Basic principles and instrumentation of medical ultrasound

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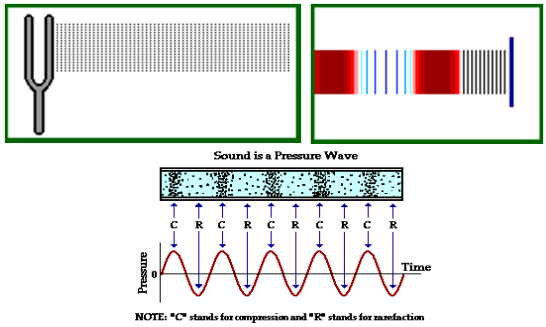
Physics

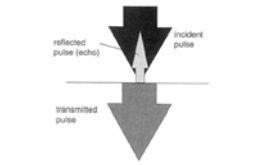
Ultrasound

- Acoustic waves with frequencies higher than 20 kHz
- Need a medium to propagate
- Longitudinal wave
- Non-ionizing radiation

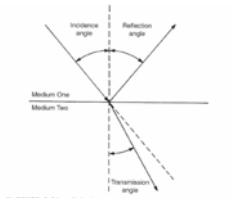


Reflection and refraction

1. Acoustic impedance mismatch (Z = density x sound speed)
2. When the reflecting object is larger than the wavelength, the reflection occurs.



■ FIGURE 2-23 Reflection and transmission at a boundary with perpendicular incidence. The incident pulse is partially reflected (echo) with the remainder (transmitted pulse) continuing into the second medium. The strengths of the reflected and transmitted pulses are determined by the impedances of the two media at the boundary.

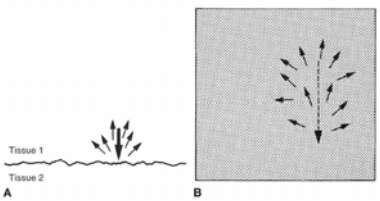


■ FIGURE 2-24 Reflection and transmission at a boundary with oblique incidence. Incidence and reflection angles are equal. The transmission angle depends on the incidence angle and the media propagation speeds.

Scattering

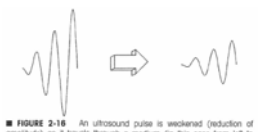
When the reflecting object is comparable in size or smaller than the wavelength, the incident wave will be scattered.

Scattering or backscattering intensities are less than specular reflection intensities

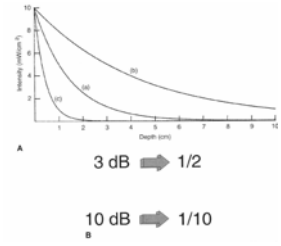


Attenuation

Attenuation is due to absorption (90%), reflection, and scattering



■ FIGURE 2-16 An ultrasound pulse is weakened (reduction of amplitude) as it travels through a medium (in this case from left to right). This weakening is called attenuation.

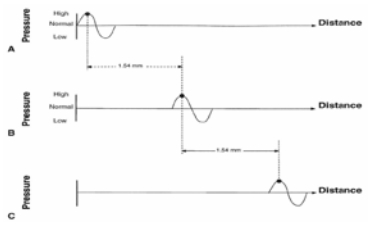


1. For soft tissues, attenuation coefficient is about 0.5 dB/MHz-cm
2. Attenuation increases with increasing frequency

TABLE 2-4 Average Attenuation Coefficients in Tissue

Frequency (MHz)	Average Attenuation Coefficient for Soft Tissue (dB/cm)	Intensity Reduction in 1-cm Path (%)	Intensity Reduction in 10-cm Path (%)
2.0	1.0	21	90
3.5	1.8	34	98
5.0	2.5	44	99.7
7.5	3.8	58	99.98
10.0	5.0	68	99.999

Propagation speed



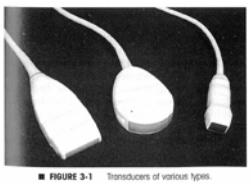
$$\lambda\ (\text{mm}) = \frac{c\ (\text{mm}/\mu\text{s})}{f\ (\text{MHz})}$$

Sound speed for soft tissues: 1540 m/s

How to generate ultrasound?

Transducer

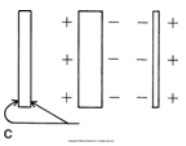
Transducer: convert one form of energy to another

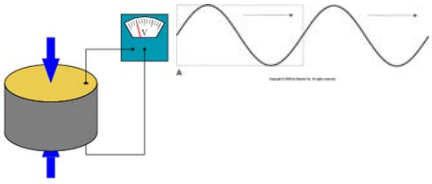


■ FIGURE 3-1 Transducers of various types.

