

UiO : Department of Physics
University of Oslo

FYS 4250

Lecture 13



Case 13



- A young couple, he is 26 years old, she is 24 years old seeks her family doctor because she has just obtained a positive pregnancy test (positive hCG, human chorionic gonadotropin). It has been 10 weeks from the start of the last normal menstrual period (LNMP). She is 174 cm tall, weighs 74 kilograms and has a blood pressure of 150/90 mmHg, a heart rate of 64 bpm, and a body temperature of 36.4 degrees Celsius. She is a non-smoker, denies drug-abuse and is a moderate alcohol drinker. She has not been drinking alcohol since she stopped using contraception. Her medical history shows that she has diabetes, type I, and that she has developed brittle diabetes with several occasions of hypoglycemia without being aware of the low glucose levels. There are no other incidents of interest in her medical history.

Case 13



- Depending on the country you live in, a typical early examination during pregnancy is an ultrasound scan

Ultrasound waves

Ultrasound > 20 kHz, normally 1-15 MHz i medicine

When a wave is sent in one direction, it will continue until reflected, deflected or absorbed.

Sound speed is independent of frequency but dependent on the medium

Sound speed is related to density, compressibility and intensity

$$c = \lambda f$$

Because the frequency remains unchanged when the medium is changed, the wavelength has to change because the speed is changed

Signal decreases 50% for 41 m of water, and 50% for 2.5 cm of muscle

Ultrasound waves

No transport of US-waves in vacuum and poor transport in gases
=> Air must **NOT** be present

Transducer must be in close contact to the object

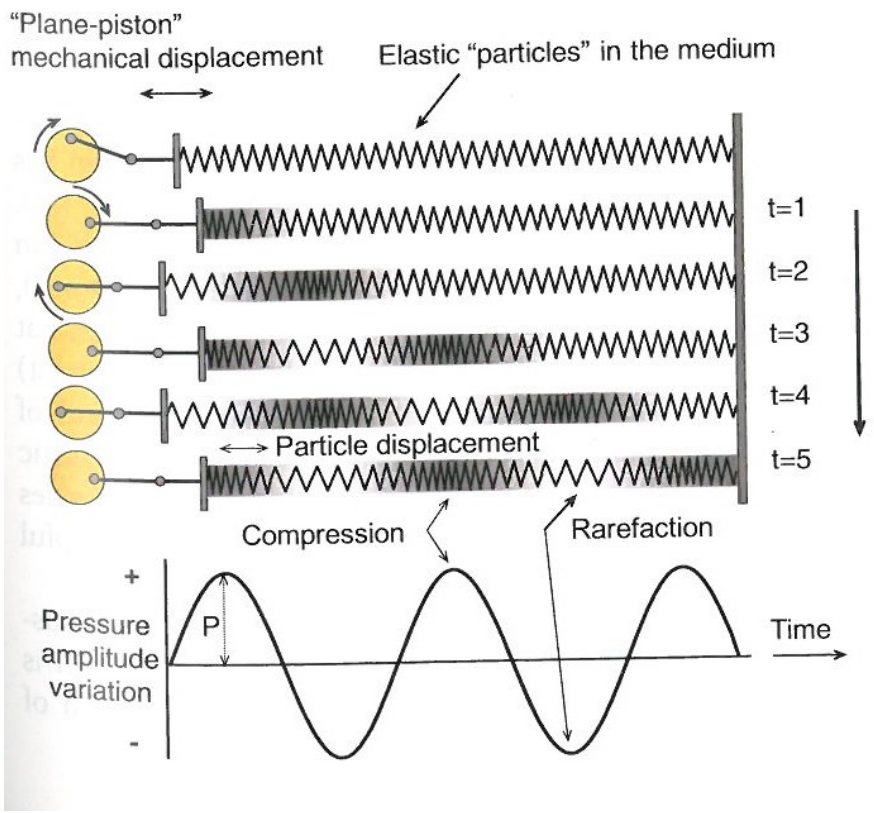
Use acoustic gel to ensure transmission from transducer to object

Bone tissue is a barrier for US

Outside the audible range for both animals and humans

Pulsed or continuous, dependent on the object. Mainly pulsed in image forming US

Ultrasound energy

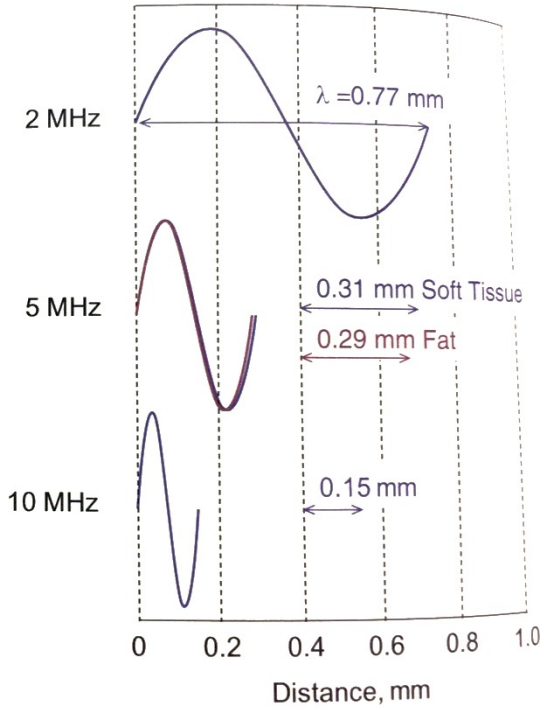


■ FIGURE 14-2 Ultrasound energy is generated by a mechanical displacement in compressible medium, which is modeled as an elastic spring. Energy propagation is shown as a function of time, resulting in areas of compression and rarefaction with corresponding variations in positive and negative pressure amplitude, *P* (lower diagram). Particles in the medium have only minor displacement as the wave front passes.

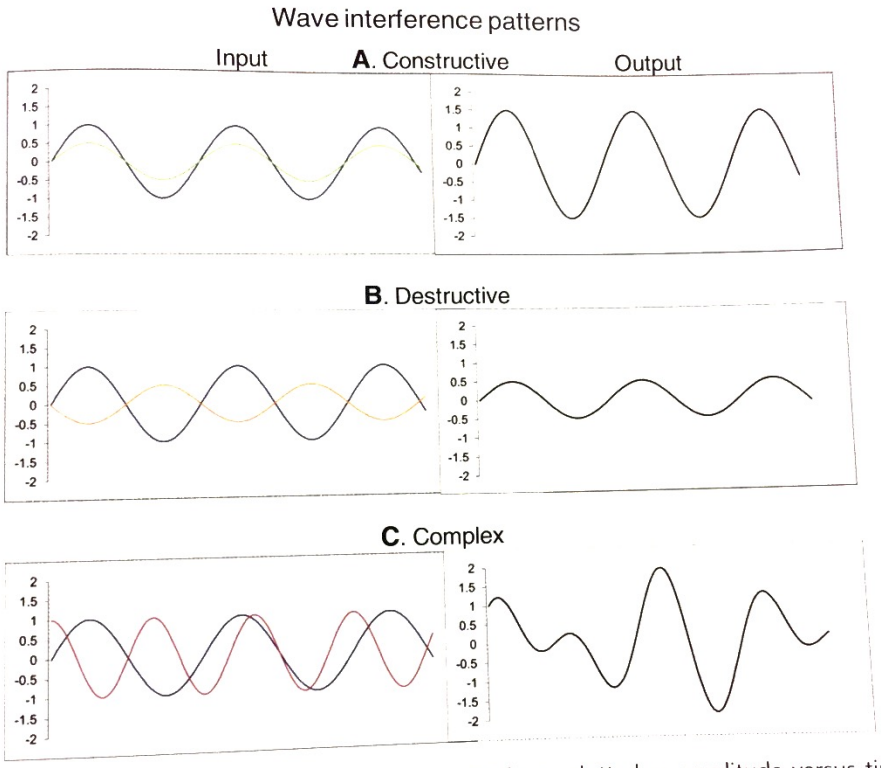
Bushberg et al, The essential physics of medical imaging

Ultrasound wavelength

■ **FIGURE 14-3** Ultrasound wavelength is determined by the frequency and the speed of sound in the propagation medium. Wavelengths in soft tissue are calculated for 2-, 5-, and 10-MHz ultrasound sources for soft tissue (***blue***). A comparison of wavelength in fat (***purple***) to soft tissue at 5 MHz is also shown.



Wave interference patterns



■ **FIGURE 14-4** Interaction of waves in a propagation medium, plotted as amplitude versus time. **A.** Constructive interference occurs with two ultrasound waves of the same frequency and phase, resulting in a higher amplitude output wave. **B.** Destructive interference occurs with the waves 180 degrees out-of-phase, resulting in a lower amplitude output wave. **C.** Complex interference occurs when waves of slightly different frequency interact, resulting in an output waveform of higher and lower amplitude.

