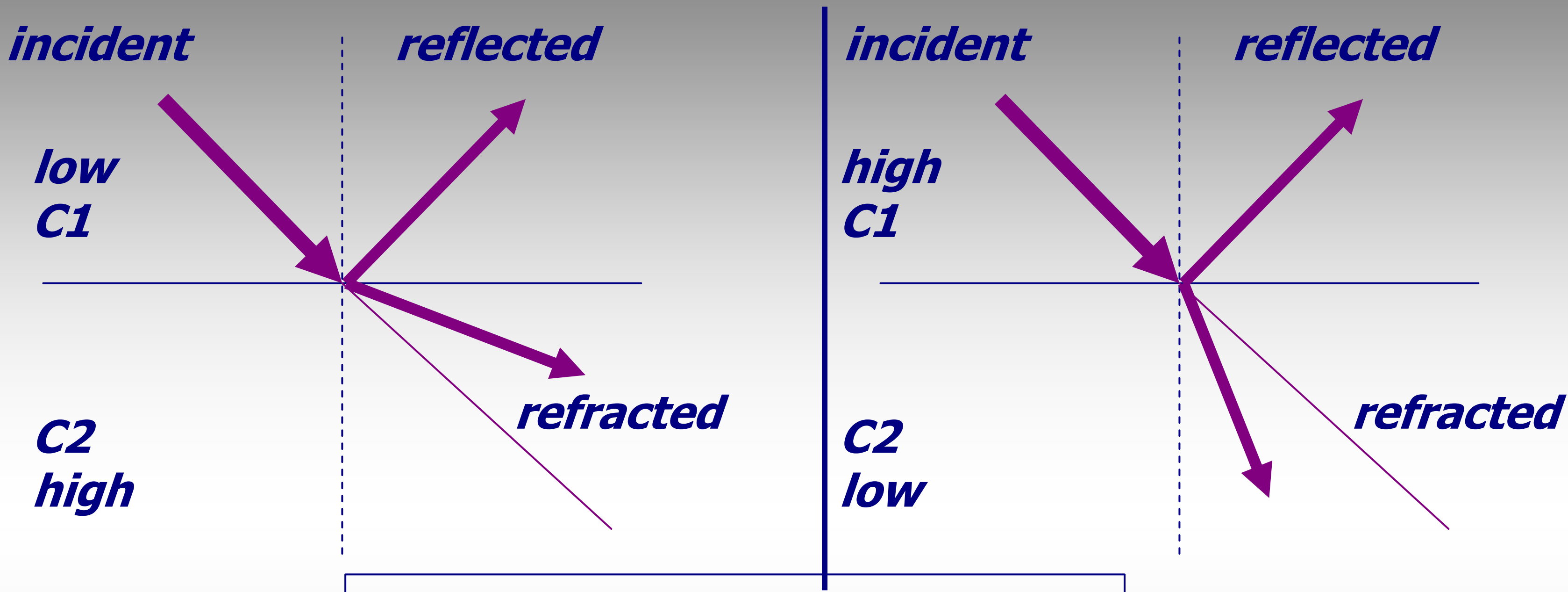


$$T = \frac{2D}{c}$$

Time Delay between
<u>**transmitted-Pulse & received Echo**</u>
indicates distance D

<u>Duty Factor</u>:99% of the functioning time is spent "listening" for echoes from interfaces in tissue

Reflection and Refraction at interfaces

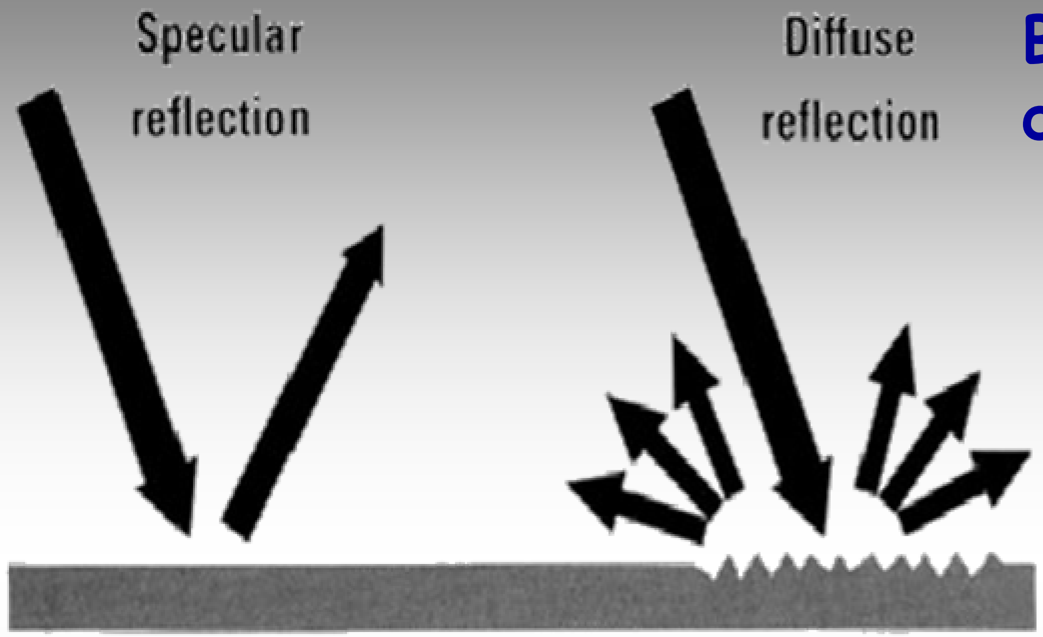


$$\frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

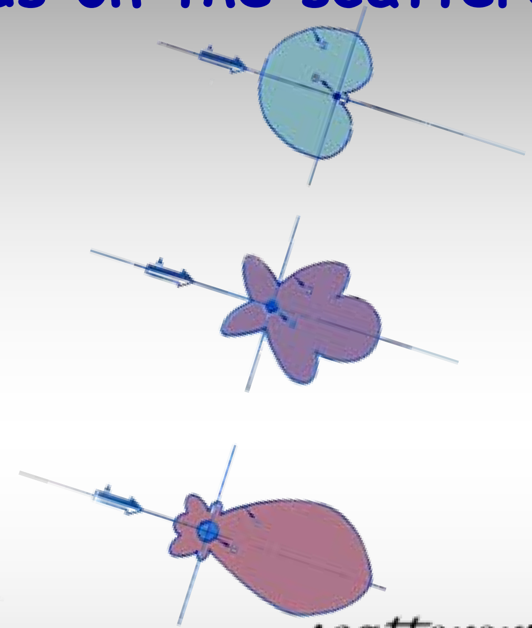
$Z_1 >> Z_2$ then $I_r \approx I_i$ (e.g.tissue → air)

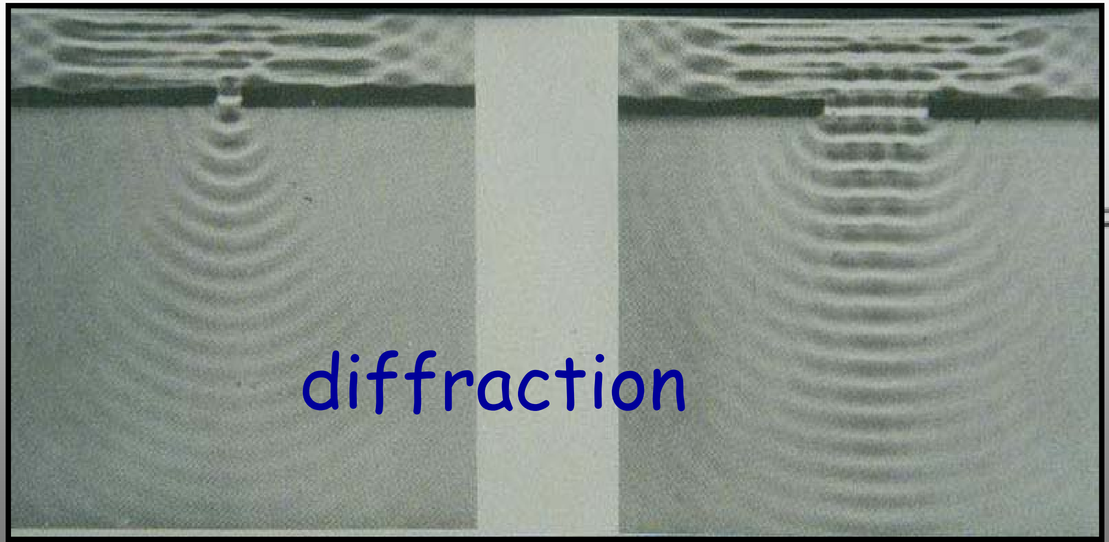
$Z_1 << Z_2$ then $I_r \approx I_i$ (e.g.tissue → bone)

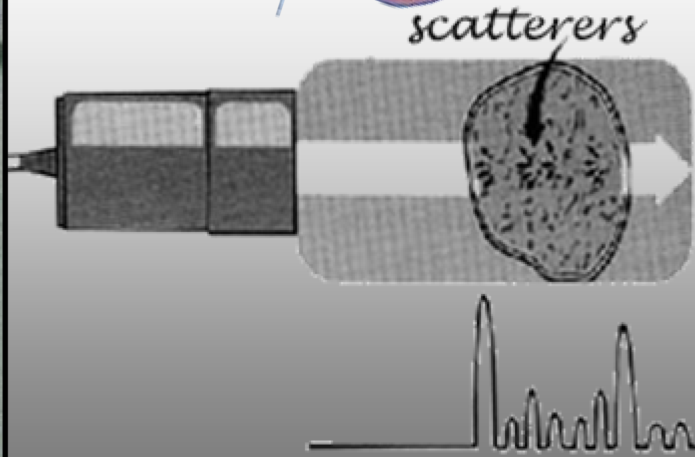
Reflection and Scattering



Backscattering of the beam depends on the scatterers size







Acoustical Power-Intensity- Relative Intensity

- **Power** is the rate that energy is transmitted into the medium (mW)
- **Intensity** is the Ultrasonic Power per unit area (mW/cm^2)

Diagnostic Ultrasound Intensity is low

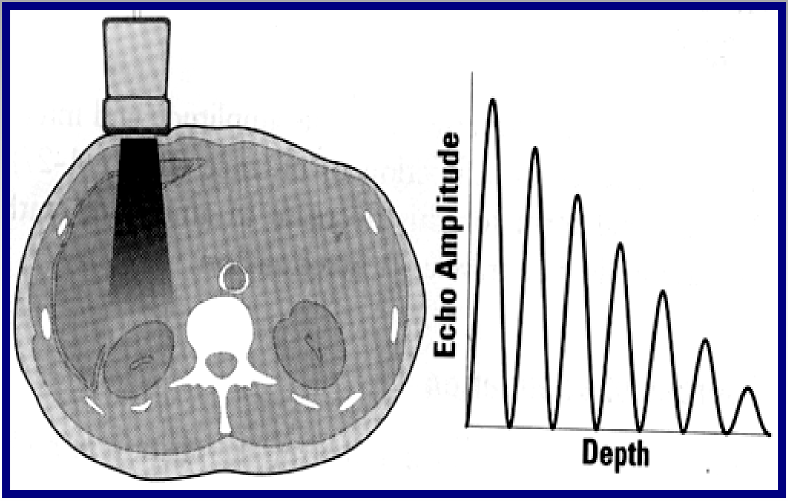
most of the times $<100\ mW/cm^2$

DeciBel

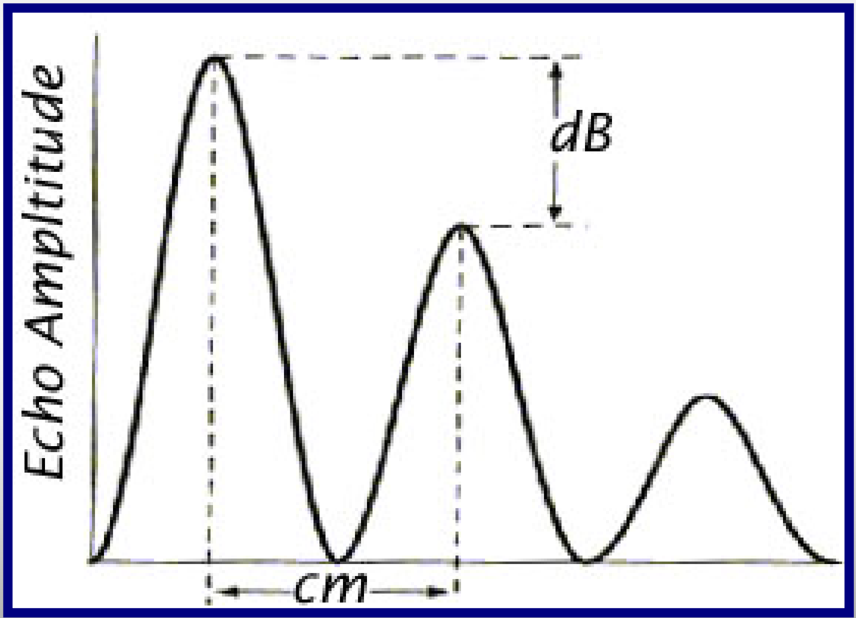
Relative Intensity Level (dB)= $10\log(I_2/I_1)$

Decibels are used to compare two signals' Intensities

Attenuation



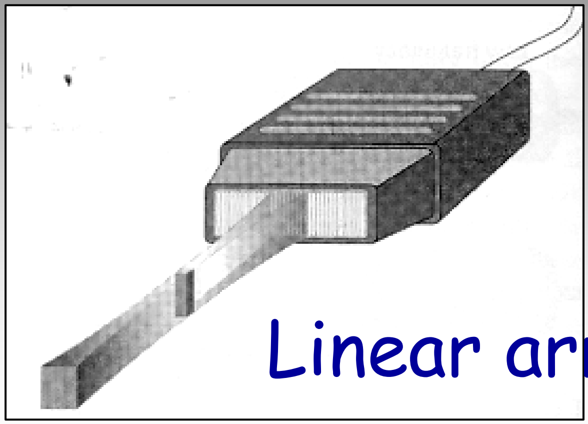
- Reflection & scattering
- Absorption (ultrasound energy is converted to heat energy)



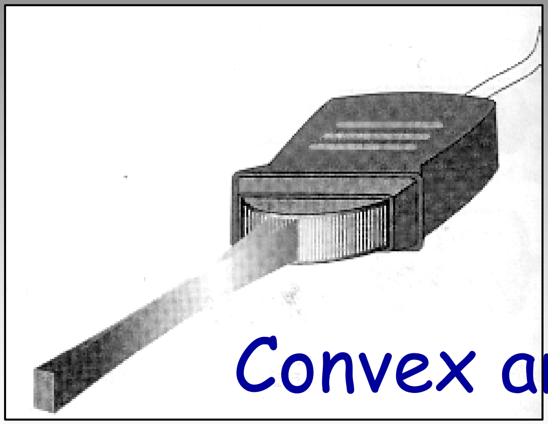
Attenuation coefficient in tissue in DB/cm /MHz