■ FIGURE 3-2 A, Loudspeaker. B, Microphone.

Piezoelectric effect





Transducer construction

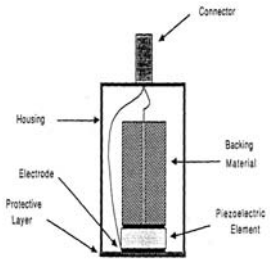


TABLE 3-1 Transducer Element Thickness* for Various Operating Frequencies

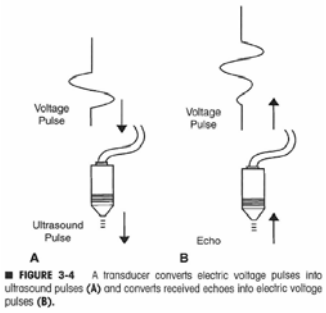
Frequency (MHz)	Thickness (mm)
2.0	1.0
3.5	0.6
5.0	0.4
7.5	0.3
10.0	0.2

*Assuming an element propagation speed of 4 mm/μs.

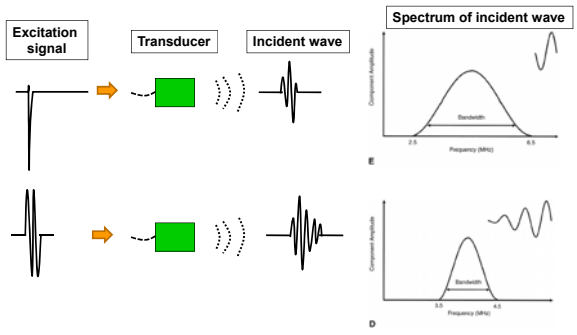
$$f_0 = \frac{c_t}{2 \cdot th}$$

Ct: velocity of element
th: thickness of element

Transducer driving



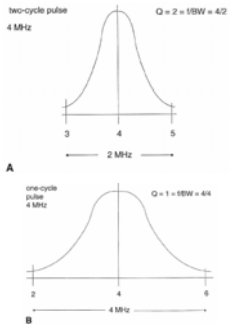
■ **FIGURE 3-4** A transducer converts electric voltage pulses into ultrasound pulses **(A)** and converts received echoes into electric voltage pulses **(B)**.



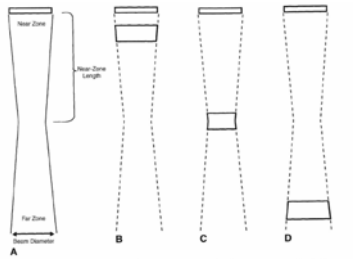
Transducer bandwidth

Bandwidth: -3 dB, -6 dB, -20 dB…

Fractional bandwidth: the bandwidth divided by the operating frequency

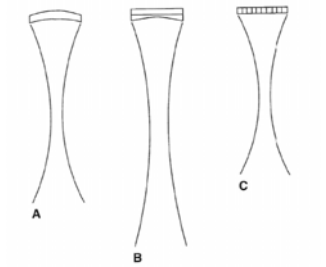


Beam profile (nonfocused)



■ **FIGURE 3-10** **A,** Beam width for a single-element unfocused disk transducer operating in the continuous wave mode. The near zone is the region between the disk and the minimum beam width. The far zone is the region beyond the minimum beam width. Intensity varies within the beam, with intensity variations being greatest in the near zone. This beam approximates the changing pulse diameter as an ultrasound pulse travels away from a transducer. **B,** An ultrasound pulse shortly after leaving the transducer. **C,** Later, the ultrasound pulse is located at the end of the near-zone length, where its width is at a minimum. **D,** Still later, the pulse is in the far zone, where its width is increasing as it travels.

Beam profile (focused)



■ **FIGURE 3-14** Sound focusing by a curved transducer element **(A)**, a lens **(B)**, or a phased array **(C)**. Lenses focus because the propagation speed through them is higher than that through tissues. Refraction at the surface of the lens forms the beam in such a way that a focal region occurs. The operation of phased arrays is described later in this chapter.