Acoustic impedance

Acoustic impedance is like the stiffness and flexibility of a compressible medium

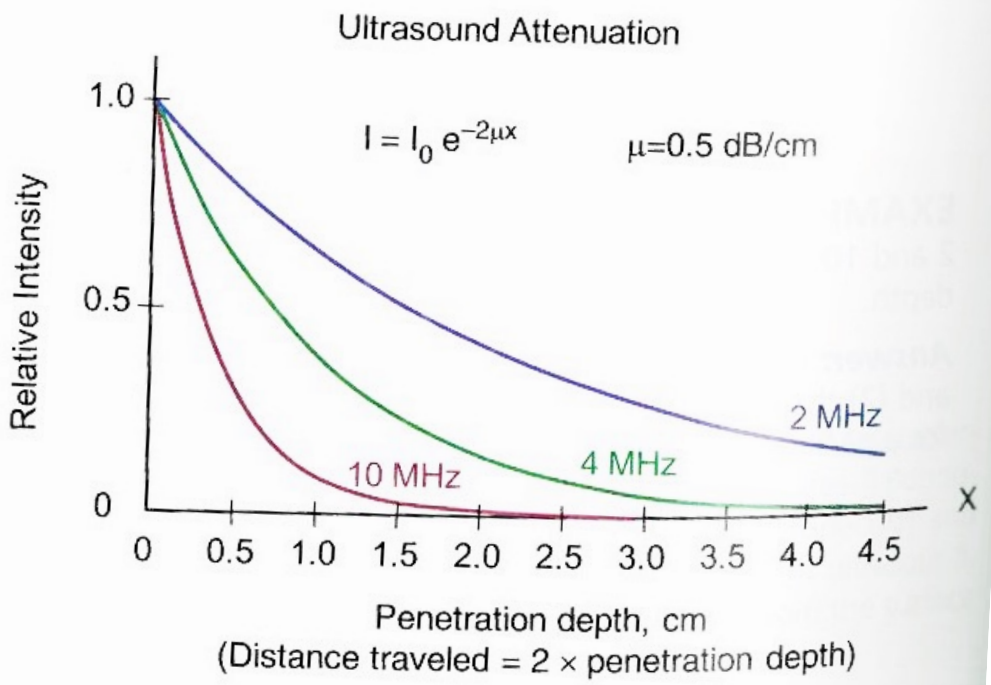
TABLE 14-3 ACOUSTIC IMPEDANCE, $Z = \rho c$, FOR AIR, WATER, AND SELECTED TISSUES

TISSUE	Z (RAYLS)
Air	0.0004×10^6
Lung	0.18×10^6
Fat	1.34×10^6
Water	1.48×10^6
Kidney	1.63×10^6
Blood	1.65×10^6
Liver	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

Bushberg et al, The essential physics of medical imaging

Ultrasound attenuation

■ FIGURE 14-7 Ultrasound attenuation occurs exponentially with penetration depth and increases with increased frequency. The plots are estimates of a single frequency ultrasound wave with an attenuation coefficient of (0.5 dB/cm)/MHz of ultrasound intensity versus penetration depth. Note that the total distance traveled by the ultrasound pulse and echo is twice the penetration depth.

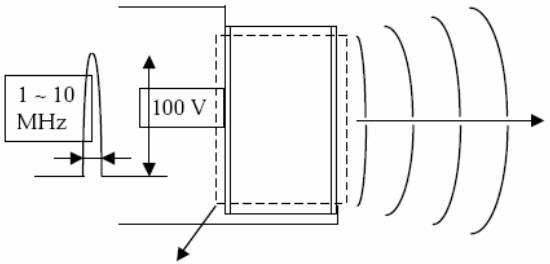


Some of the energy is scattered and lost when hitting small objects with size <= Landa. Absorbed energy is converted to heat. The transducer thickness defines the frequency, the thickness of the transducer equal to ½ Landa

The spatial resolution depends on wavelength, and the attenuation on the frequency

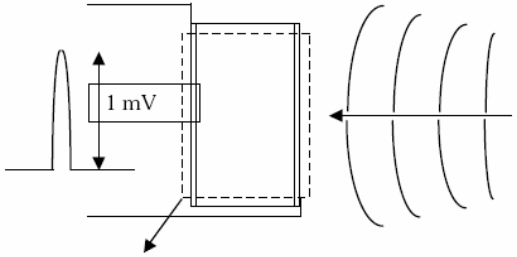
Total reflection, all of the beam is travelling along the boundary

Ultrasound piezo crystal



Shape change due to electric pulse

Piezoceramic disk expands/contracts when voltage is applied to flat faces . This creates a pressure wave: ultrasound. Electrical energy is converted into sound.



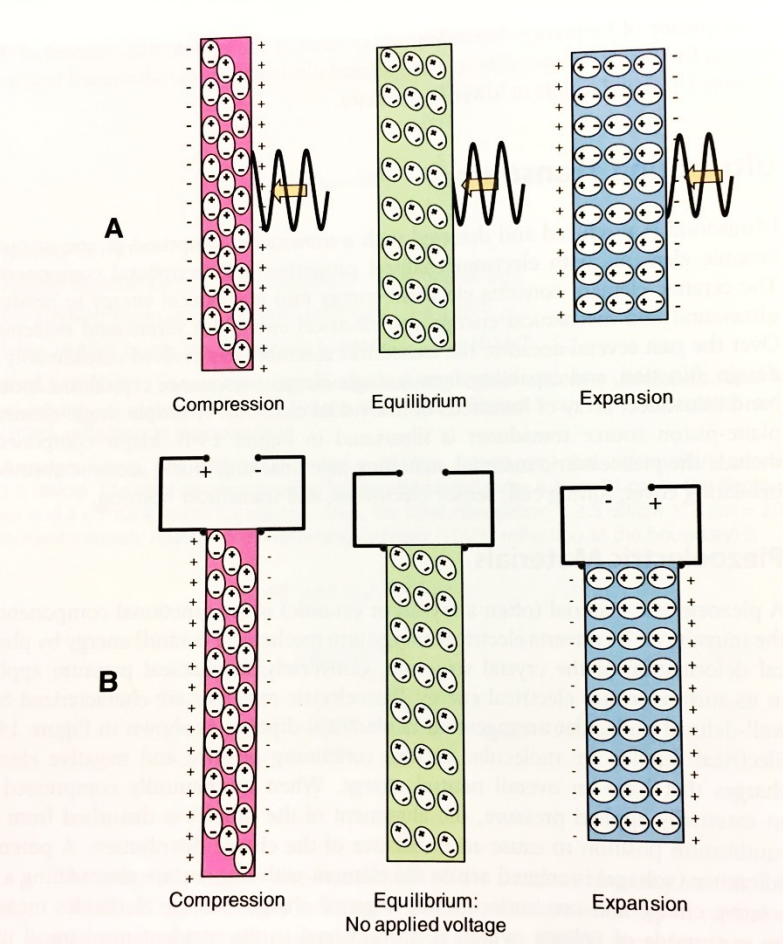
electrical signals due to shape changes

The same **Piezoceramic disk** is used to convert reflected sound waves to weak electrical signals

When stressed, a voltage is produced. When a voltage pulse is applied, the ceramic deforms

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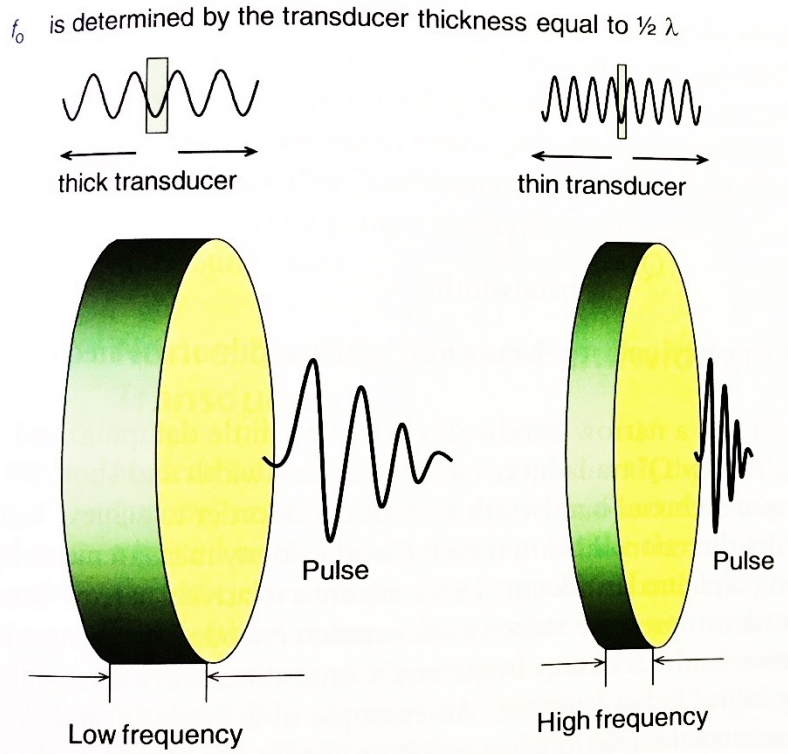
The piezoelectric element



A – under influence of mechanical pressure. Surface electrodes measure the charge variation as a function of time
B – External voltage source applied to surface causes compression or expansion from equilibririum -> realignment of the dipole

Bushberg et al, The essential physics of medical imaging

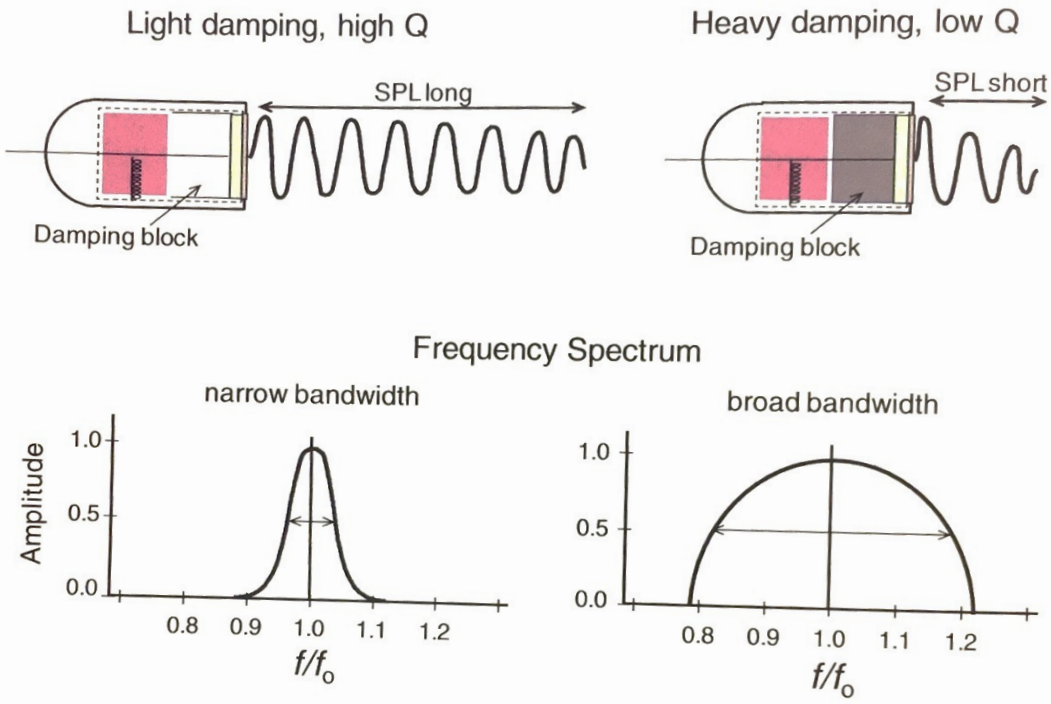
The piezoelectric element



■ **FIGURE 14-10** A short-duration voltage spike causes the resonance piezoelectric element to vibrate at its natural frequency, f_0, which is determined by the thickness of the transducer equal to ½ λ. Low-frequency oscillation is produced with a thicker piezoelectric element. The spatial pulse length (SPL) is a function of the operating frequency and the adjacent damping block.