Tissue	Attenuation at 1MHz (dB/cm)
Water	0.0002
Blood	0.18
Liver	0.50
Muscles	1.20

Real time Transducer types

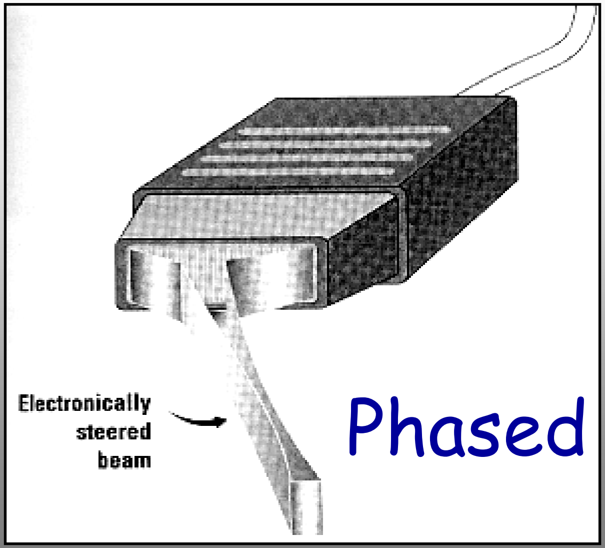


Linear array



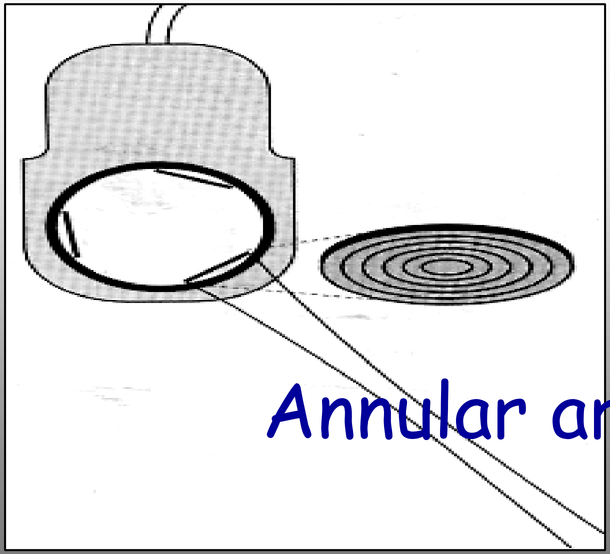
Convex array

Electronically steered



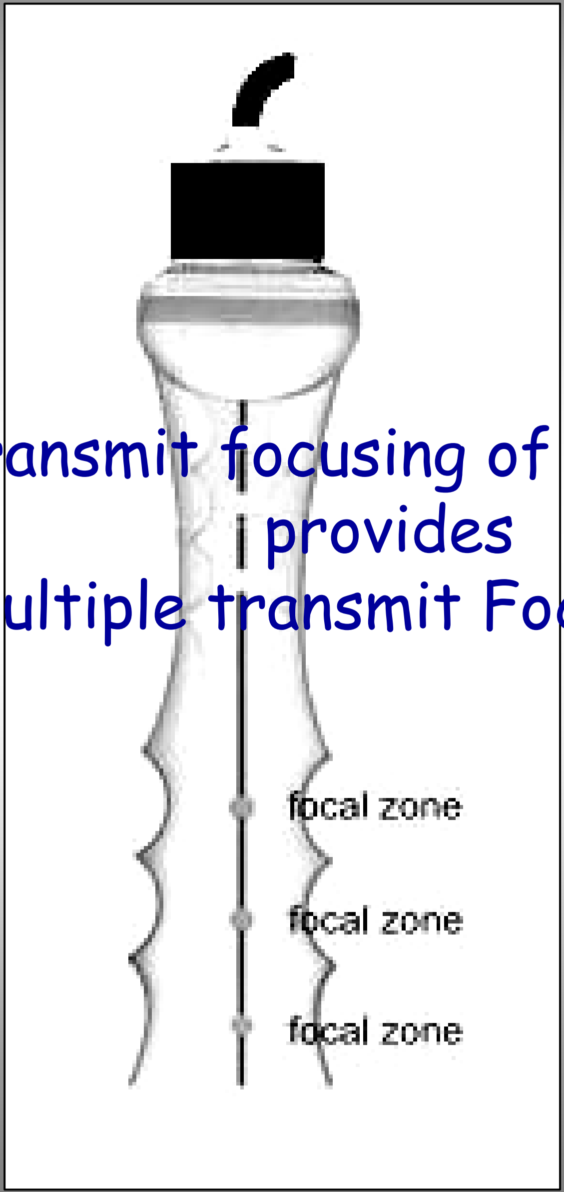
Phased array

Mechanically swept

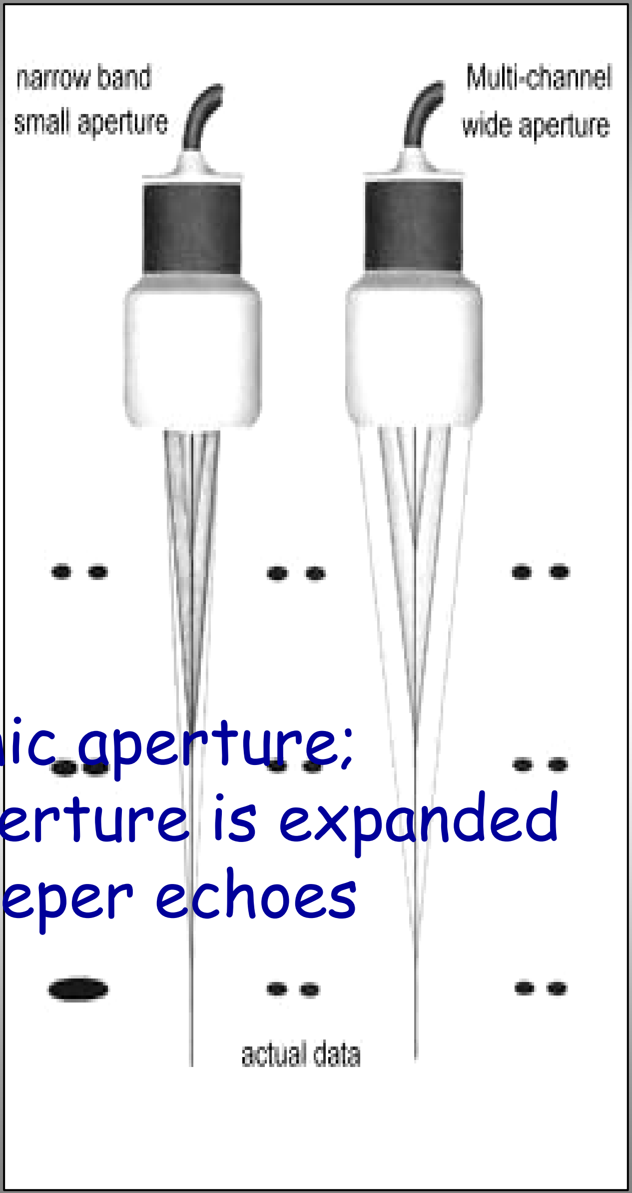


Annular array

Effective Control of focal distance

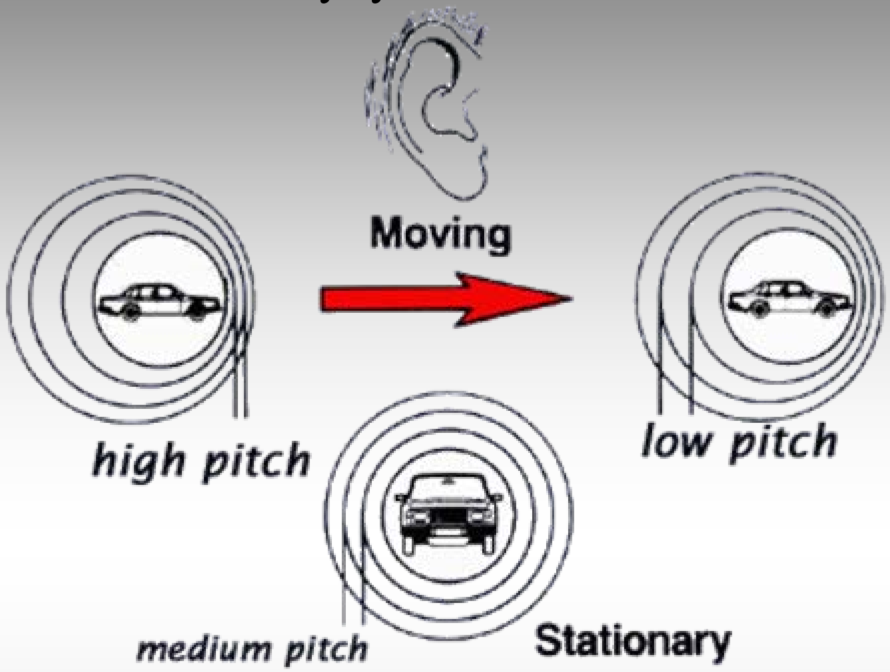


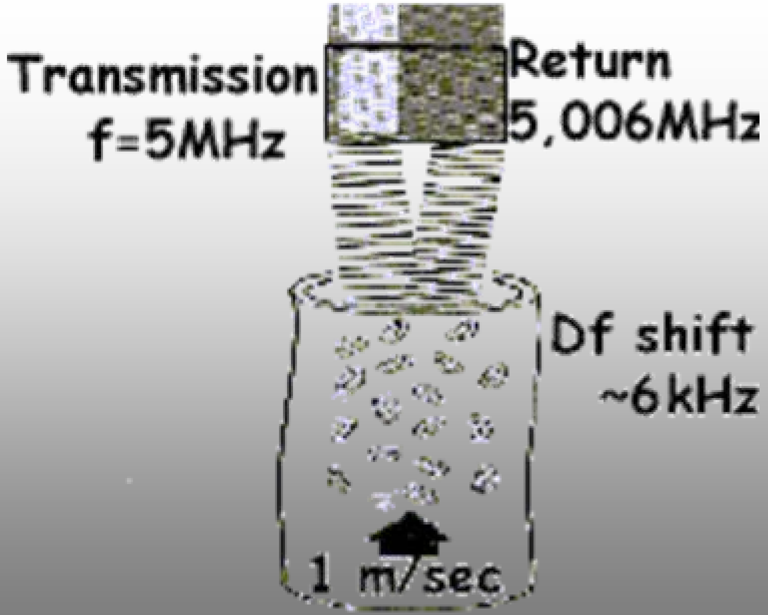
Transmit focusing of the beam provides
Multiple transmit Focal Zones



Dynamic aperture;
the active aperture is expanded for deeper echoes

Doppler Effect- Doppler shift



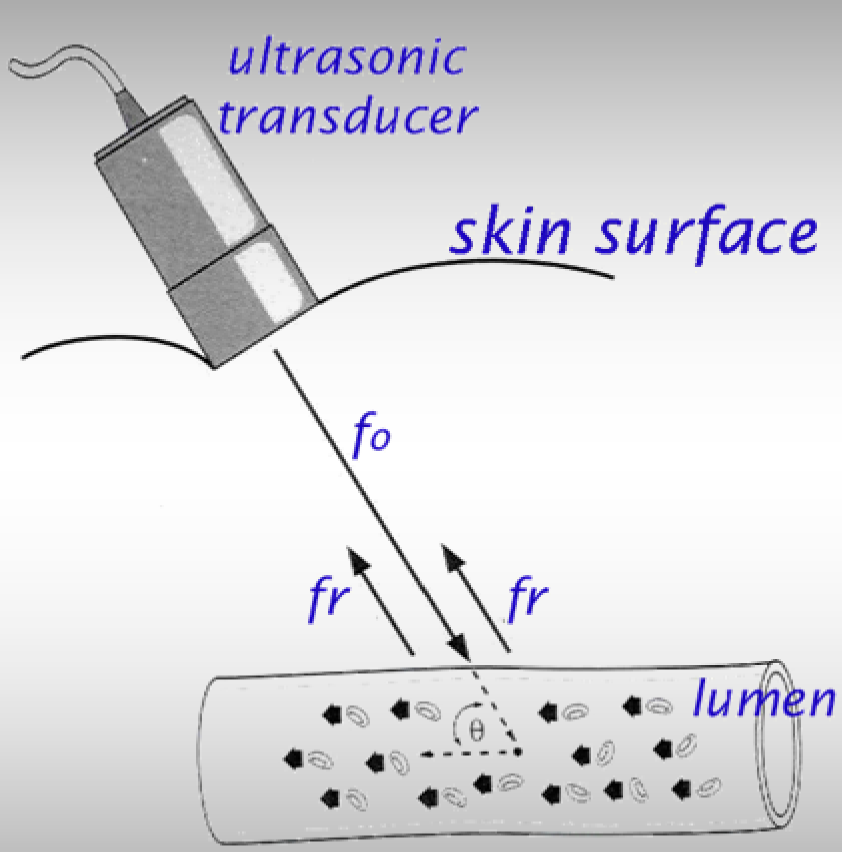


Doppler equation :

$Df = 2\ f\ v\ \cos\vartheta / c$

Doppler effect in medical Ultrasound quantify & image blood flow

The angle of incidence between the ultrasound beam and the estimated flow direction is the <u>Doppler angle</u>.