Focal length $fl = \frac{\delta}{1 - c2/c1}$

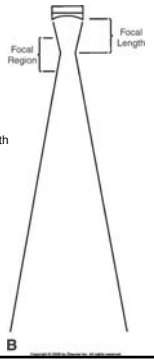
C1: velocity in lens
C2: velocity in medium

Beam width $w_b = 2\lambda \cdot (f - number) = 2\lambda \cdot \frac{fl}{a_p}$

f_l: focal length

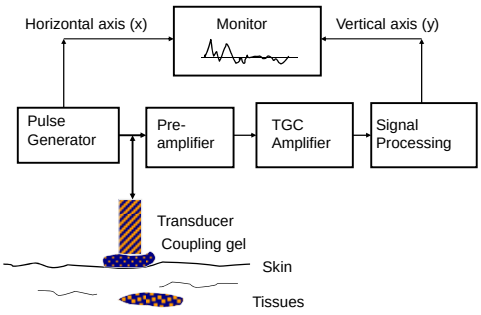
TABLE 3-3 f-Number Ranges

Focus	f Number
Weak	>6
Moderate	2-6
Strong	<2

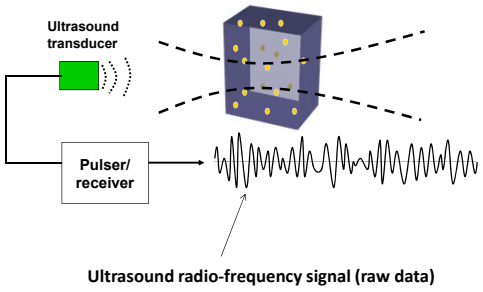


How to form an ultrasound image?

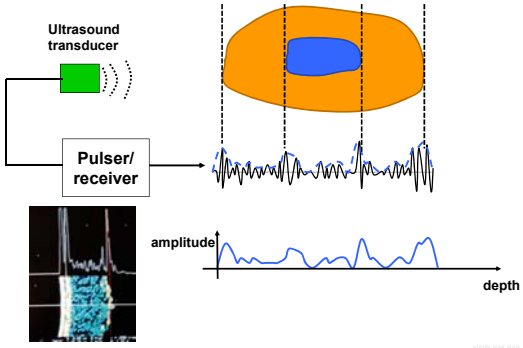
Pulse-echo system



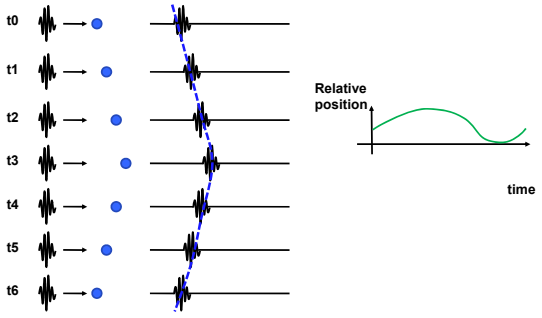
An ultrasonic signal



A (amplitude)-mode imaging



M (motion)-mode imaging



B (brightness)-mode scan

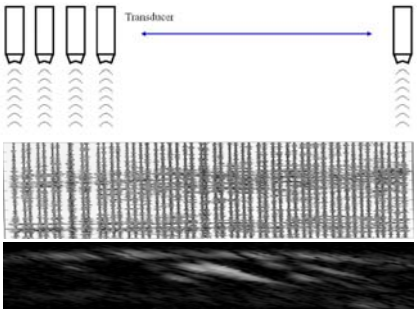
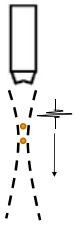


Image resolution



Axial resolution

$$Axial\ resolution = \frac{1}{2}(pulse\ duration)\cdot(sound\ speed)$$

Bandwidth ↑ ⇨ **Better axial resolution**

Pulselength ↓

Frequency ↑

Image resolution

Lateral resolution

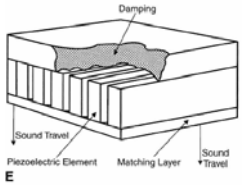
$$determined\ by\ beamwidth,\ w_b = 2\lambda\cdot(f-number) = 2\lambda\cdot\frac{fl}{a_p}$$

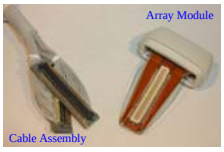
Transducer focusing ↑ ⇨ **Better lateral resolution**