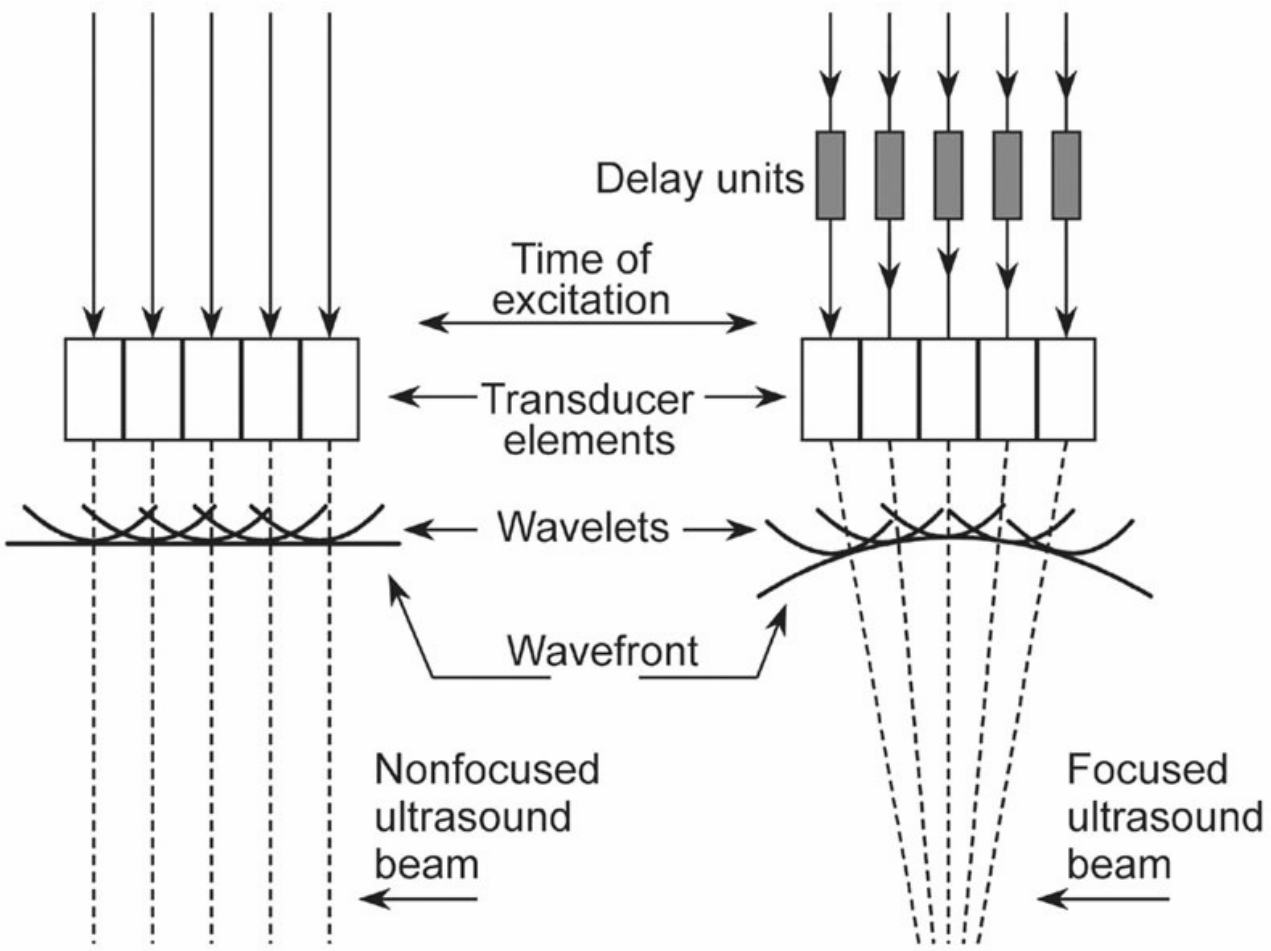
SPL = spatial pulse length

The damping block



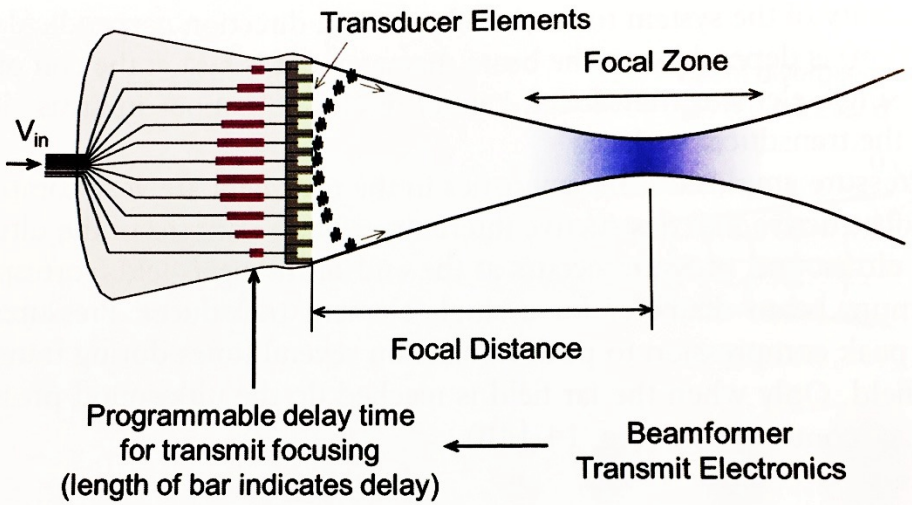
■ **FIGURE 14-11** Effect of damping block on the frequency spectrum. The damping block is adjacent to the backside of the transducer and limits the vibration of the element to a small number of cycles. Light damping allows many cycles to occur (**top left**), which results in an extended SPL (number of cycles times the wavelength) and a narrow frequency bandwidth (range of frequencies contained in the pulse (**bottom left**). Heavy damping reduces the SPL and broadens the frequency bandwidth (**top and bottom right**). The Q factor describes the center frequency divided by the bandwidth.

Phased array transducer, beam shape



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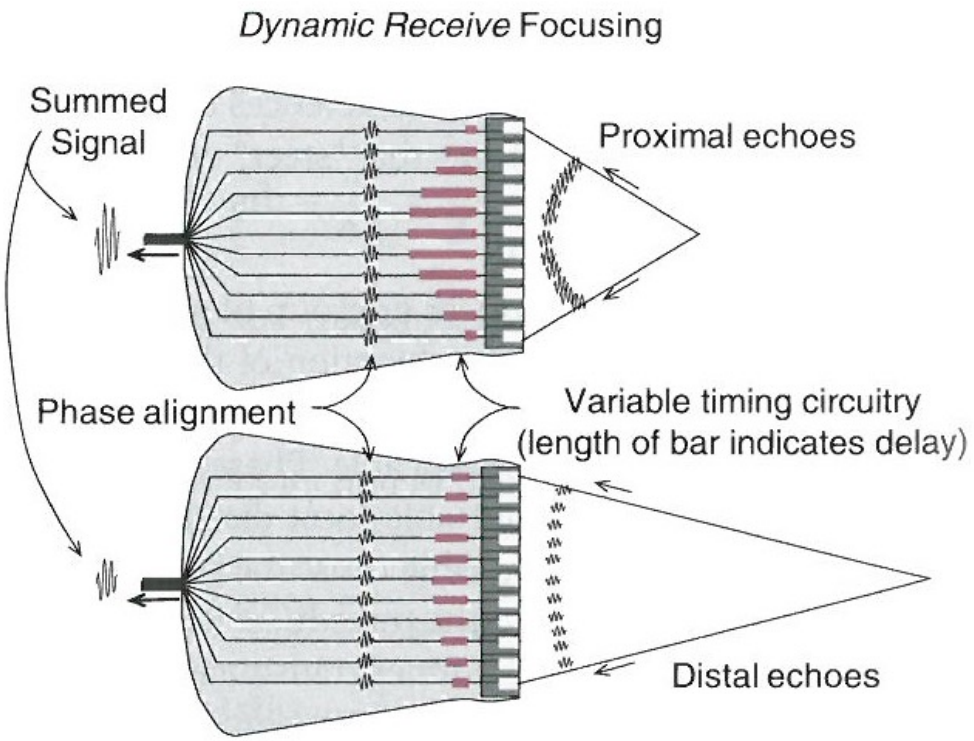
The phased array transducer