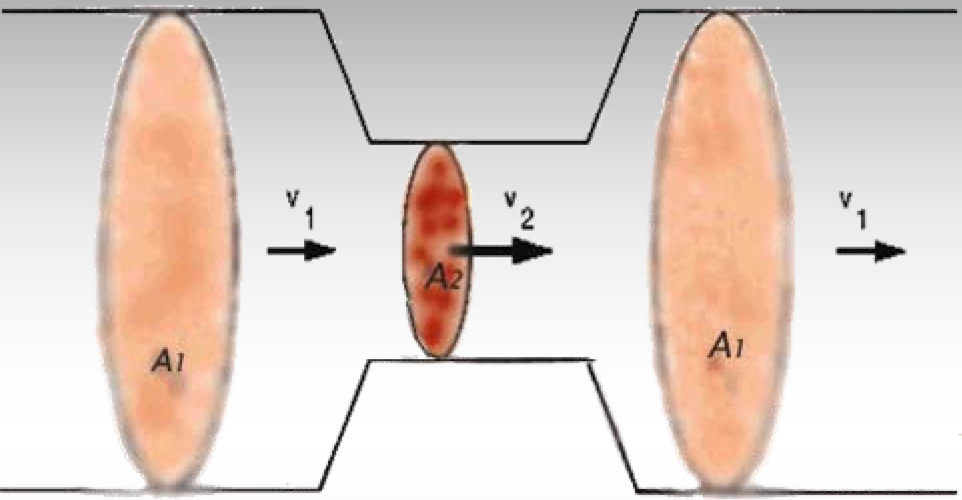


The Doppler angle affects detected Doppler frequencies

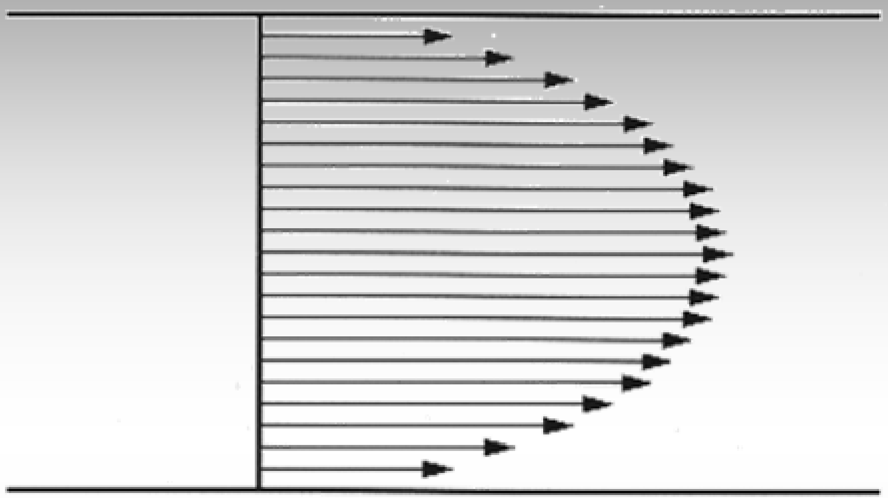
No Doppler frequency shift is detected at Doppler angle equal to 90°

Haemodynamics

Constant flow



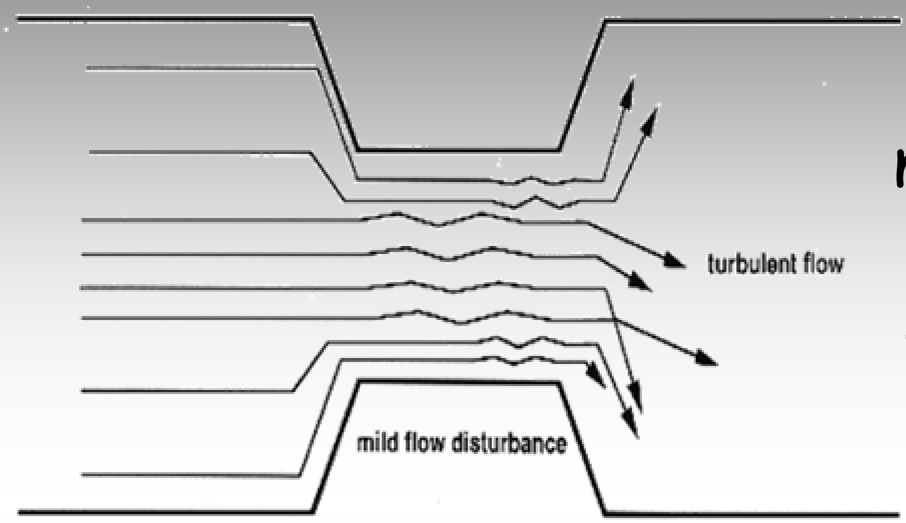
Parabolic flow



In constant flow, as the cross-sectional area (A) decreases, the velocity (v) increases.

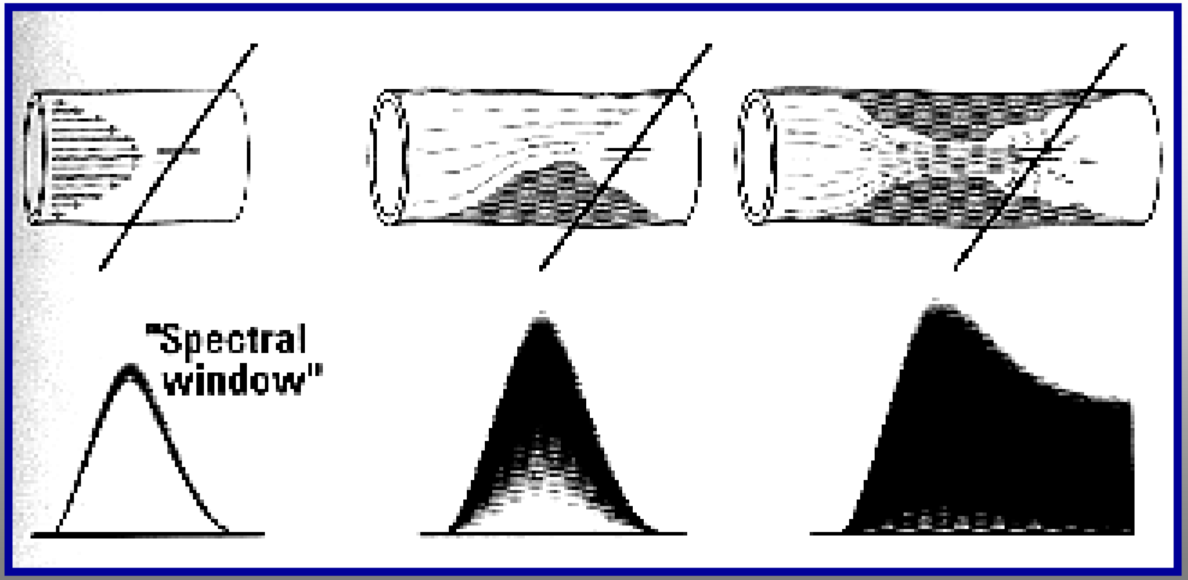
Blood Flow occurs as laminar or parabolic, with the fastest velocity in the center, and a progressive decrease in velocity toward the vessel wall.

Disturbed flow

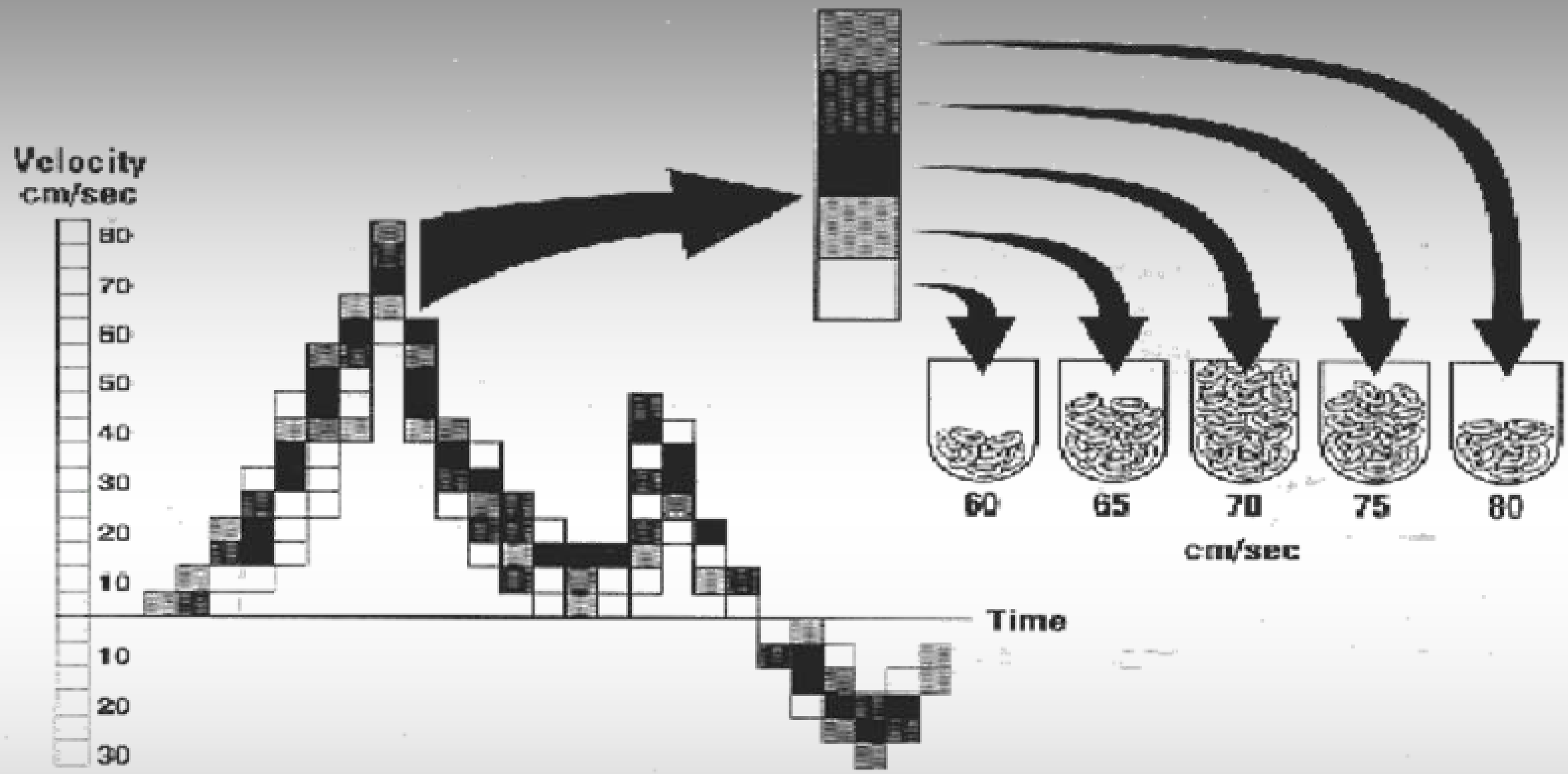


Disruption of the orderly laminae within the region of narrowing (**mild flow disturbance**), and disorganized, multi-directional flow vectors distal to the stenosis (**turbulent flow**).

The presence of obstructions may be detected from the Spectrum

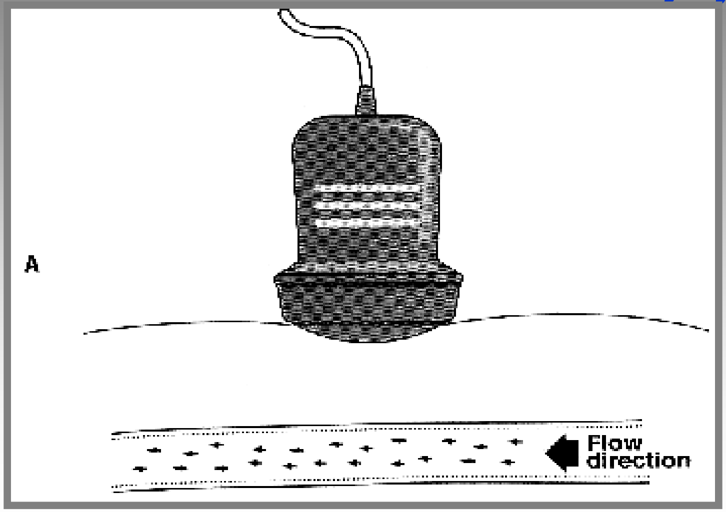


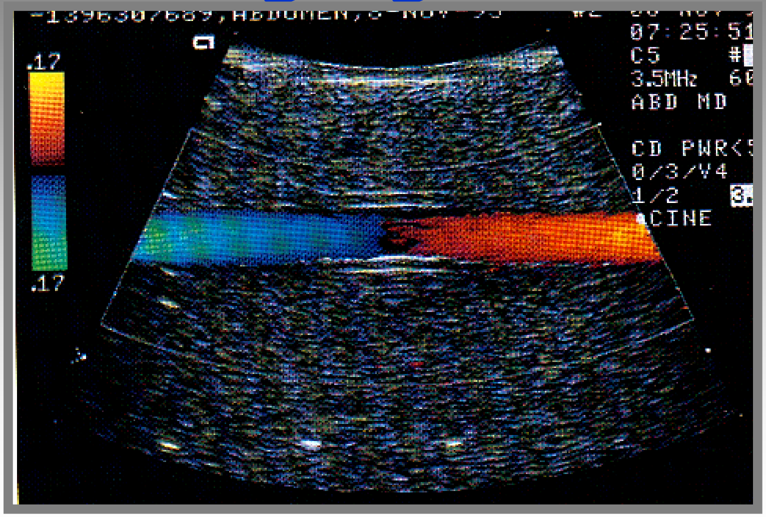
Doppler Spectrum Analysis



Spectral Doppler is useful when detailed quantitative information about flow velocities is important

Color Doppler Imaging





Flow direction is arbitrarily assigned-

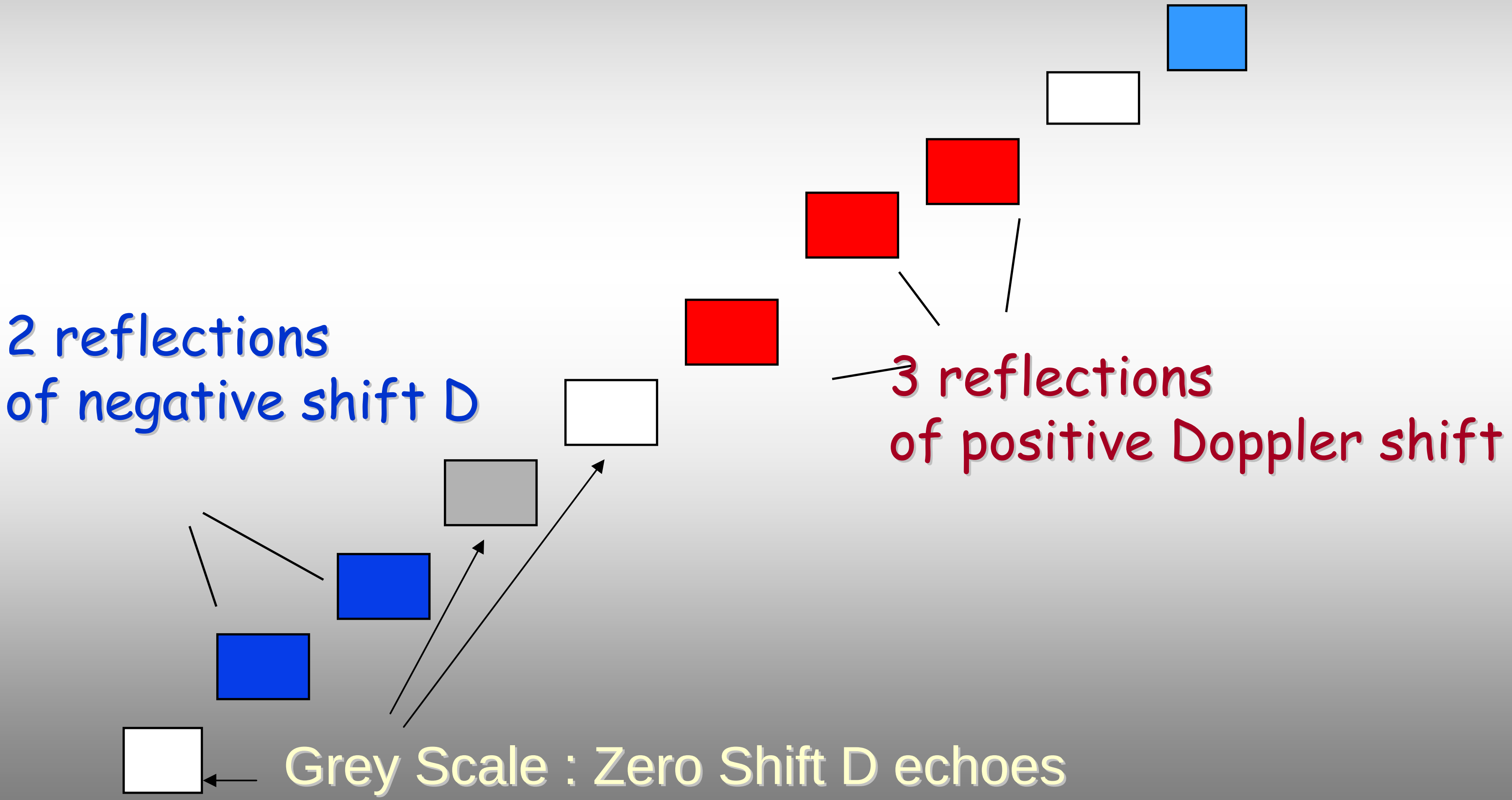
- Red-coded is <u>towards</u> the transducer
- Blue-coded flow is <u>away</u> from the transducer
- more saturated colors have a lower frequency shift.