Beamwidth ↓

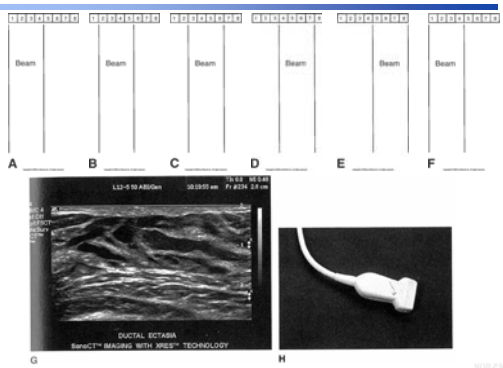
Array transducer

Array transducer

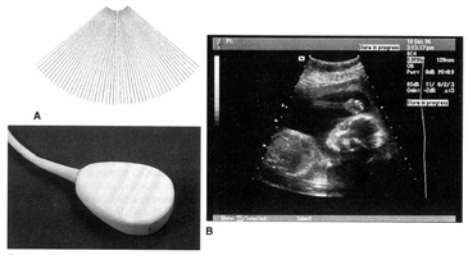




Linear sequenced array

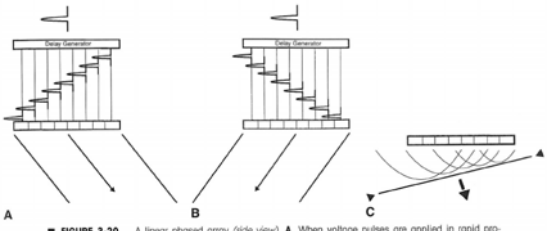


Convex (curved) array

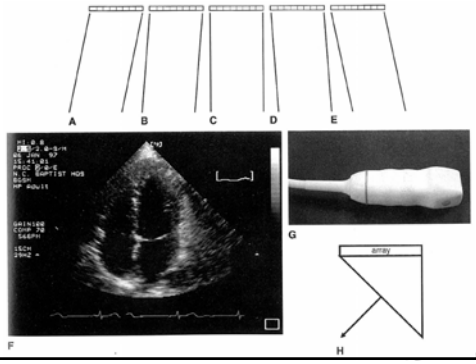


■ **FIGURE 3-19** **A,** Convex arrays send pulses out in different directions from different points across the curved array surface. **B,** A sector-type image with a curved top is produced by a convex array. **C,** A convex array transducer.

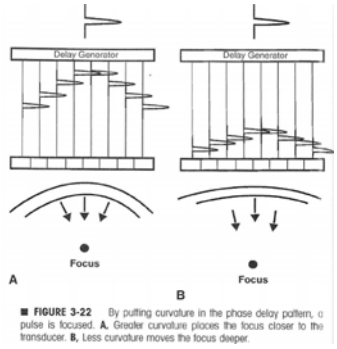
Phased array



■ **FIGURE 3-20** A linear phased array *(side view)*. **A,** When voltage pulses are applied in rapid progression from left to right, one ultrasound pulse is produced that is directed to the right. **B,** Similarly, when voltage pulses are applied in rapid progression from right to left, one ultrasound pulse is produced that is directed to the left. **C,** The delays in **A** produce a pulse the combined pressure wavefront of which *(arrowheads)* is angled from lower left to upper right. A wave always travels perpendicular to its wavefront, as indicated by the arrow.

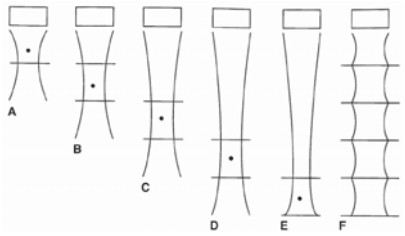


Electronic focus



■ **FIGURE 3-22** By putting curvature in the phase delay pattern, a pulse is focused. **A,** Greater curvature places the focus closer to the transducer. **B,** Less curvature moves the focus deeper.

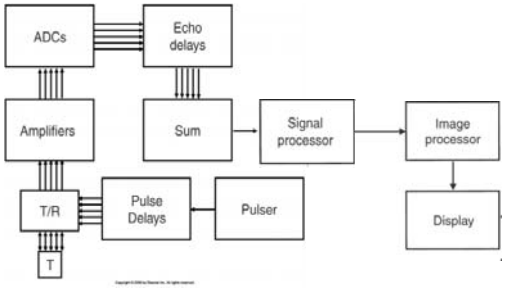
Multiple focusing



■ **FIGURE 3-24** Multiple-transmit focus uses a pulse for each focus. In this example, five pulses focused at different depths (**A** to **E**) are needed to produce a montage image (**F**) with an effectively long focus (narrow beam). Only the echoes from the focal region of each pulse are used to produce the image. The rest are discarded. **G,** Five foci at 2, 5, 8, 12, and 16 cm. **H,** Triple foci at 3, 9, and 15 cm. Note the reduced frame rates (5 and 8 Hz, compared with 18 and 16 Hz in Figure 3-23).