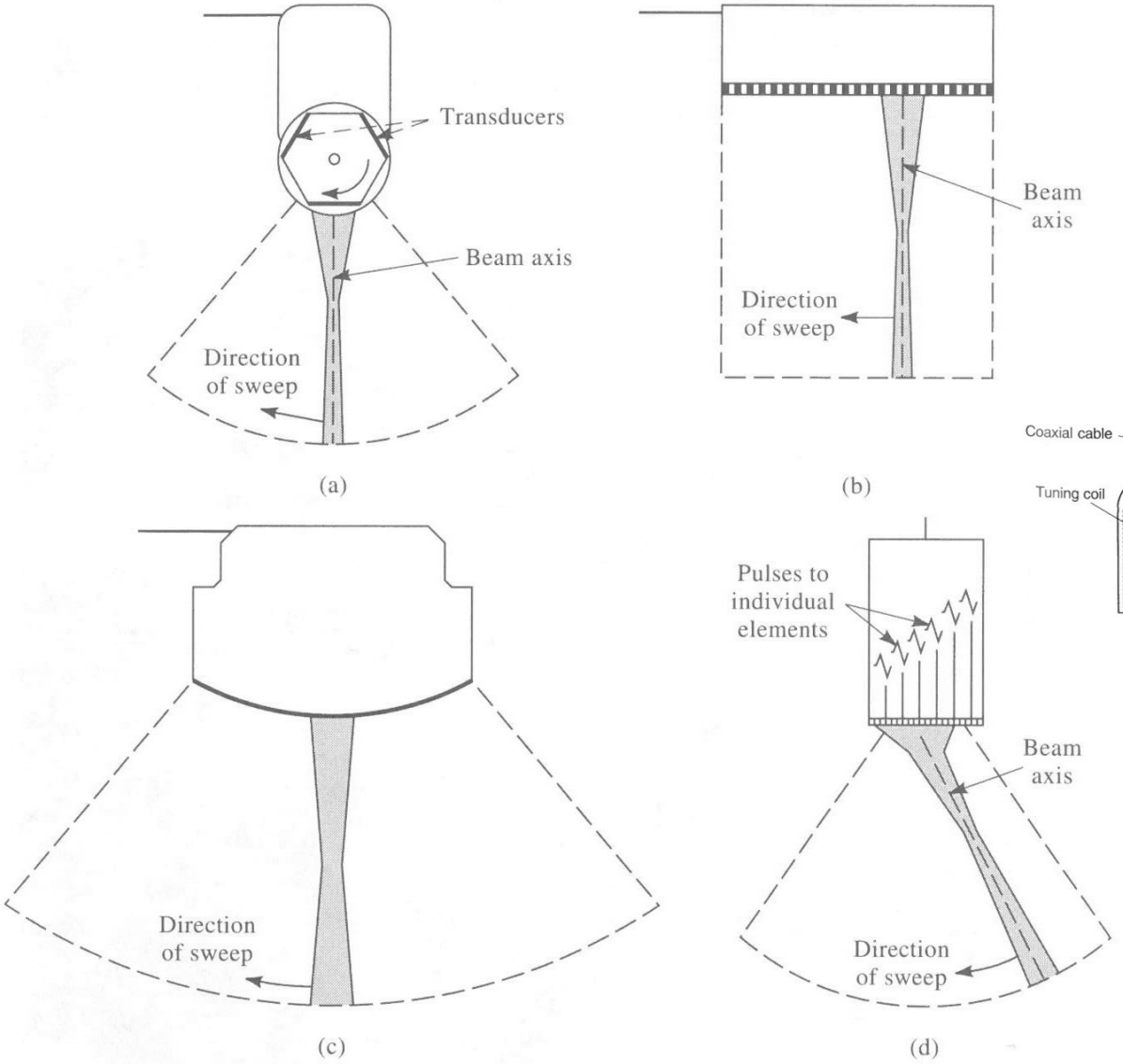
■ **FIGURE 14-15** A phased-array transducer assembly uses all elements to produce the ultrasound beam. Focusing is achieved by implementing a programmable delay time (beam former electronics) for the excitation of the individual transducer elements (focusing requires the outer elements in the array be energized first). Phase differences of the individual ultrasound pulses result in a minimum beam diameter (the focal distance) at a predictable depth in tissue.

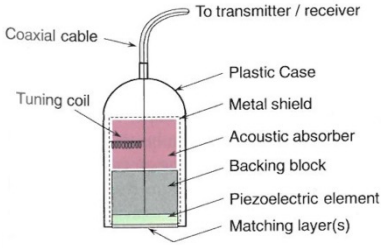
Dynamic receive focusing

■ FIGURE 14-16 Dynamic receive focusing. All transducer elements in the phased array are active during the receive mode, and to maintain focus, the receive focus timing must be continuously adjusted in order to compensate for differences in arrival time across the array as a function of time (depth of the echo). Depicted are an early time (top illustration) of proximal echo arrival and a later time of distal echo arrival. To achieve phase alignment of the echo responses by all elements, variable timing is implemented as a function of element position after the transmit pulse in the beam former. The output of all phase-aligned echoes is summed.



4 different probe-principles





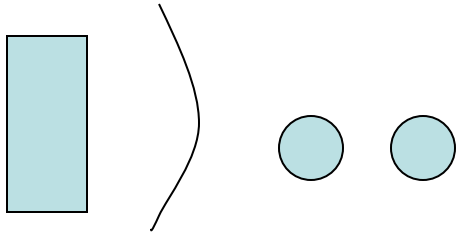
■ FIGURE 14-8 A single-element ultrasound transducer assembly is comprised of the piezoelectric ceramic, the backing block, acoustic absorber, tuning coil and metal shield, transducer housing, coaxial cable and voltage source, and the ceramic to tissue matching layer.

Figure 12.30 Ultrasound scan heads. (a) Rotating mechanical device. (b) Linear phased array which scans an area of the same width as the scan head. (c) Curved linear array can sweep a sector. (d) Phasing the excitation of the crystals can steer the beam so that a small transducer can sweep a large area.

Two types of resolution

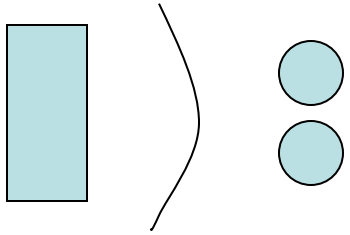
Axial resolution: Ability to discriminate two objects in parallell to the beam.

Best at high frequencies



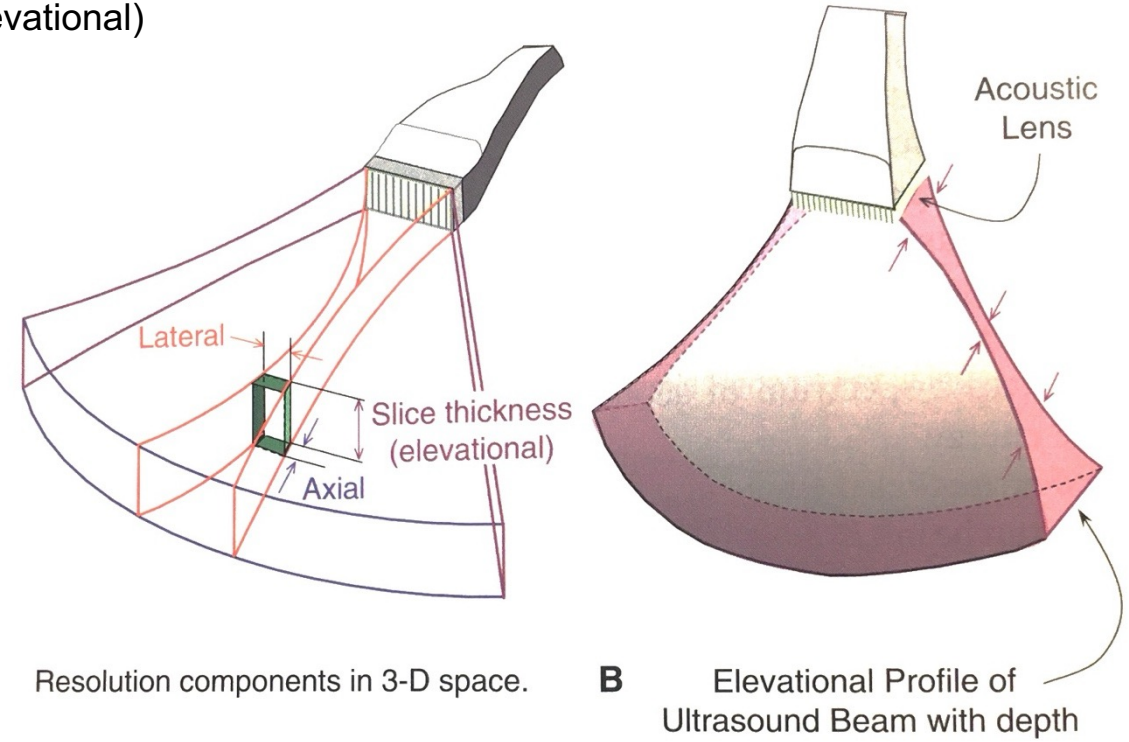
Lateral resolution: Ability to discriminate two objects perpendicular to the beam

Best at the focal zone



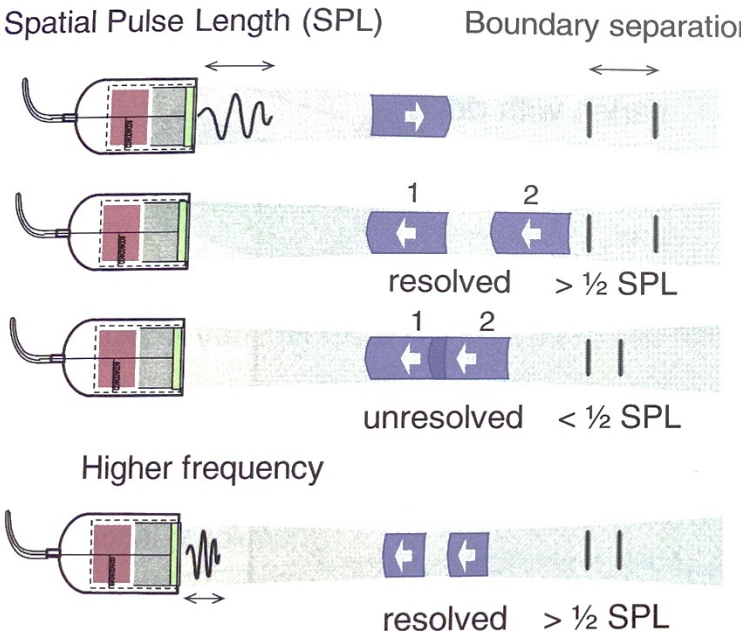
Axial resolution

Resolution = ability to discern between two closely spaced objects in the direction of the beam (axial), perpendicular to the beam (lateral) or perpendicular to the image plane (elevational)