<u>color write priority</u>

Color will appear, in preference, where there is no echo (color threshold)

- quickly detect the region of highest velocity in a stenotic artery,
- or reveal an intra-renal artery that is invisible on grey scale.

Color Doppler Image Creation



Ultrasound Image Artifacts

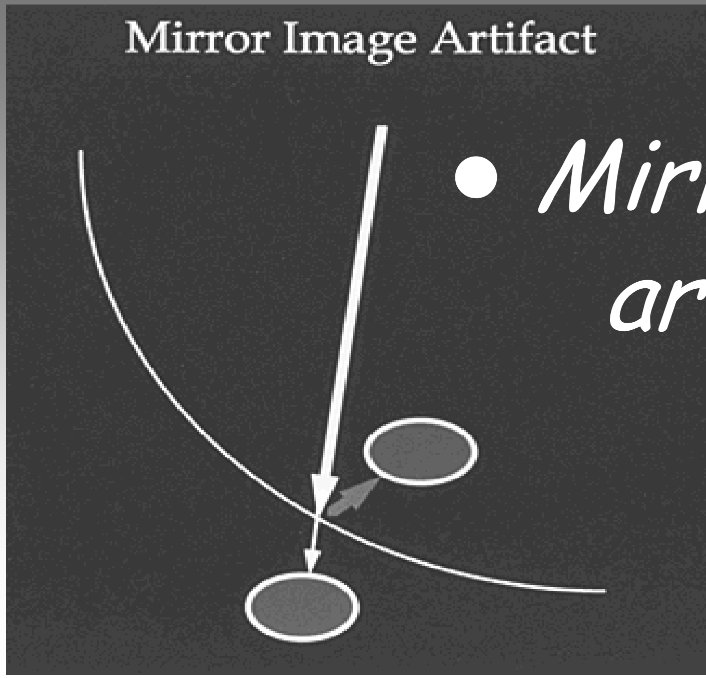
Are structures and features on an image that do not have one-to-one correspondence to the object being scanned

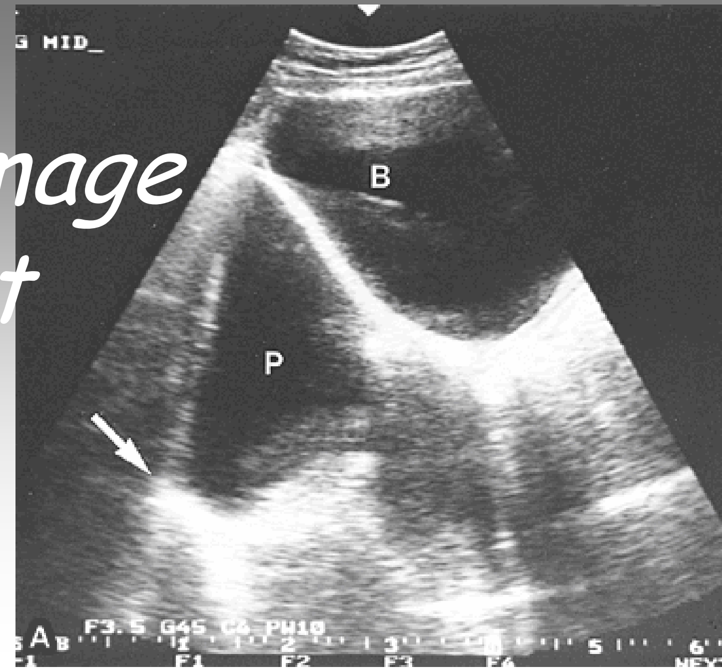
Assumptions in ultrasound scanners

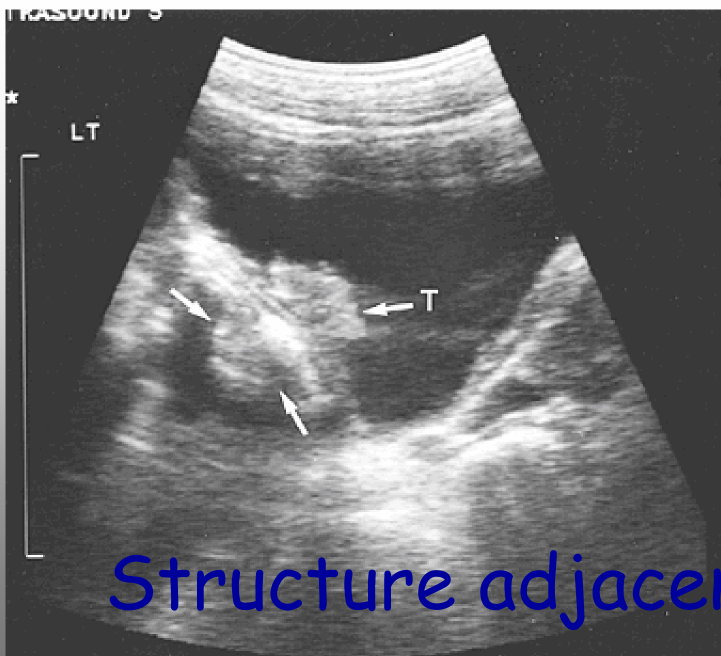
- Reflectors giving rise to echoes lie along the transmitted beam axis
- The speed of sound is constant equal to 1540m/sec
- The echo strength only indicates organ echogenicity

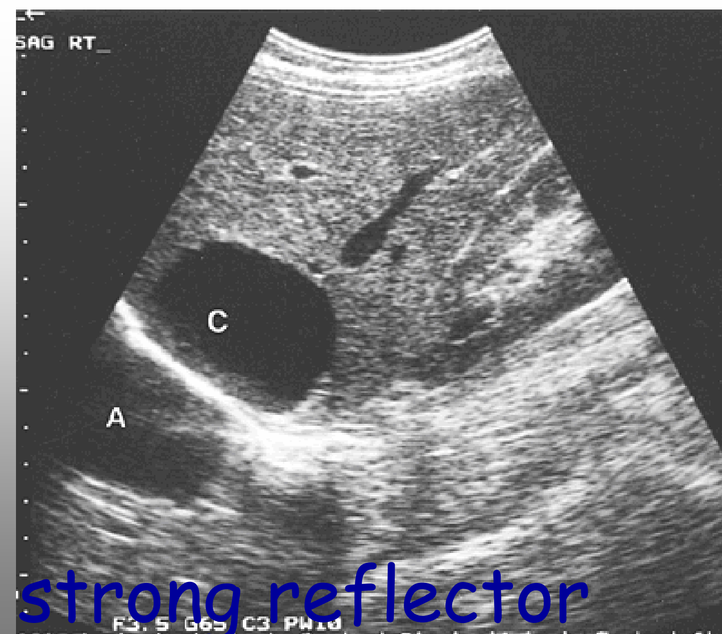
➡ *In reality, these assumptions are never completely met.*