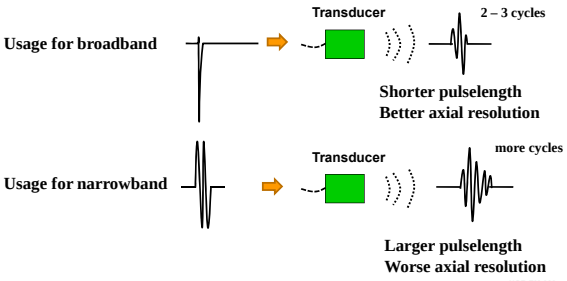
Modern imaging system

Block diagram of B-scan system



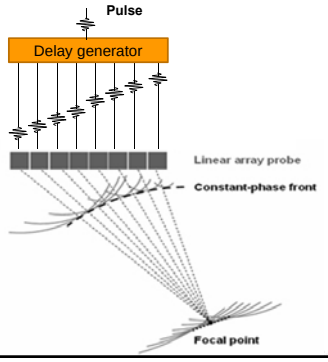
Pulser

Pulser is used to produce a signal with high energy and short duration to drive the ultrasound transducer



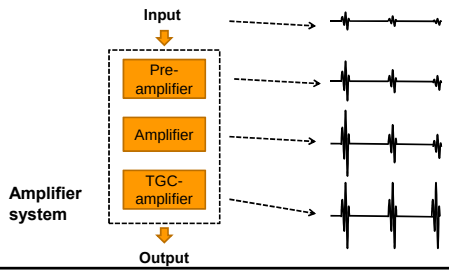
Pulse delays

Pulse delay is used for electronic focus and scan

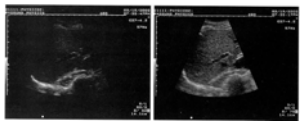


Amplifiers

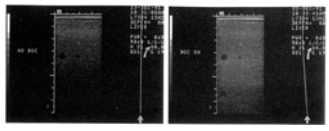
Amplifiers are used because echoes are typically weak.
---Pre-amplifier
---Amplifier
---TGC (Time gain compensation) amplifier



Amplifiers- Gain and TGC effects



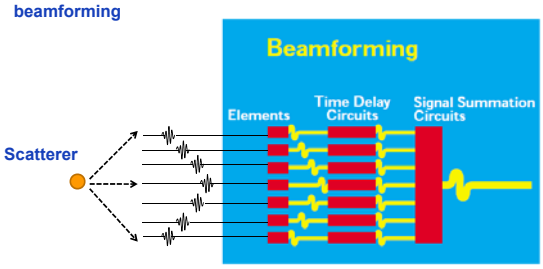
Gain is low Gain is high



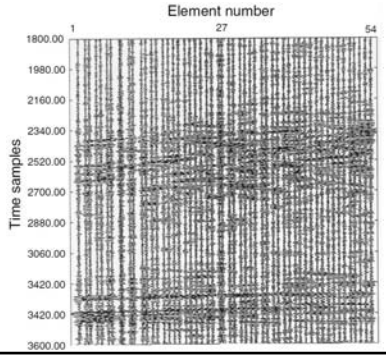
Before TGC After TGC

Echo delays and sum

Echo delay and sum means beamforming



Beamformed channel data

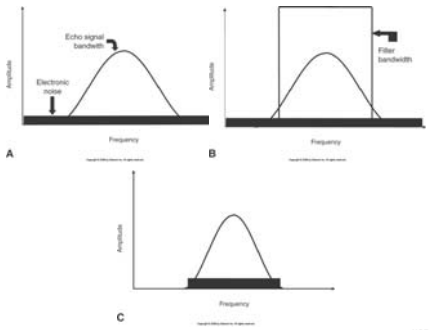


Signal process

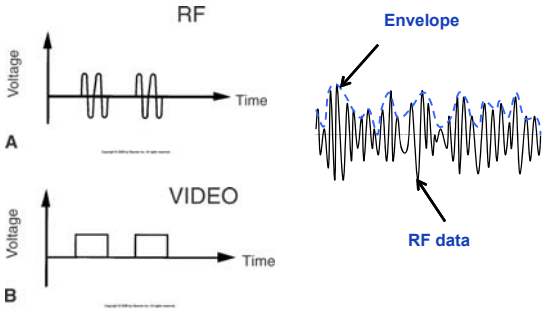
- ✓Filtering
  -- remove noises or preserve signals in the frequency range of interest
- ✓Envelope detection
  -- convert RF data into video data for display
- ✓Compression
  -- the process of decreasing the difference between the smallest and largest echo amplitude
- ✓Dynamic range adjustment