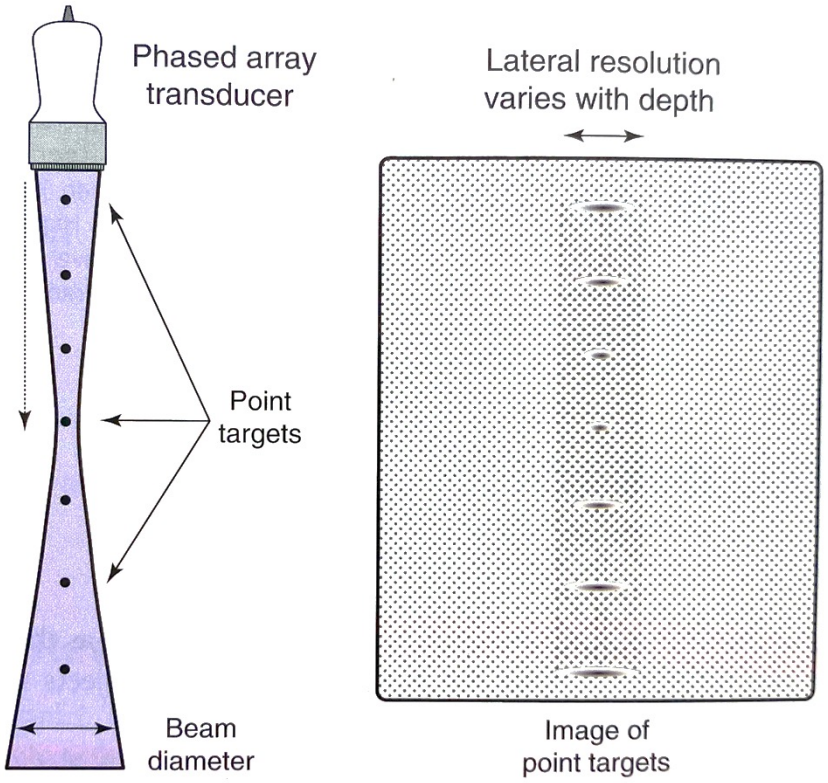
■ FIGURE 14-19 **A.** The axial, lateral, and elevational (slice-thickness) contributions in three dimensions are shown for a phased-array transducer ultrasound beam. Axial resolution, along the direction of the beam, is independent of depth; lateral resolution and elevational resolution are strongly depth dependent. Lateral resolution is determined by transmit and receive focus electronics; elevational resolution is determined by the height of the transducer elements. At the focal distance, axial is better than lateral and lateral is better than elevational resolution. **B.** Elevational resolution profile with an acoustic lens across the transducer array produces a focal zone in the slice-thickness direction.

Axial resolution



■ **FIGURE 14-20** Axial resolution is equal to ½ SPL. Tissue boundaries that are separated by a distance greater than ½ SPL produce echoes from the first boundary that are completely distinct from echoes reflected from the second boundary, whereas boundaries with less than ½ SPL result in overlap of the returning echoes. Higher frequencies reduce the SPL and thus improve the axial resolution, as shown in the lower diagram.

Lateral resolution



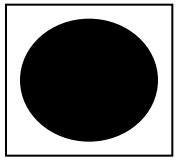
■ **FIGURE 14-21** Lateral resolution indicates the ability to discern objects perpendicular to the direction of beam travel and is determined by the beam diameter. Point objects in the beam are averaged over the effective beam diameter in the ultrasound image as a function of depth. Best lateral resolution occurs at the focal distance; good resolution occurs over the focal zone.

Ultrasound waves

Eccocharacteristics

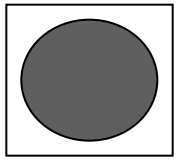
Anechoic (ecco-free)

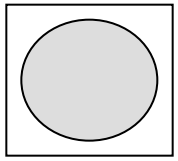
- Tissue without acoustic interface looks black



Hypoechoic (poor ecco)

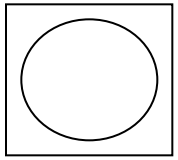
- Tissue with low ecco-genesity will be dark grey
- Tissue with medium ecco-genesity will be light grey





Hyperechoic

- Ecco rich tissue, from light grey to white

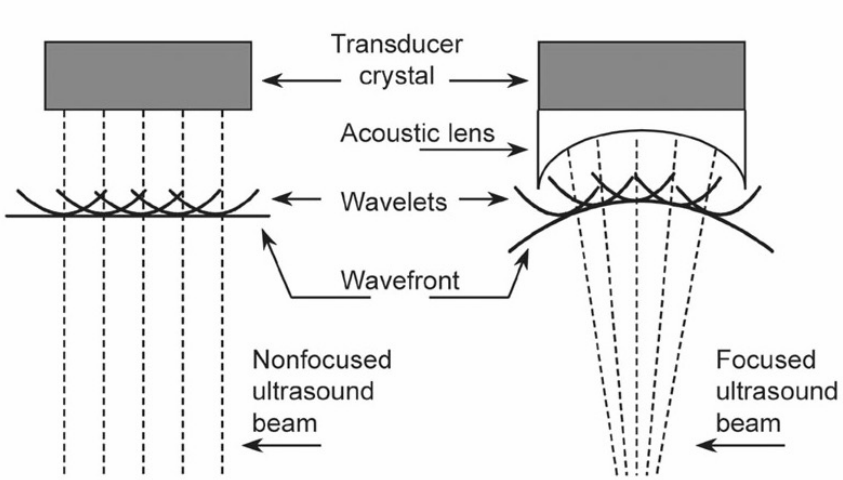


Modern ultrasound devices



Ultrasound transducer frequency vs resolution

- A 15 MHz scan has very good resolution but penetrates a short distance only
- A 3 MHz scan can penetrate far into the body, but the resolution is poor
  - High frequency = High resolution
  - High frequency = Poor range



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Ultrasound (US), A-mode (amplitude)

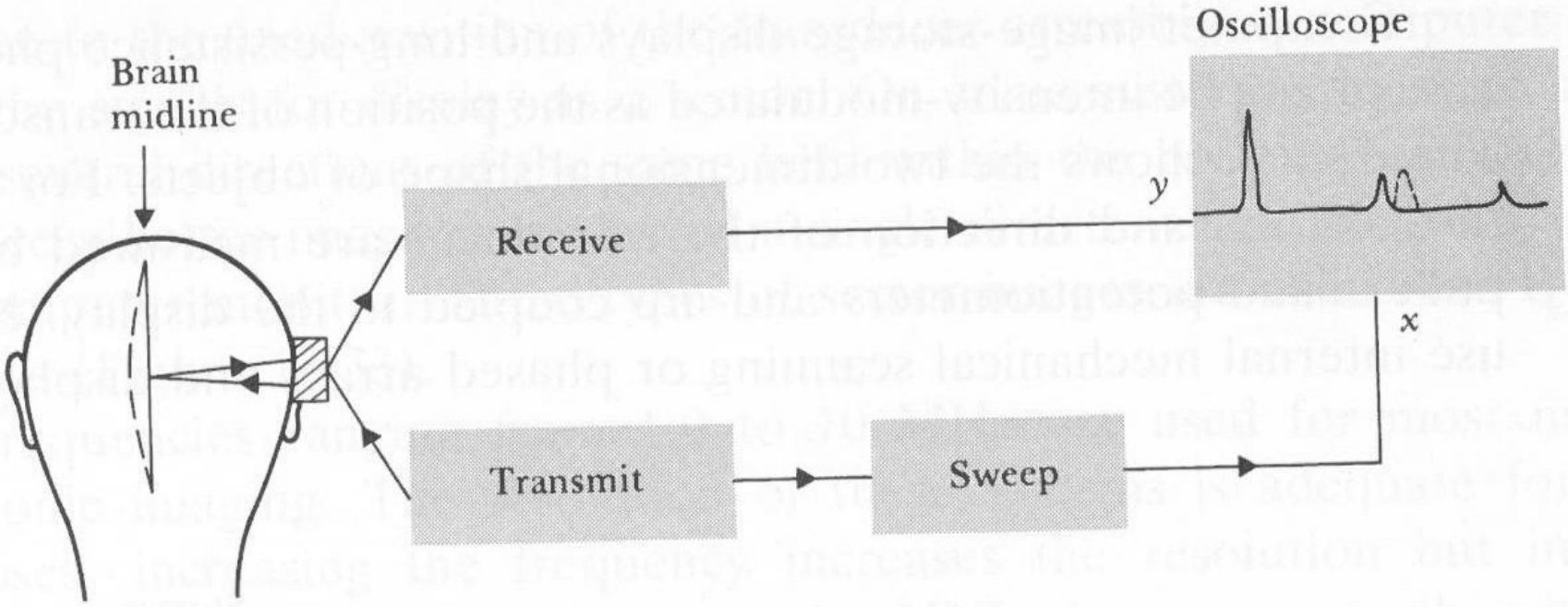


Figure 12.31 A-mode scan of the brain midline

Time delay between transmitted pulse and its echo is a maesure of the depth of the tissue interface
Each change of tissue type, a reflection results
Displacement of the brain midline. Scanning from both sides, should be symmetric, a tumor or blood clot could move the cerebral hemispheres to shift the midline
Obsolete now