- *Mirror image artifact*



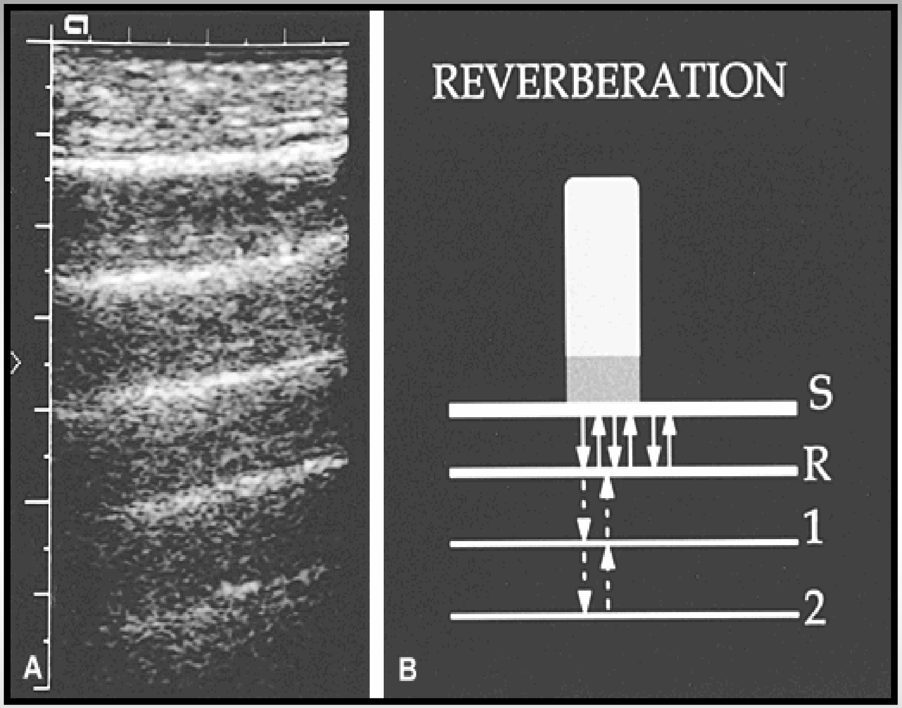


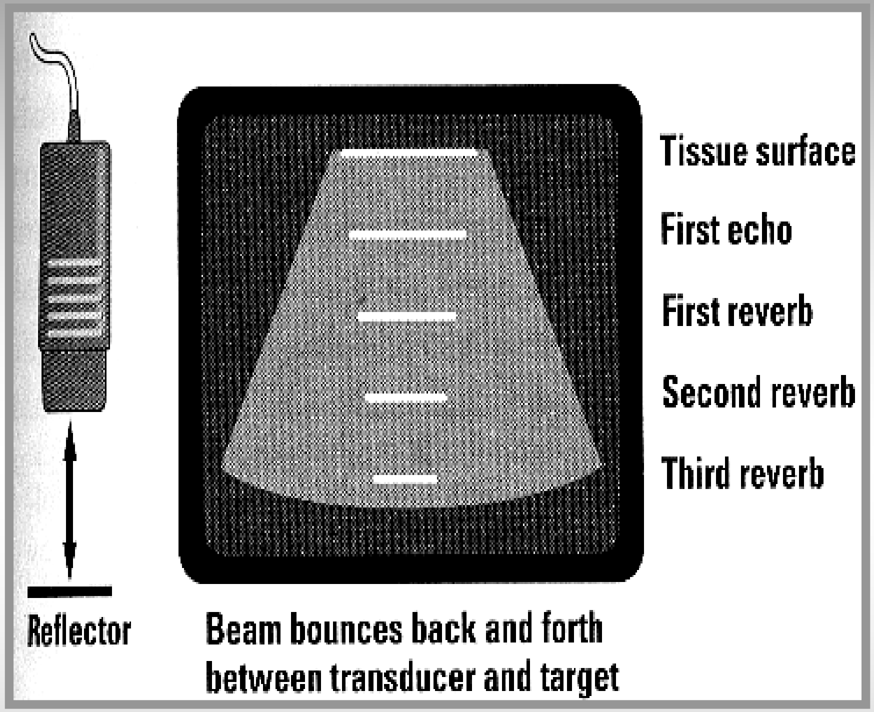




Structure adjacent to a strong reflector

•Reverberation artifacts

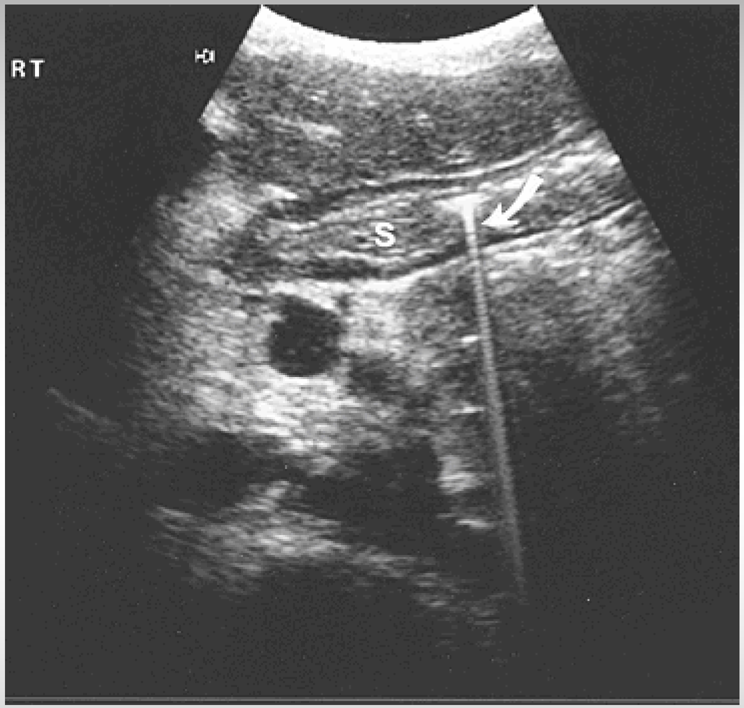


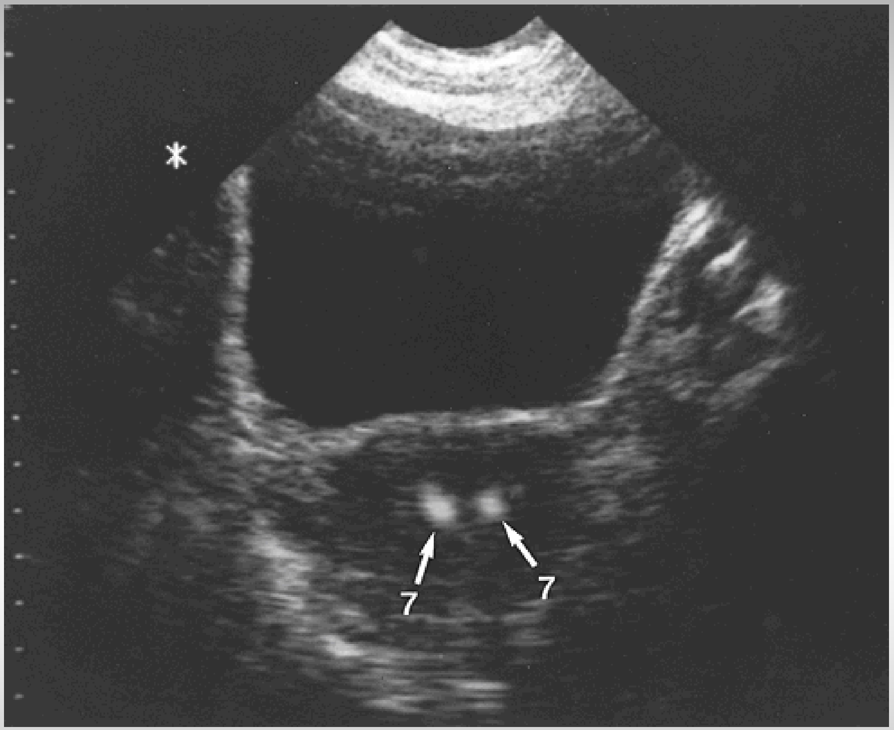


Echo of significant magnitude is partially reflected at the transducer surface & redirected towards the interface

Ring Down or Comet Tail Artifact

Refraction Artifact or Copper-14 Artifact

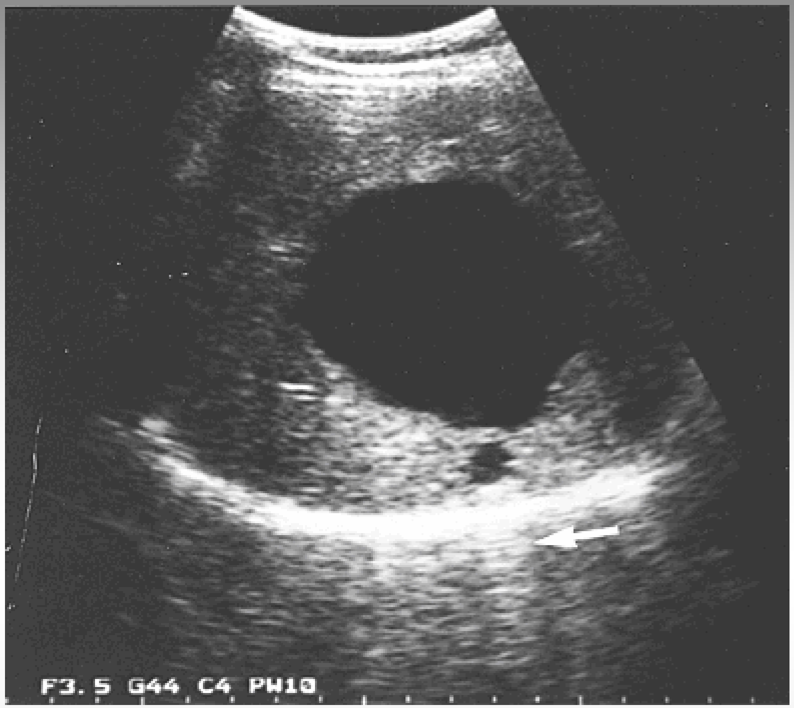


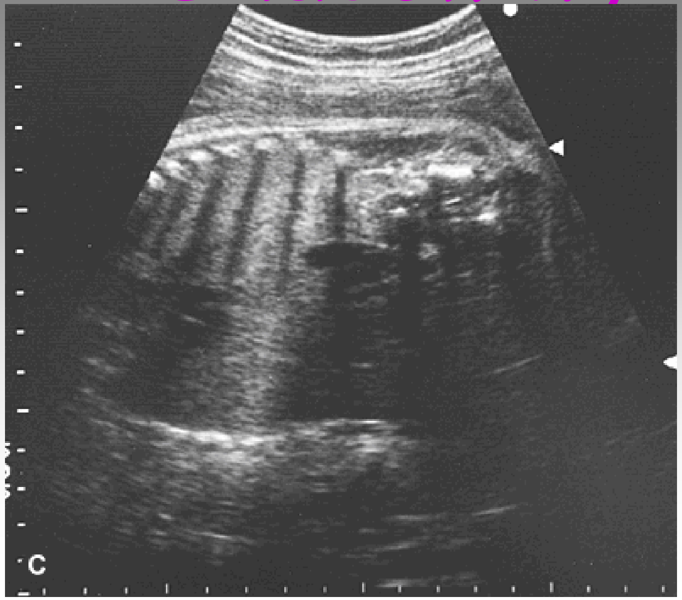


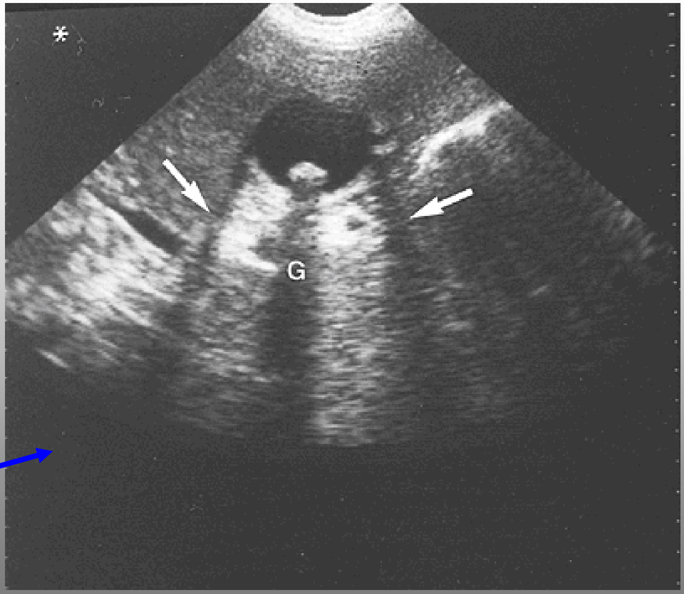
Cause: a piece of metal or a collection of gas