Signal process- Filtering

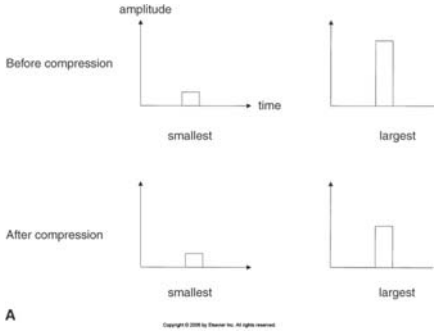
Filtering



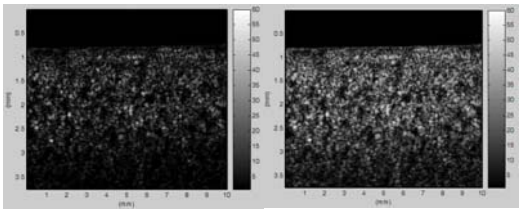
Signal process- Envelope detection (demodulation)



Signal process- Compression



Signal process- Compression



Before compression

After compression

Signal process- dynamic range adjustment

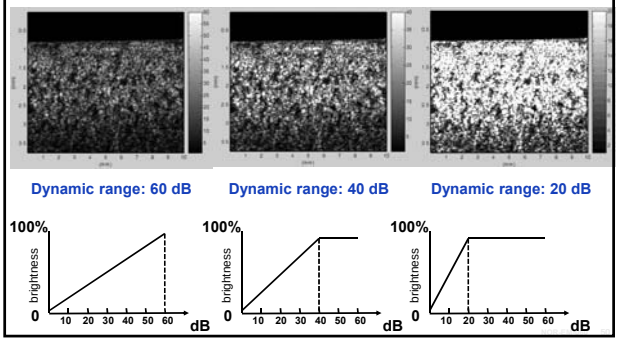


Image process

✓Scan conversion
-- translate the echo data into the output data that needs to be displayed on a monitor

✓Preprocessing
-- persistence
-- panoramic imaging
-- compounding
-- harmonic imaging
-- 3D imaging

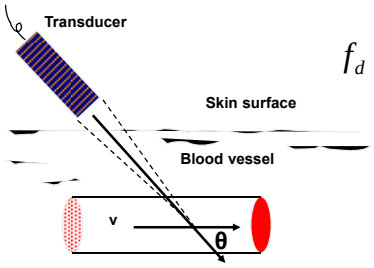
✓Postprocessing
-- gray scale adjustment
-- color mapping