Time motion US, M-mode

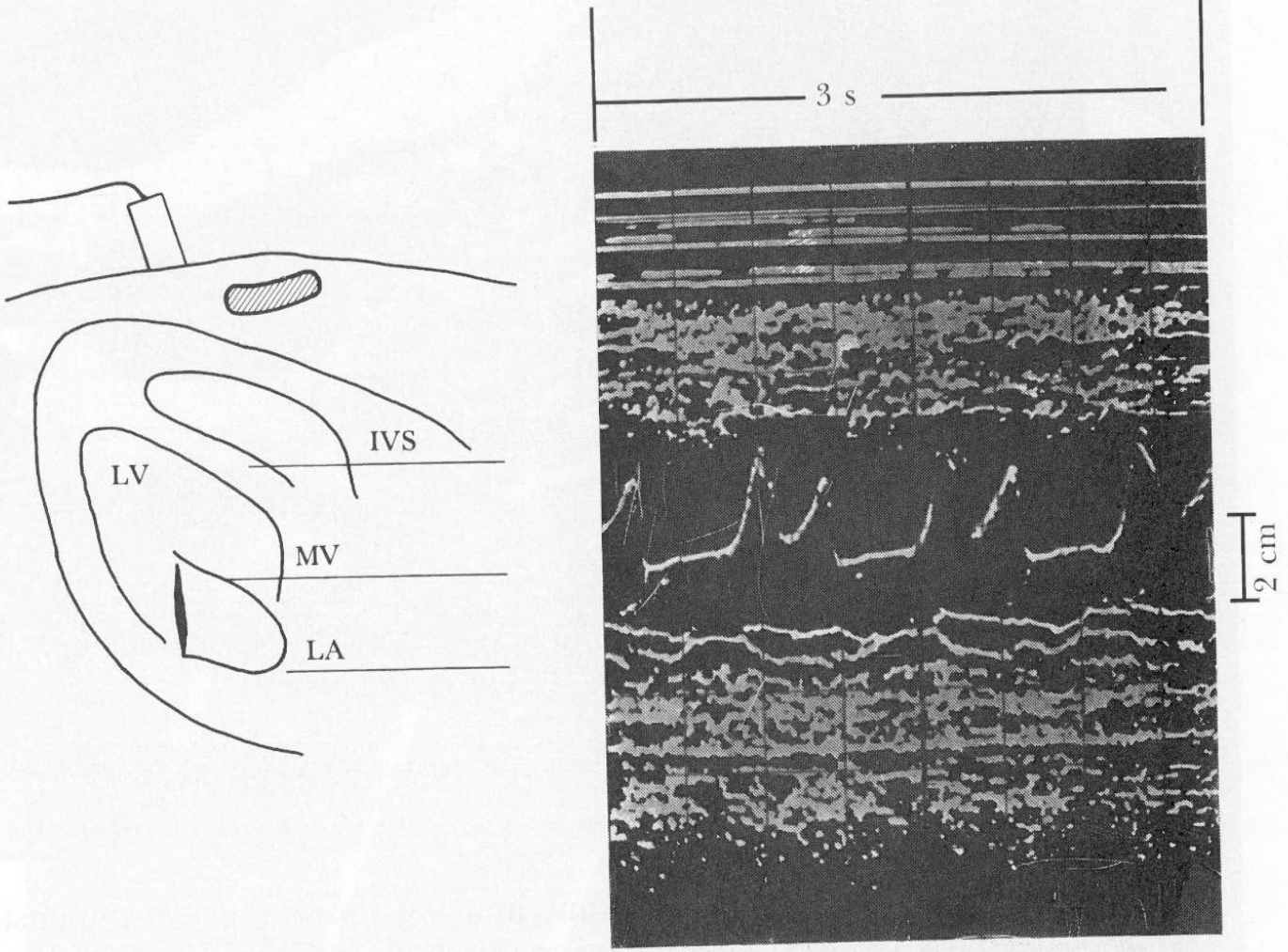
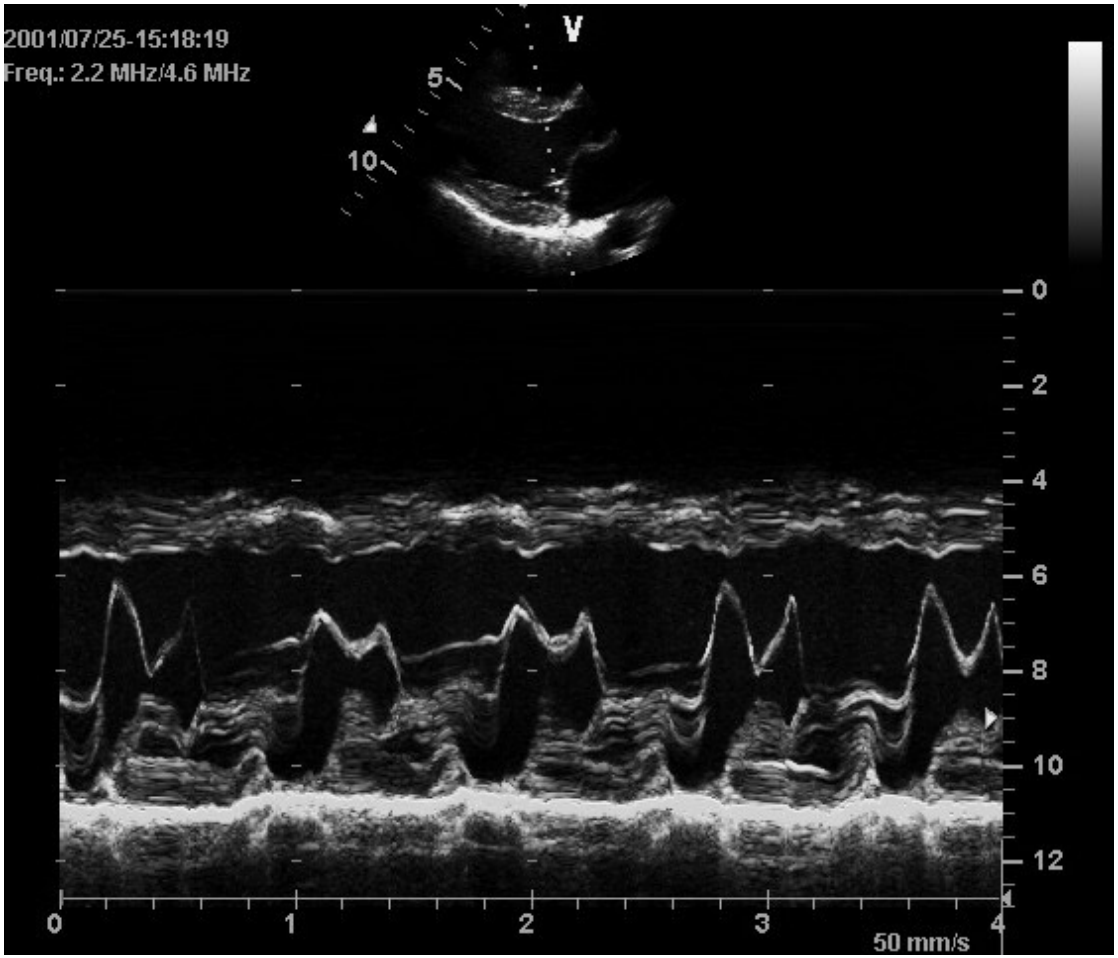


Figure 12.32 **Time-motion ultrasound scan of the mitral valve of the heart** The central trace follows the motions of the mitral valve (MV) over a 3-s period, encompassing three cardiac cycles. The other traces correspond to other relatively static structures, such as the interventricular septum (IVS) and the walls of the left atrium (LA).

Strength of the echo is used to modulate intensity of the display against echo-return time with zero time at the top of the display, image can be shown as moving to the right.

Position of tissues as a function of time = Time motion scan

M-mode Ultrasound (motion)



UiO

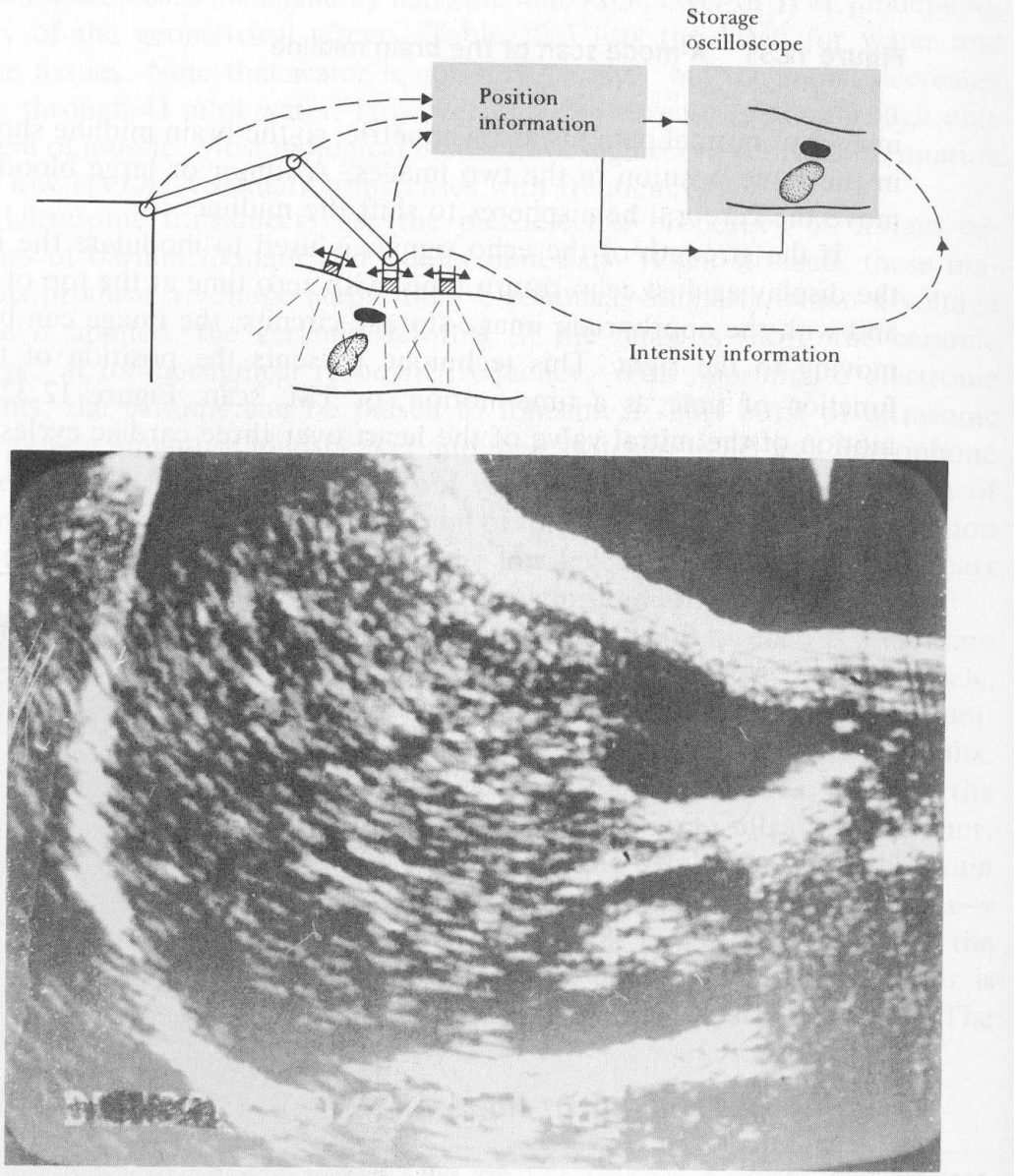


Figure 12.33 (a) B-mode ultrasonic imaging shows the two-dimensional shape and reflectivity of objects by using multiple-scan paths. (b) This B-mode ultrasonic image, which corresponds to (a), shows the skin of the belly at the top right, the liver at the left center, the gall bladder at the right above center, and the kidney at the right below center. The bright areas within the kidney are the collecting ducts.