Duplication of a copper 7 IUD

Enhancement - Shadowing

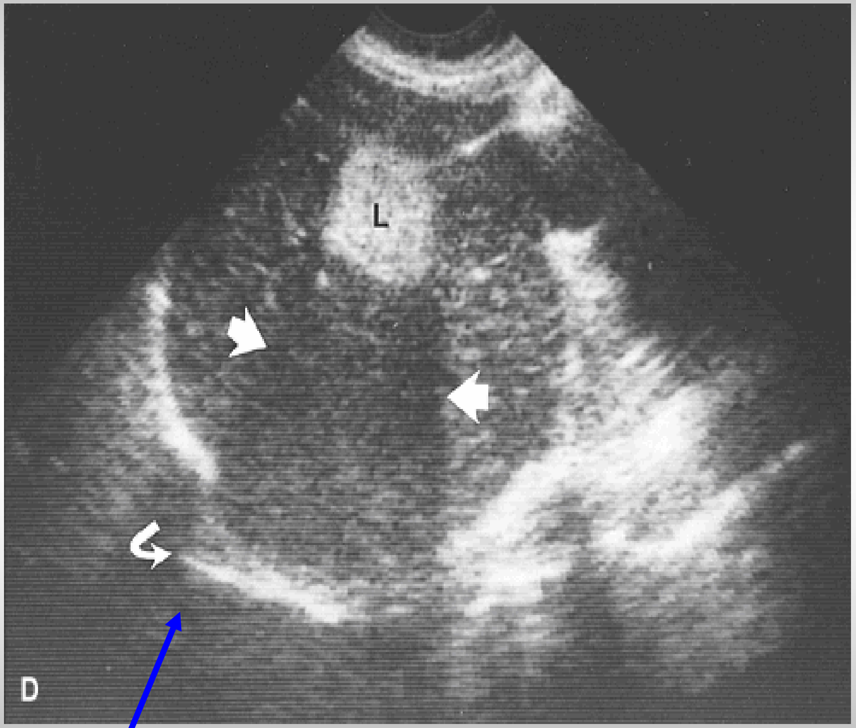






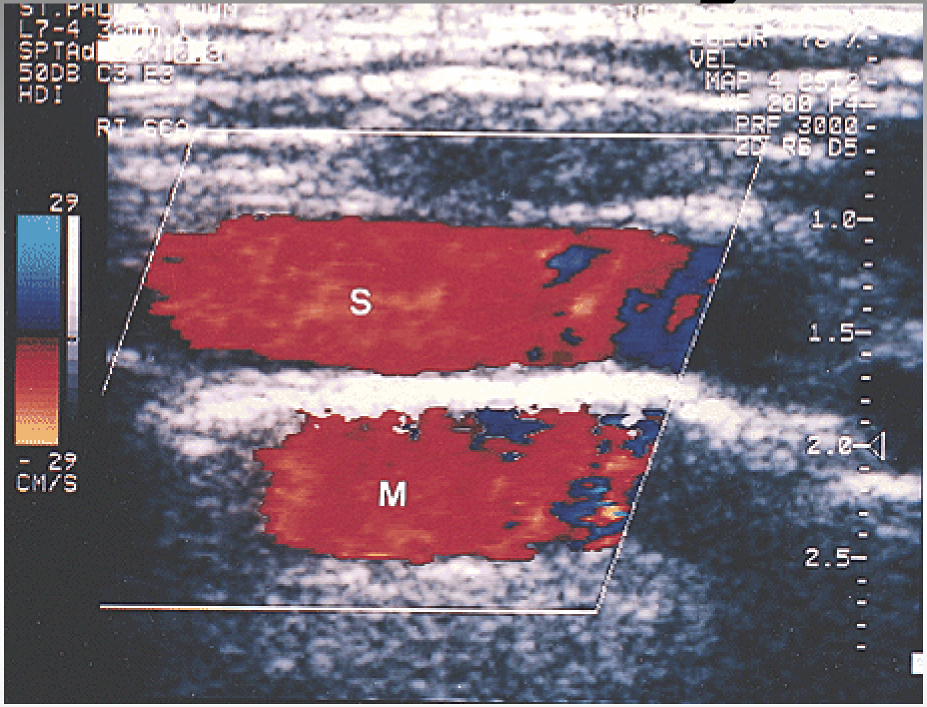
Reflective & Refractive Shadowing

Beam width or Side Lobe Artifact



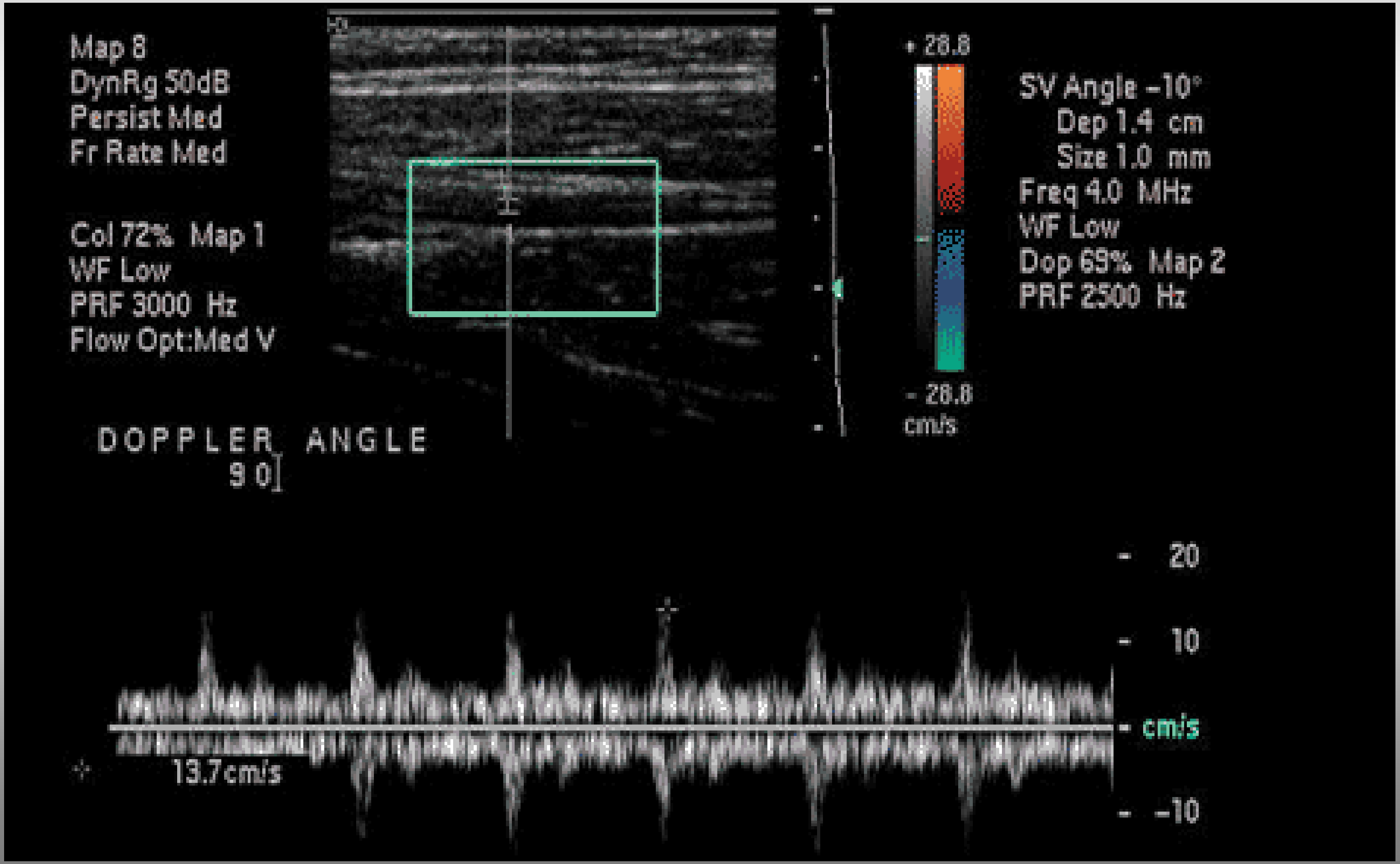
Propagation speed error artifact

Color flow mirror-image artifact

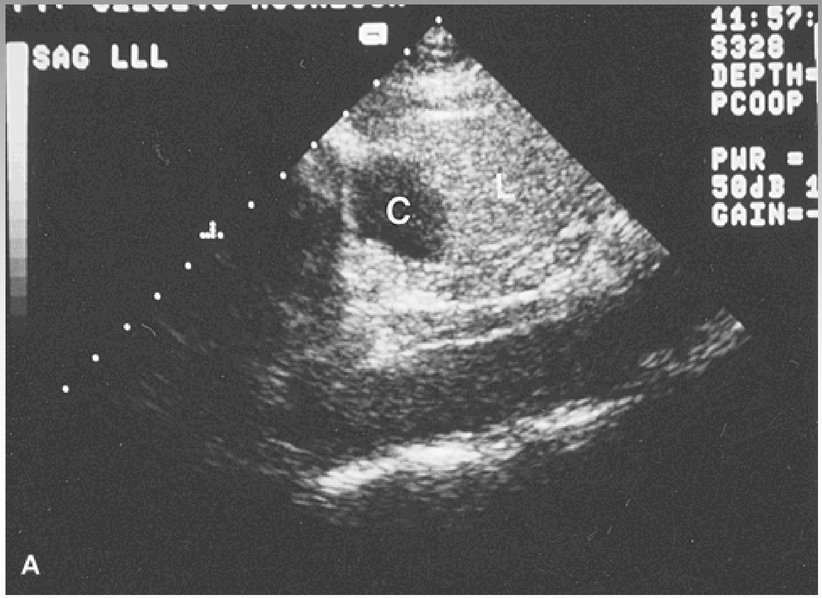


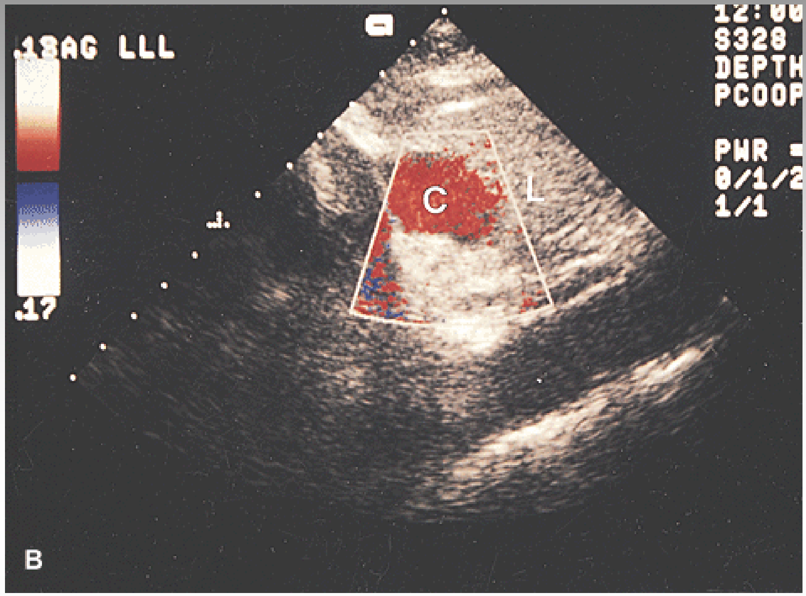
The artery is adjacent to the apex of the right lung the air-pleura interface serves as the acoustic mirror causing mirror images of the vessel & the flow within the lumen

Spectral mirror image artifact. This artifact may occur with a Doppler angle of 90° and manifests as bidirectional flow, with identical spectra in both directions ("mirror image").



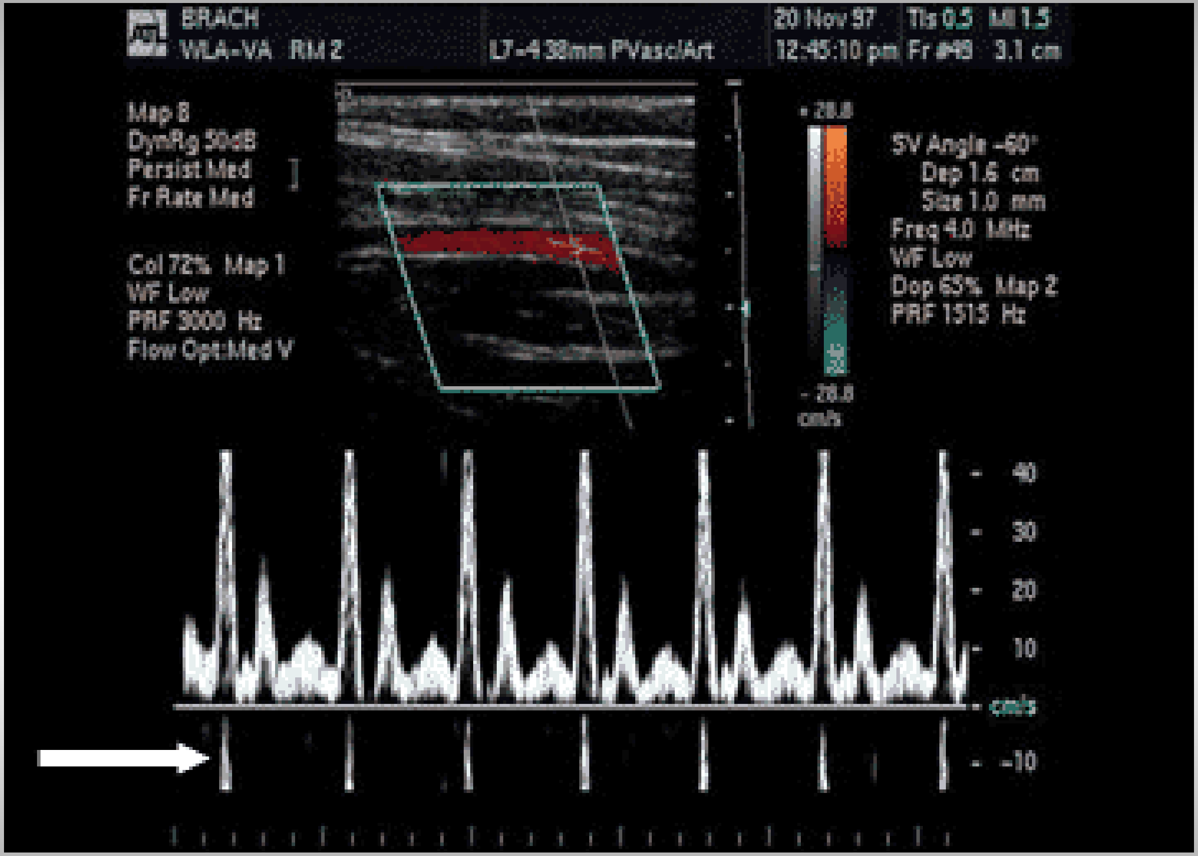
Color where no flow (color noise)





- Cyst in left lobe of liver simulating left ventricular aneurysm
- Color flow doppler showing artifactual flow due to transmitted pulsations from the left ventricle

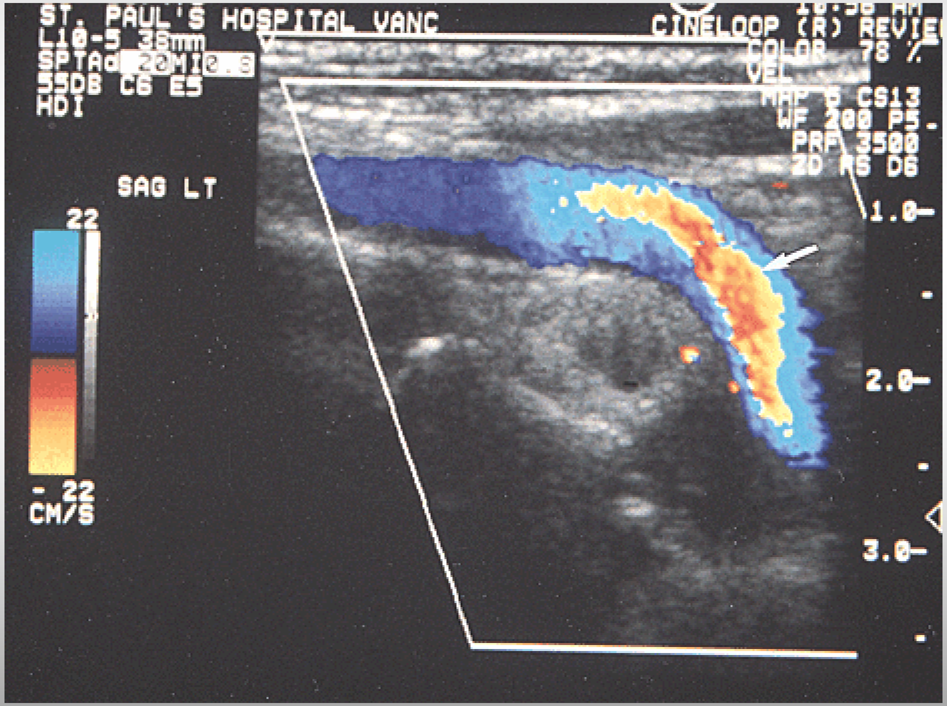
Aliasing, pulsed Doppler. There is folding over of forward flow in the reverse direction, below the baseline.



To eliminate aliasing: adjust the velocity or frequency scale on the Doppler spectral display

Aliasing- *Nyquist Frequency*

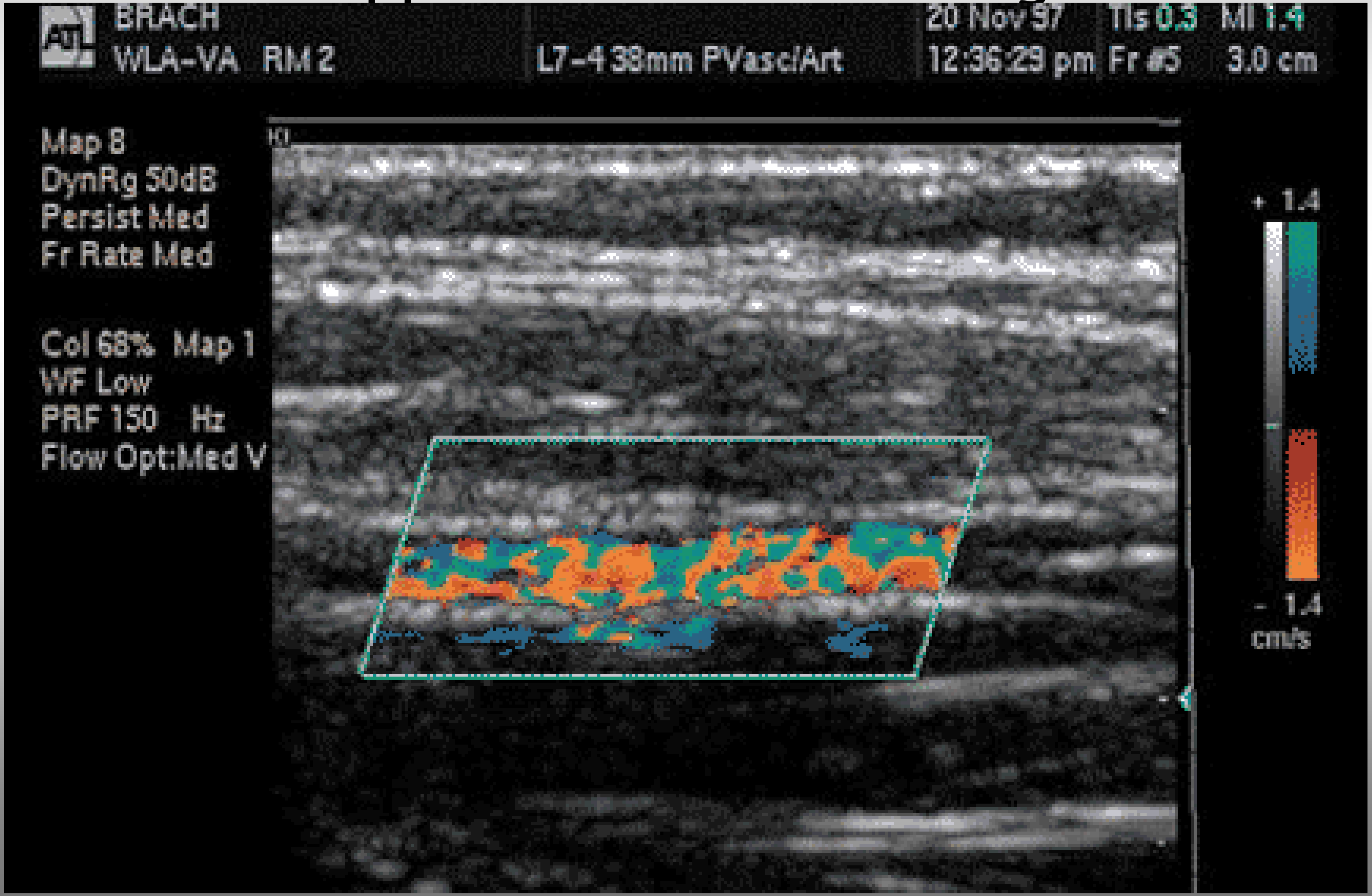
Pulse Repetition Frequency must be at least double to the maximum Doppler shift frequency [PRF=2 NF]