Doppler ultrasound

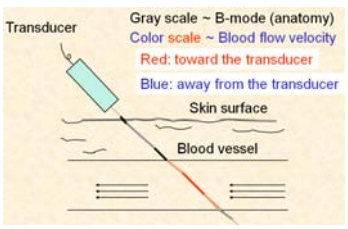
Doppler equation

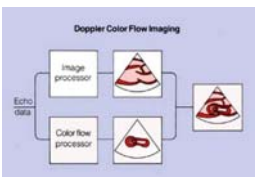
Doppler shift frequency

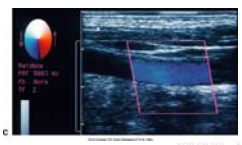
$$f_d = \frac{2v\cos\theta}{c} f$$



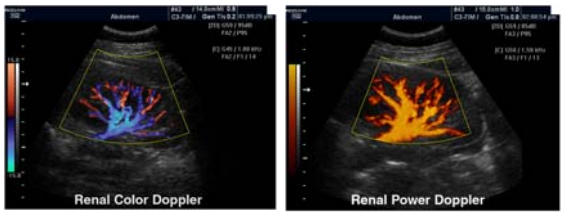
Color Doppler image





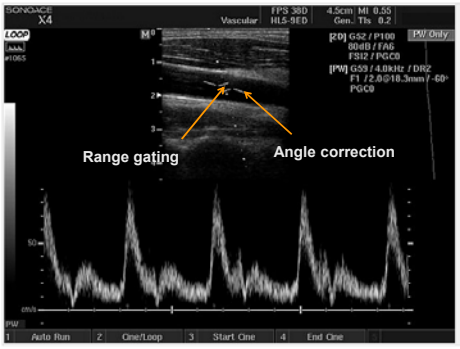


Power Doppler ultrasound

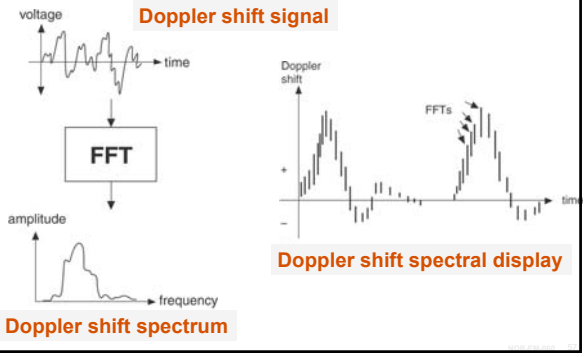


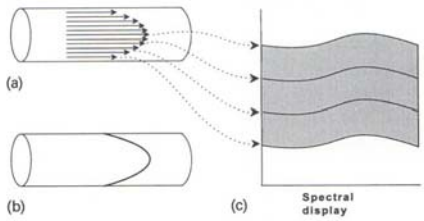
Color Doppler Power Doppler

Pulse wave Doppler

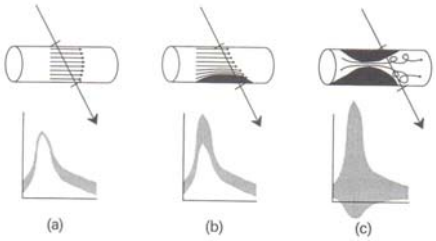


Spectrum analysis



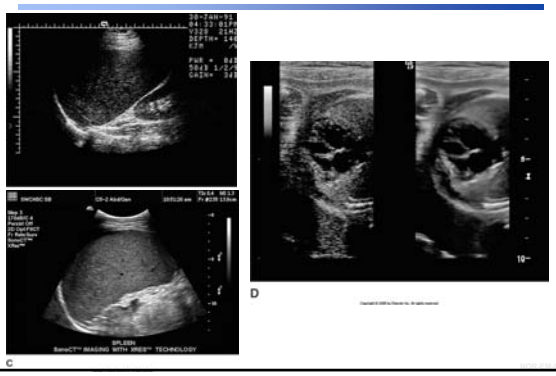


Spectral broadening is caused by flow properties

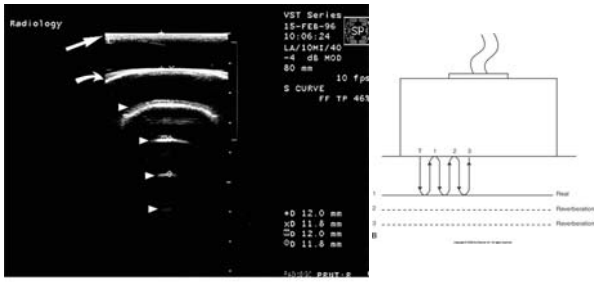


Artifacts

Acoustic speckle

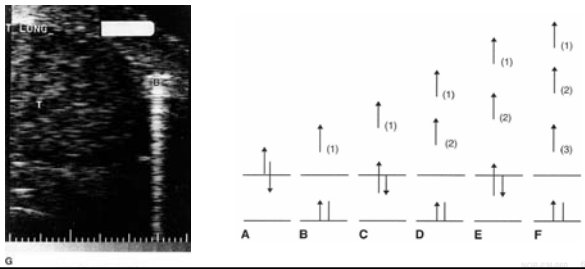


Reverberation (multiple reflection)

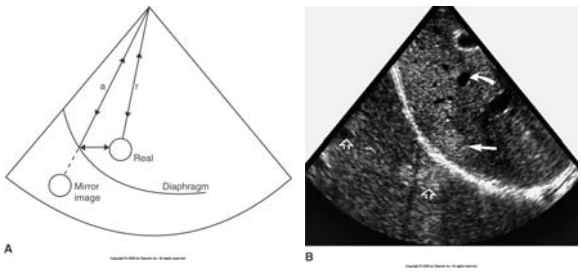


Comet tail

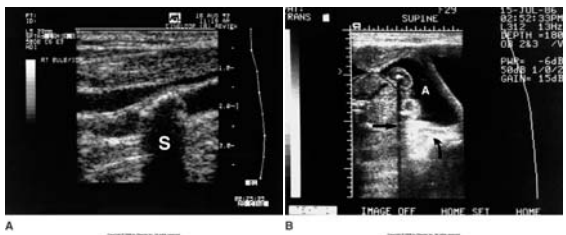
A particular form of reverberation
- Closely spaced
- Discrete echoes