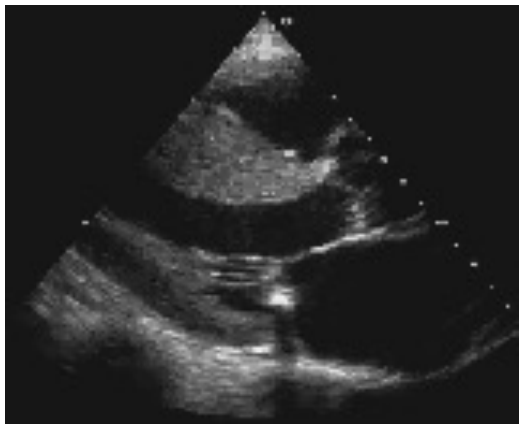
B-mode

B-mode (Brightness)

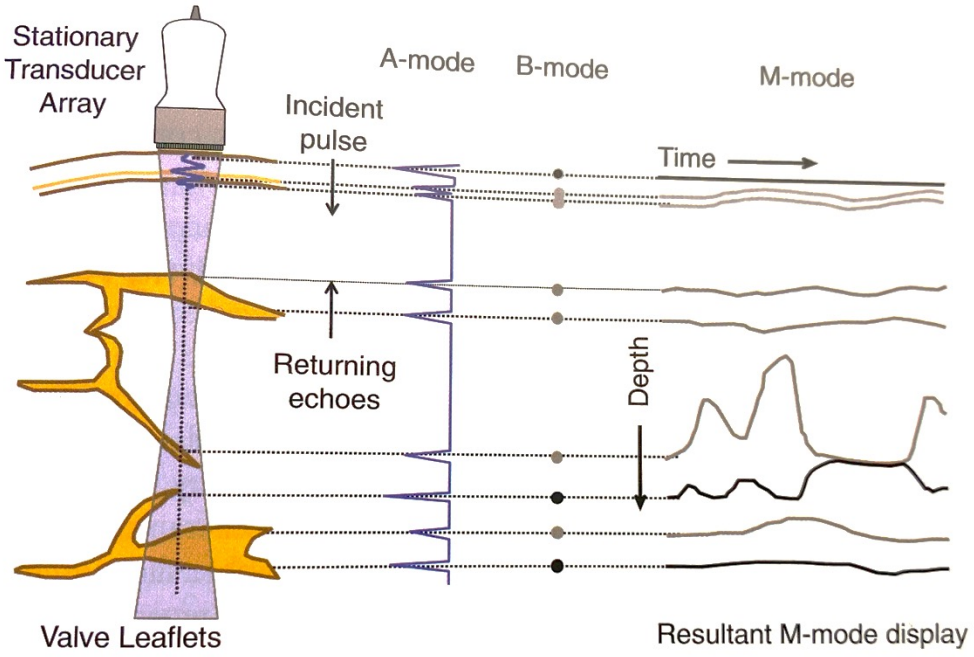
Same as A-mode, but twodimensional graphical display where brightness indicates the amplitude to reflected sound

Most modern US-systems is realtime 2D or 3D. Multiple crystals or mobile crystals

Up to 100 images per second

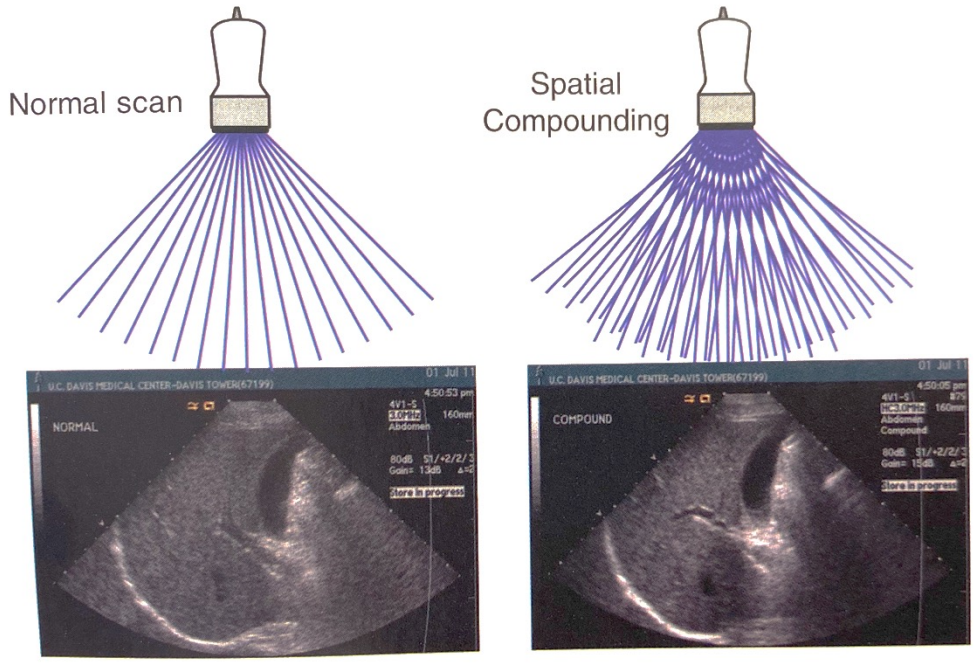


Summarized A, B og M-mode



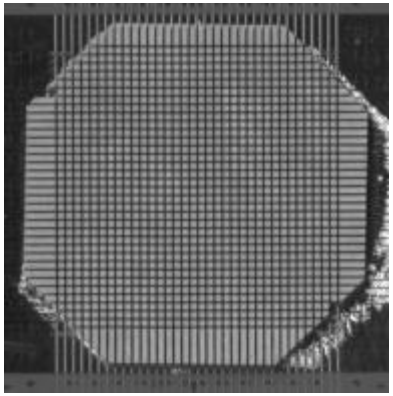
■ **FIGURE 14-29** Ultrasonic data are acquired with a stationary transducer or transducer array. The A-mode data (vertical ***blue*** trace) represent echo amplitudes during one pulse-echo period. The amplitudes are encoded to brightness (B-mode) as a series of variable intensity dots. The A-mode line and corresponding B-mode dots change position as the valve leaflets move within the stationary beam. By deflecting the dots horizontally in time on a storage display, motion graphs (M-mode) are created, depicting the periodic (or lack of periodic) motion.

Summarized A, B og M-mode



■ **FIGURE 14-33** A vector phased array transducer (**left**) in the normal acquisition mode insonates tissues to yield a sector image. Compound scanning (**right**) uses ultrasound beams produced at several angles achieved by electronic steering (three are shown above) to acquire directional acoustic image data subsequently averaged to produce a single image. Note the oversampling patterns in this mode, and since the scan lines are acquired sequentially, the frame rate is reduced by the number of insonation angles used to produce the compound image.

Piezoelectric array-probe





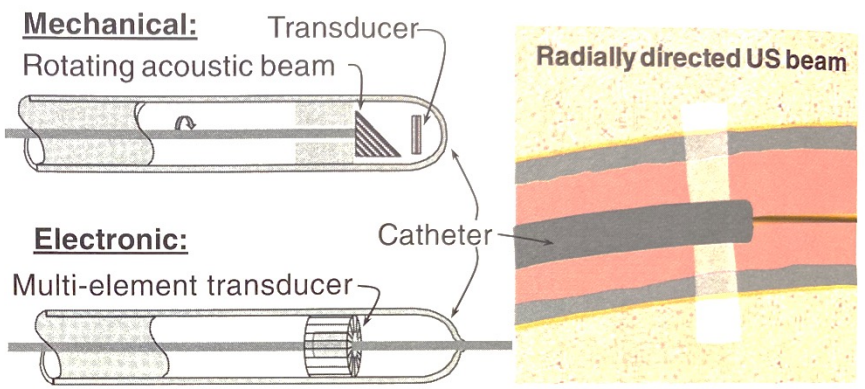
Volumetric scan realtime

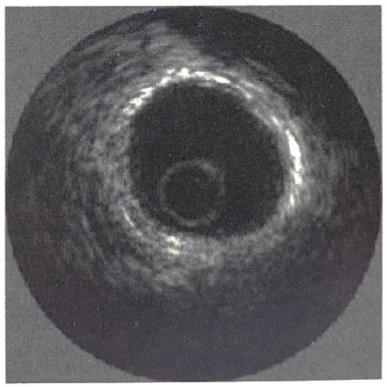
Possibilities for multiplan reslicing retrospectively

Realtime volume rendering

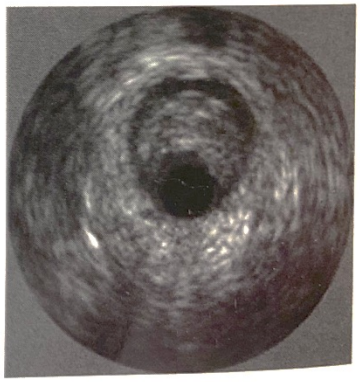
Piezoelectric array-probe

■ **FIGURE 14-50** Intravascular ultrasound: devices and images. Catheter-mounted transducer arrays provide an acoustic analysis of the vessel lumen and wall from the inside out. Mechanical (rotating shaft and acoustic mirror with a single transducer) and electronic phased-array transducer assemblies are used. Images show a normal vessel lumen (**lower left**) and reduced luminal stenosis and plaque buildup (**lower right**).