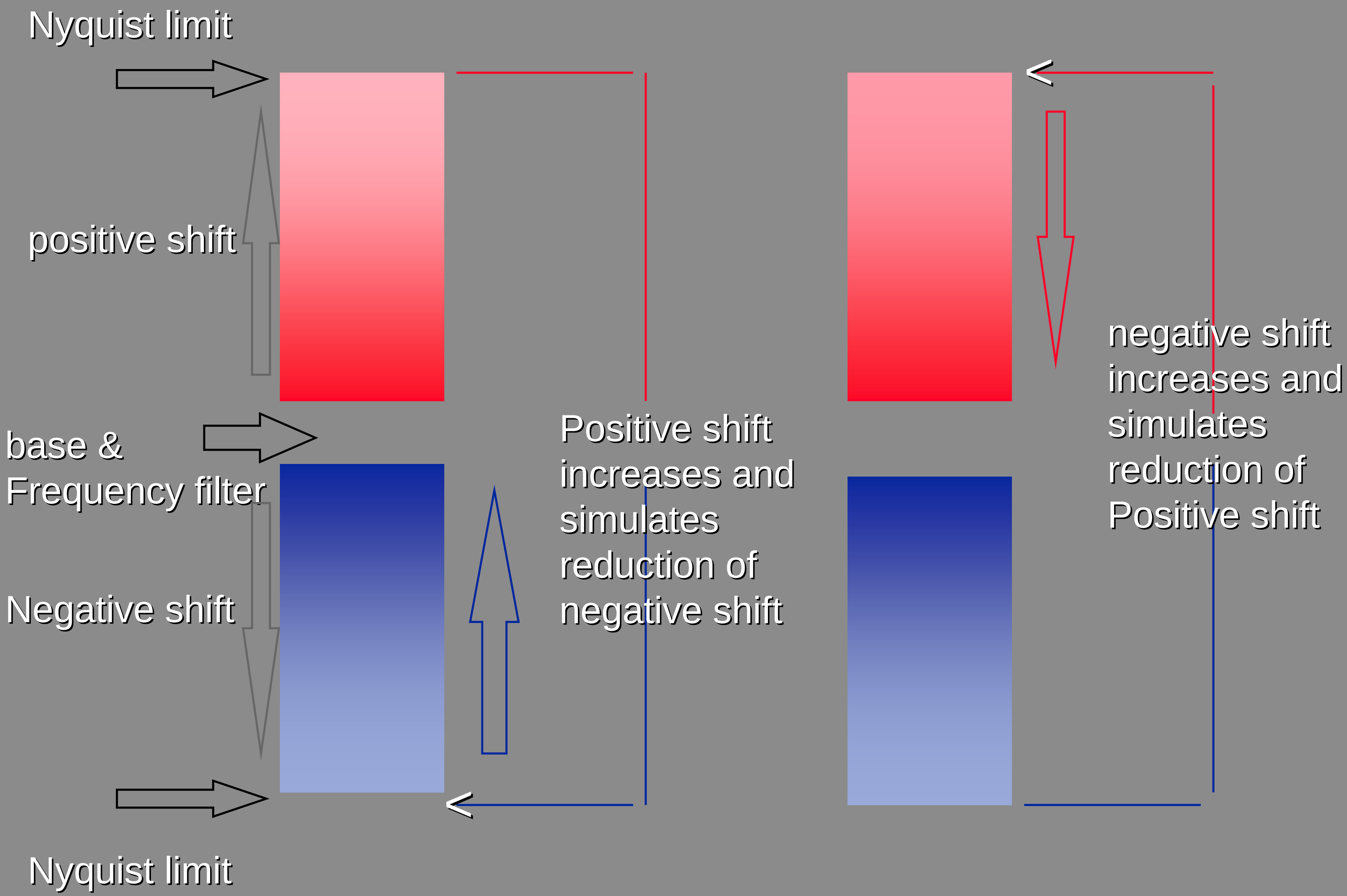


A combination of laminar with faster flow towards the center and the curvature of the vessel.

<u>Aliasing, in the absence of a stenotic jet</u>

Aliasing, color Doppler There is heterogeneity of colors within the vessel lumen, which is one of the color Doppler appearances of aliasing.



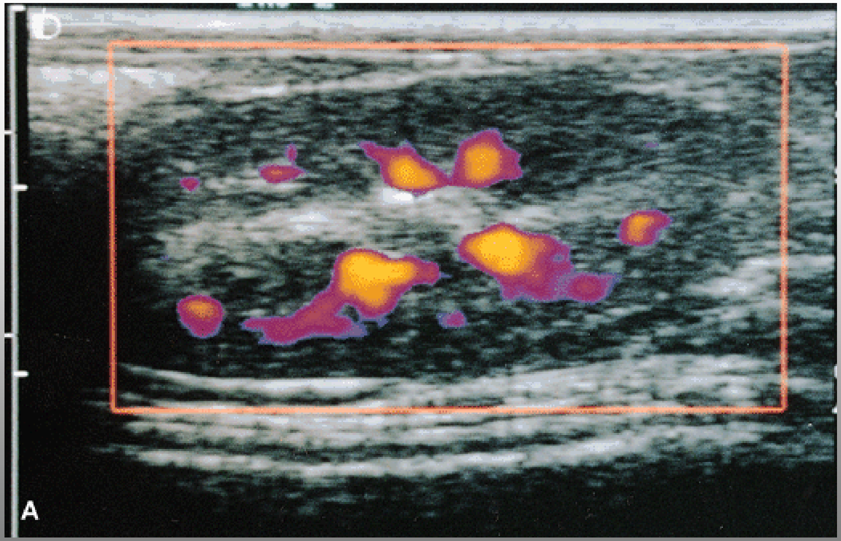


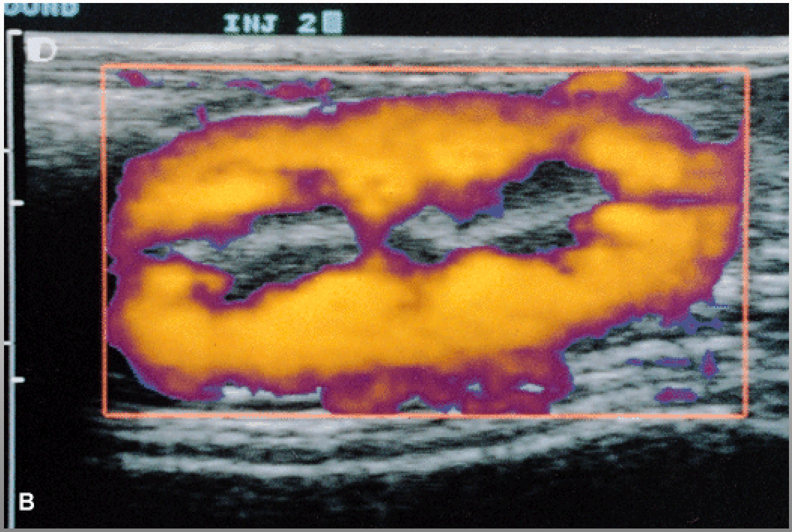
False shift- Aliasing

Contrast Enhancement

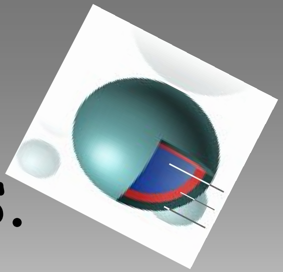
- As Ultrasound is used to study smaller & deeper structures, the spatial resolution of grey scale & doppler sensitivity becomes impaired.

- Ultrasound contrast agents improve the sensitivity & specificity of ultrasound diagnosis

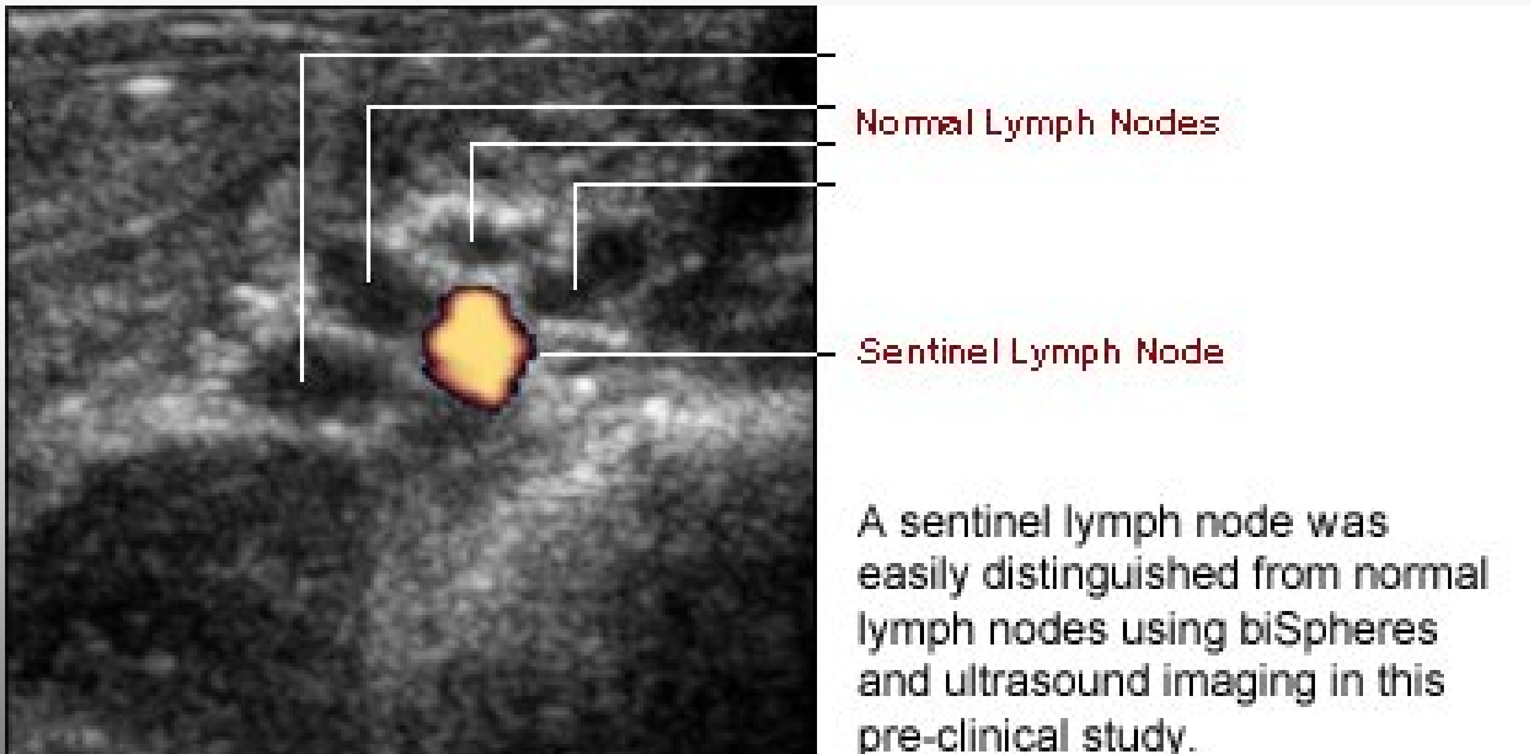




An ultrasound scan of a lymph node following uptake of submicron biSpheres.

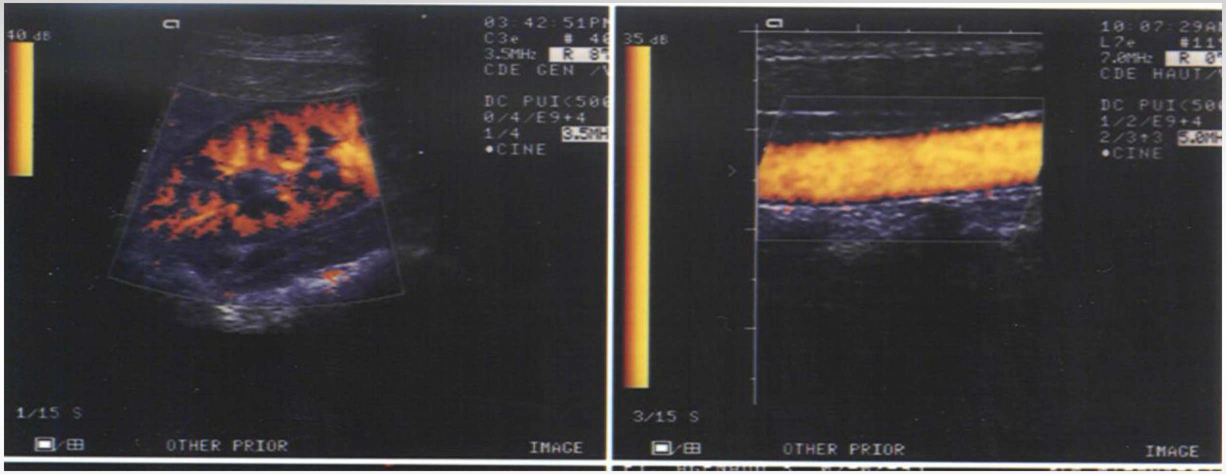


- Contrast agent bispheres possess the same flow characteristics as red blood cells and circulate along with the red blood cells.



Power Doppler Technique

Estimates the total strength of the Doppler signal & is related to the number of red blood cells moving , regardless of the velocity



sensitive in detecting the presence & volume of flow

Other characteristics of **power Doppler** flow imaging:

✓absence of directional information,

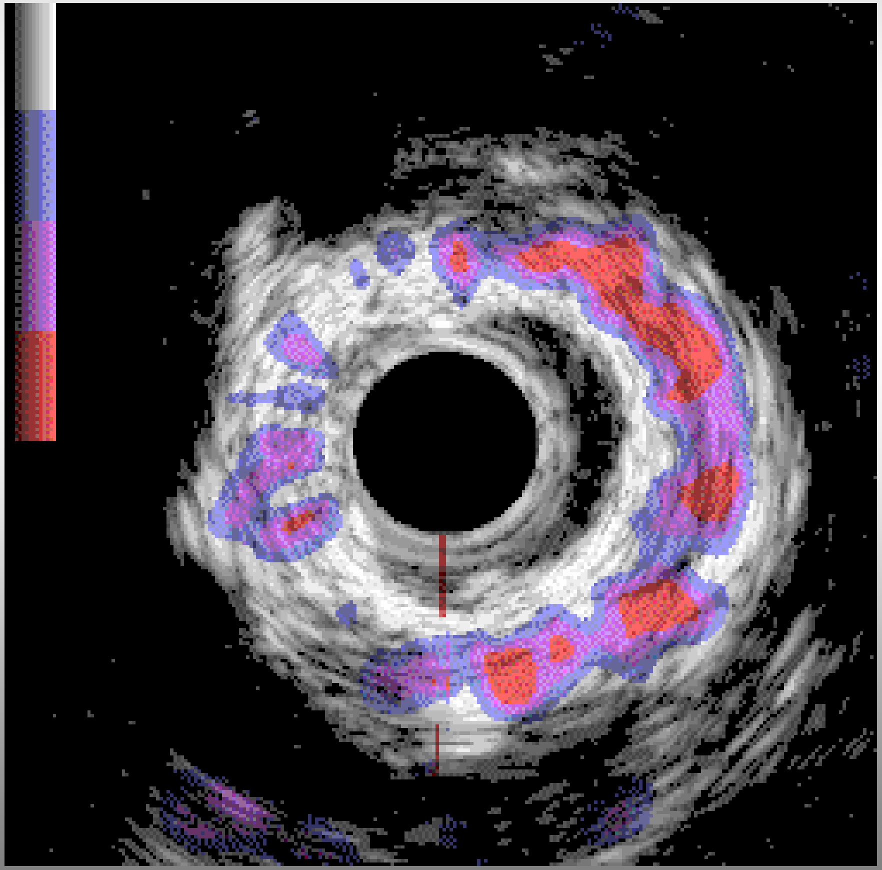
✓absence of aliasing,

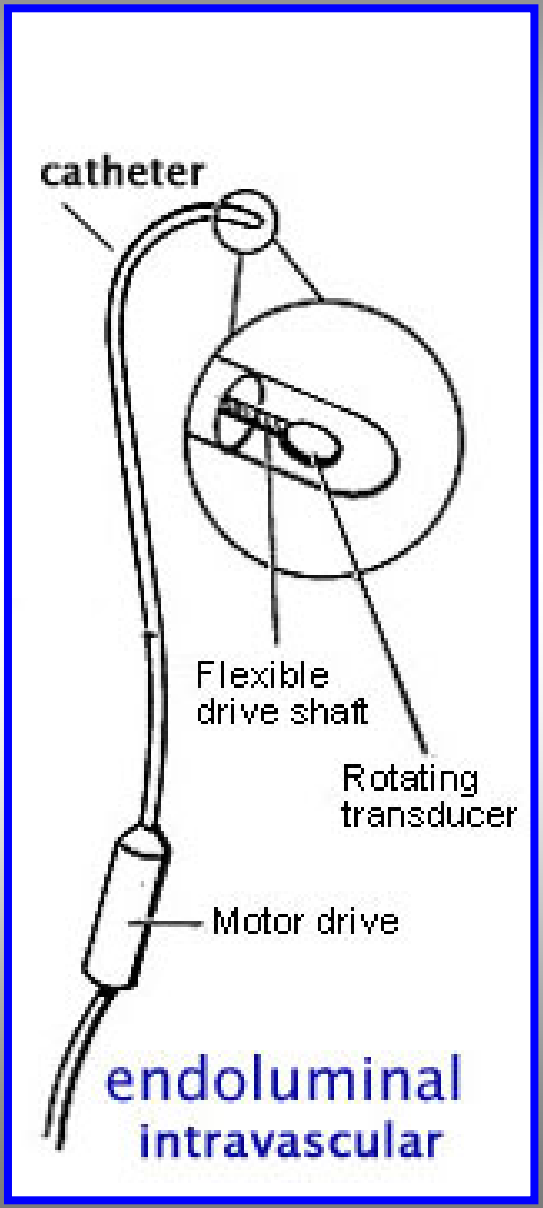
✓insensitivity to angle of flow.

❖ Imaging of arterial walls degeneration by intravascular transducer

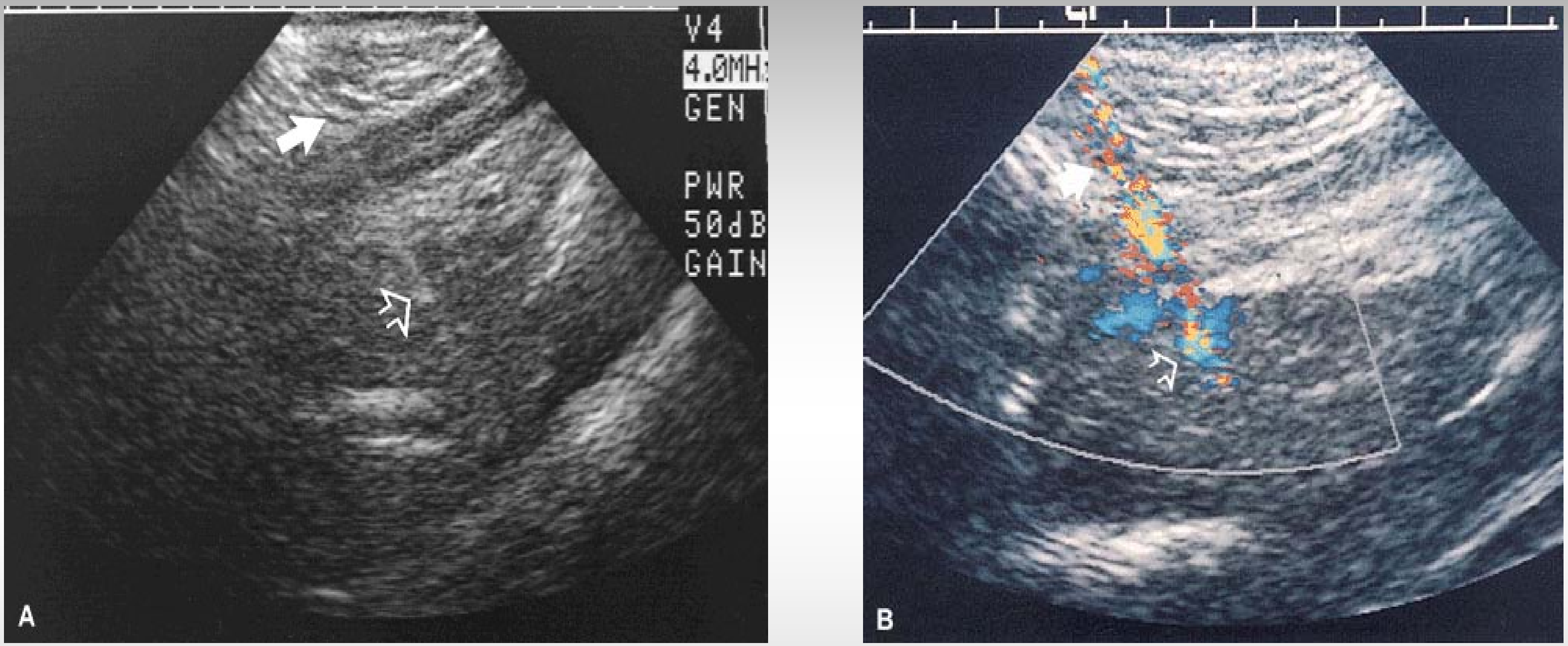
vascular wall and atherosclerotic plaques

Tissue Characterization Information appears as different colours` distribution





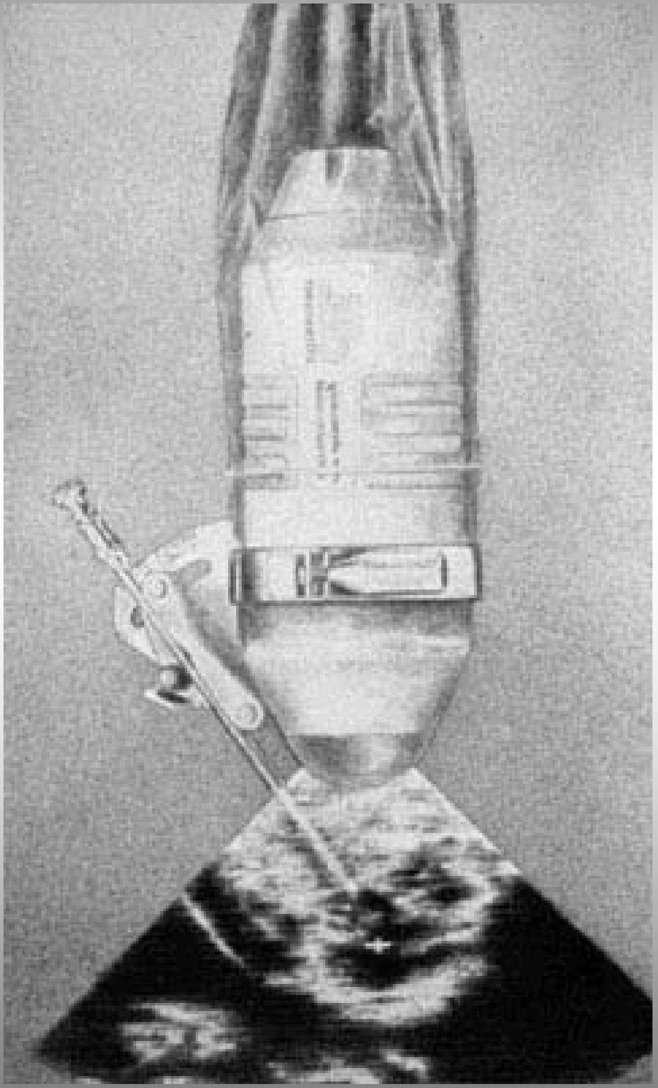
Ultrasound biopsy



Routine liver biopsy by ultrasound.
The needle part within proximal tissue is better visualized by color ultrasound

Intraoperative ultrasound

Artist's conception of closed brain biopsy, demonstrating ability of ultrasound to detect needle position within the brain



Transducer frequencies used in **Intraoperative ultrasound**, vary from 5 to 10 MHz, depending on the organ imaged and the depth of the lesions. Higher-frequency transducers give better resolution but poor depth penetration.

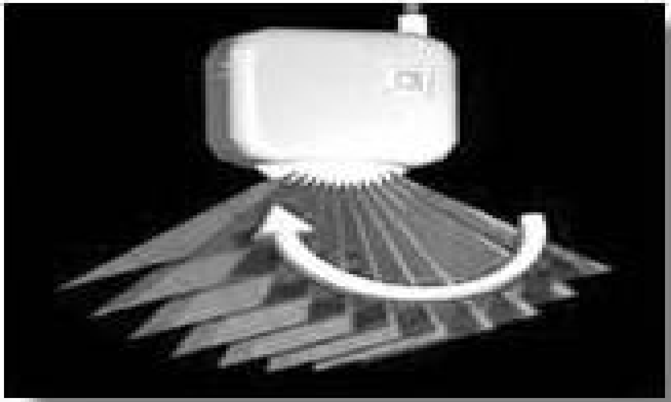
Colour pictures display more information than grey scale images?

- **Grey scale pictures are limited to the grey scale tones.**
- **Colour pictures can display grey scale tones, plus the tones available for every colour on each image.**

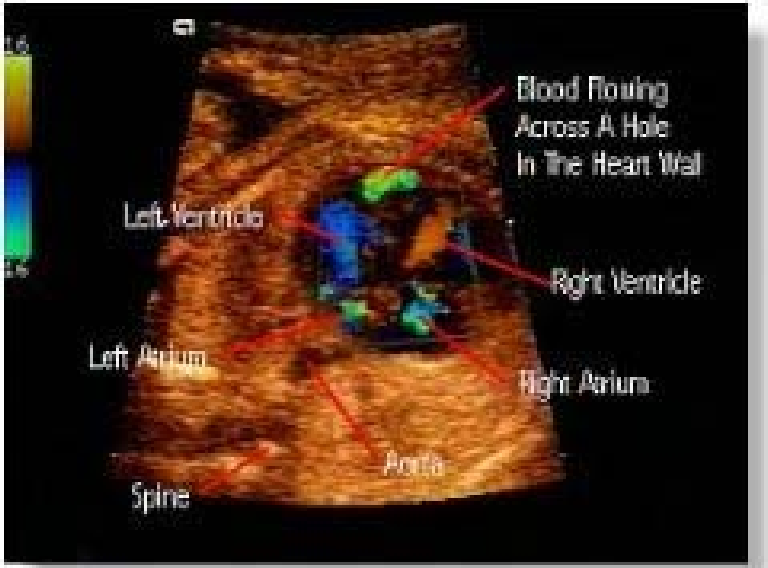
Structures are enhanced on the right image colour processing does improve contrast resolution and makes diagnosis easier.

3-D/ colour ultrasound

Manufactures are using 2D arrays and mechanically swivelled transducers to produce 3-D sonograms



Hand-held 3-D probe from Kretztechnik

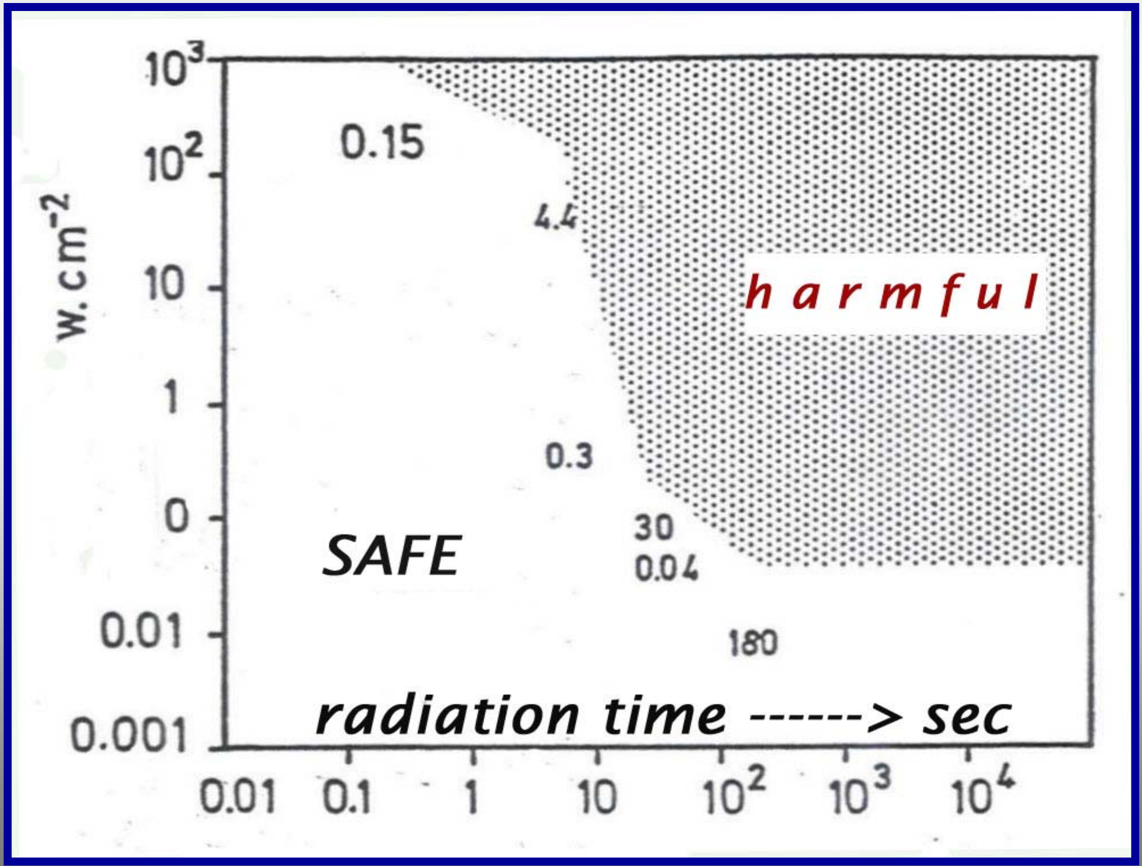


color doppler assessment of a VSD ***

Official Statement of the
American Institute of Ultrasound in Medicine

SAFETY IN TRAINING AND RESEARCH

Diagnostic ultrasound has been in use since the late 1950's
No confirmed adverse biological effects on patients resulting from this usage have ever been reported.



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