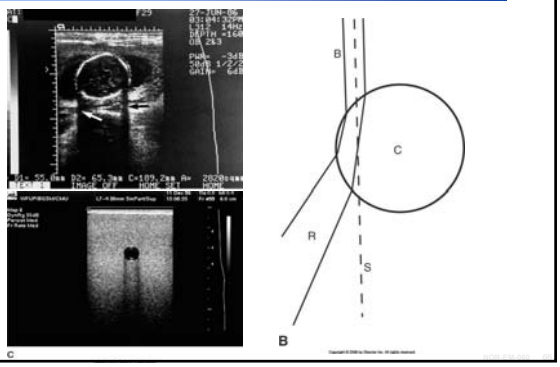


Mirror-image artifact

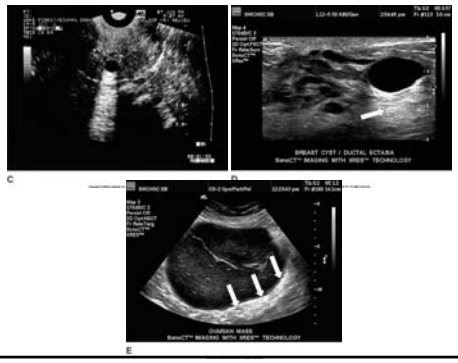


Shadowing effect

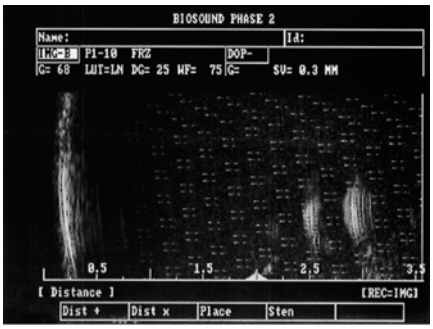




Enhancement



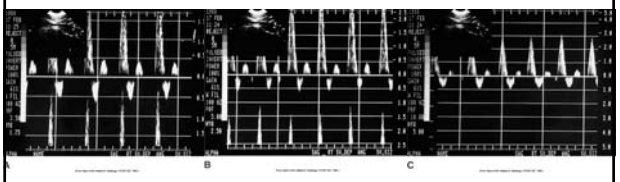
Interference (electronic noise)



Doppler aliasing

Increasing PRF (脈衝重複頻率) to reduce artifacts

Doppler aliasing



Increasing PRF

Safety considerations

Power measurement

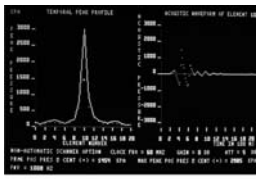
Power meter

Intensity measurement

B

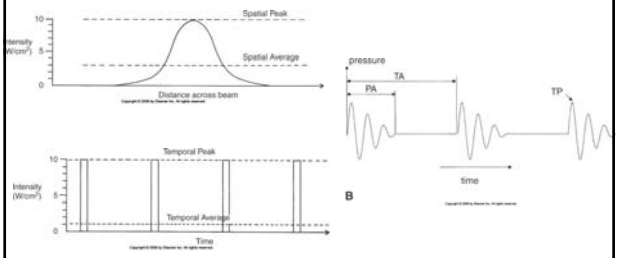
Hydrophone

A



B

Intensity description



Six intensity definitions

- Spatial average-temporal average (I_{SATA})
- Spatial peak-temporal average (I_{SPTA})
- Spatial average-pulse average (I_{SAPA})
- Spatial peak-pulse average (I_{SPPA})
- Spatial average-temporal peak (I_{SATP})
- Spatial peak-temporal peak (I_{SPTP})

TABLE 9-1 510(k) Guide Spatial Peak–Temporal Average in Situ Intensity Upper Limits

Diagnostic Application	I_{SPTA} (mW/cm²)
Cardiac	430
Peripheral vessel	20
Ophthalmic	17
Fetal imaging and other*	94

*Abdominal, intraoperative, pediatric, small organ (breast, thyroid, testes), neonatal cephalic, adult cephalic.

Ultrasound thermal effects

- Attenuation due to absorption, producing heat
- Temperature increase depends on intensity, frequency, exposure time, tissue perfusion….
- Temperature rises are considered significant if they exceed 2°

Mechanical effects (nonthermal)

- Radiation force
  - -- The force from a sound beam on a absorber
- Streaming
- Cavitation
  - -- Production and behaviors of bubbles in a liquid medium

A

ALARA principle