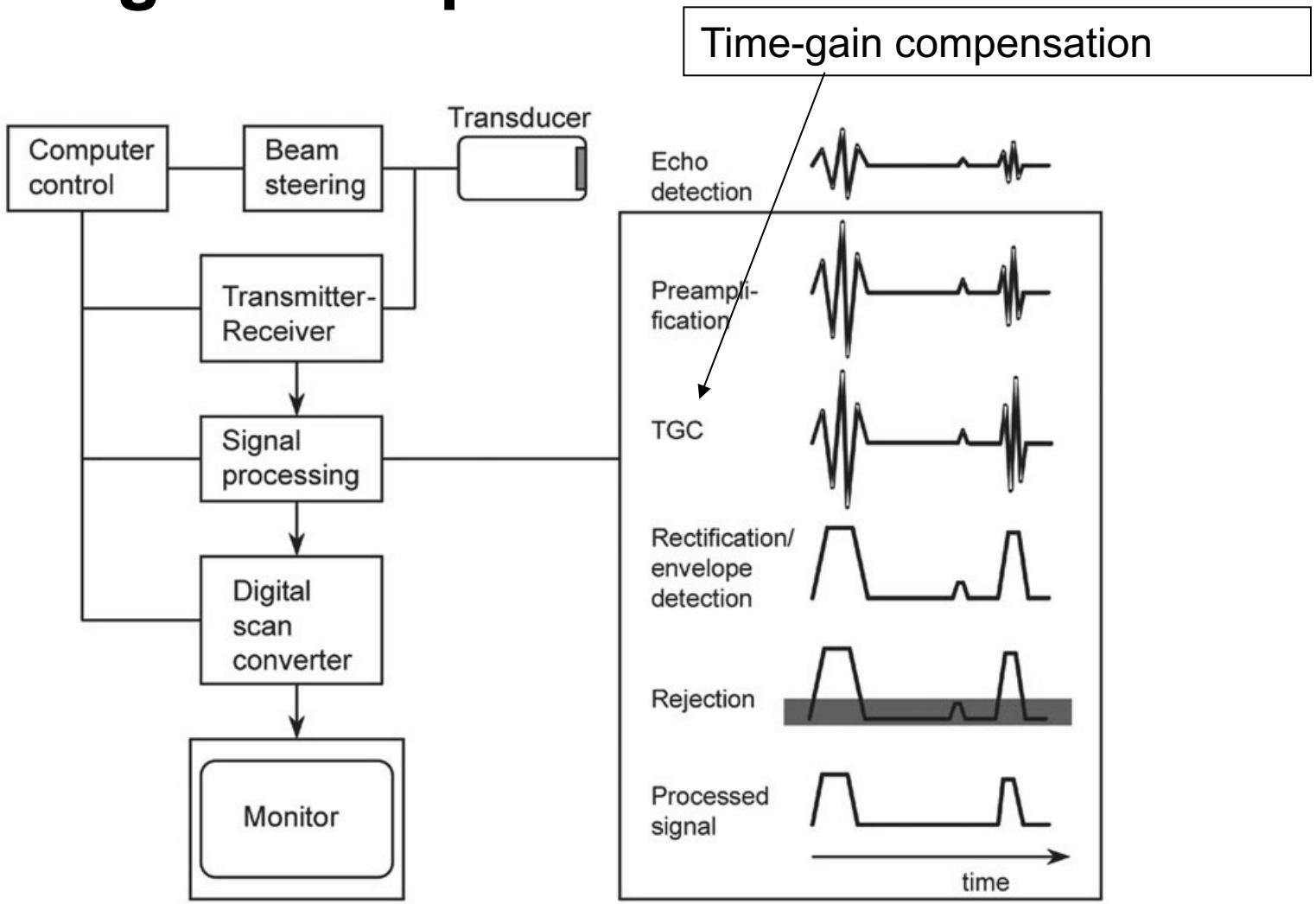


Normal vasculature



Elliptical stenosis

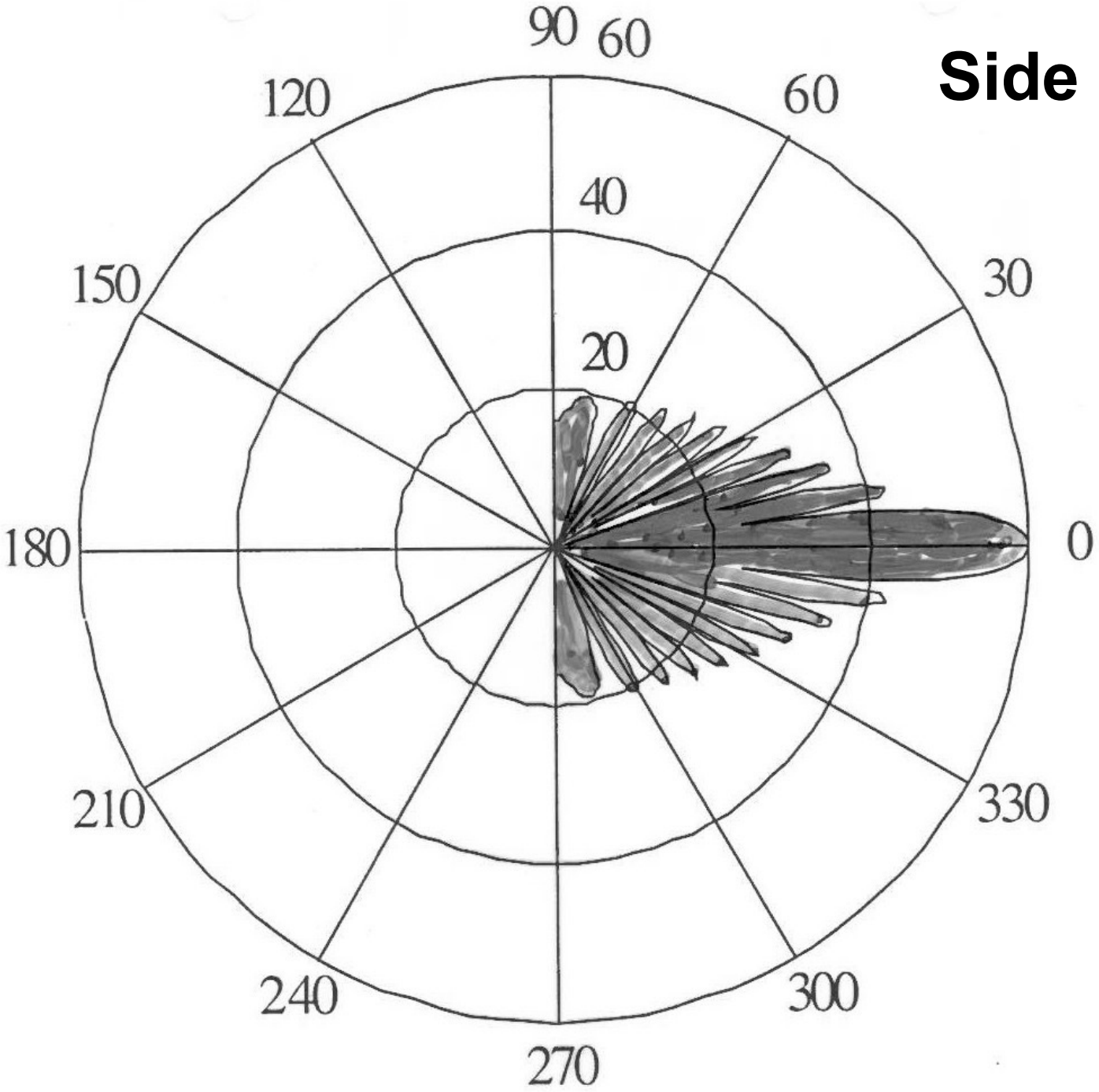
Time-gain compensation



Kilde: Alejandro Frangi

Time-gain compensation: Reducing artifacts in the B-mode intensity images by increasing intensity with depth

Side lobes



Exercise

Form groups of 2 or 3 students, and discuss:

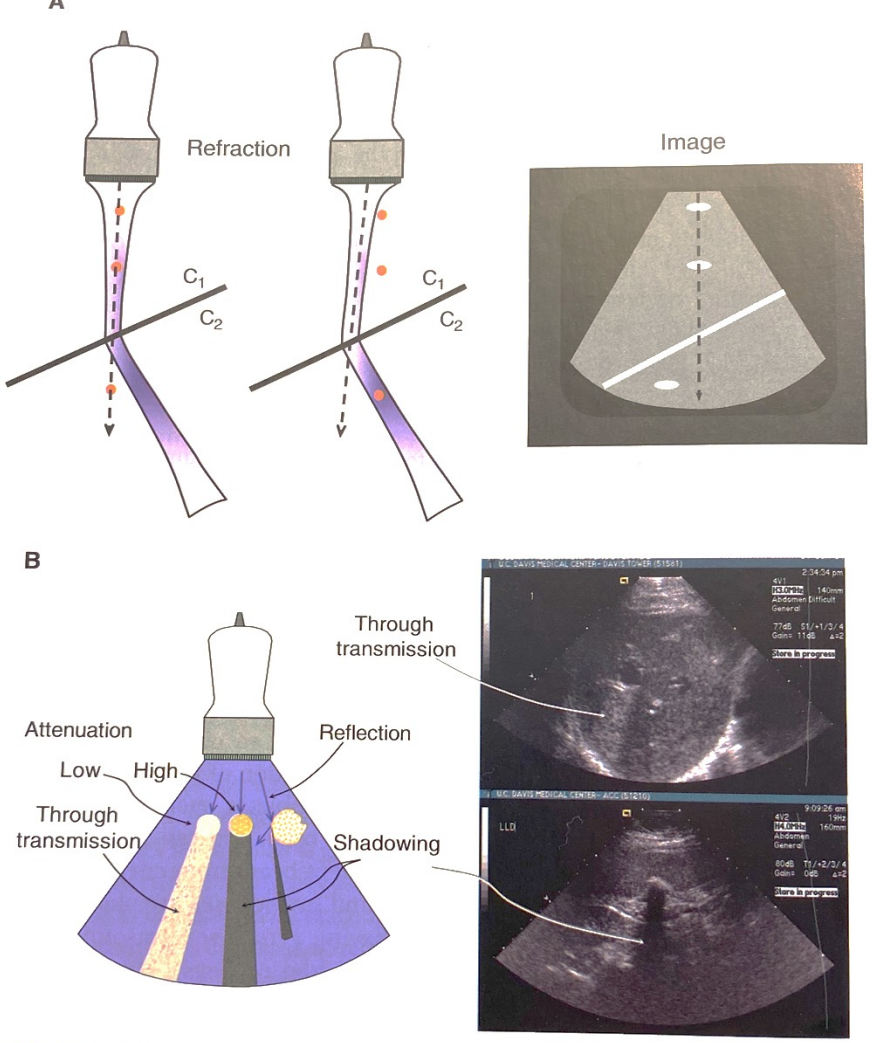
- What are the main sources of error in a regular Ultrasound system?



http://integrativeosteopathy.com.au/wp-content/uploads/2015/08/Exercise.jpg

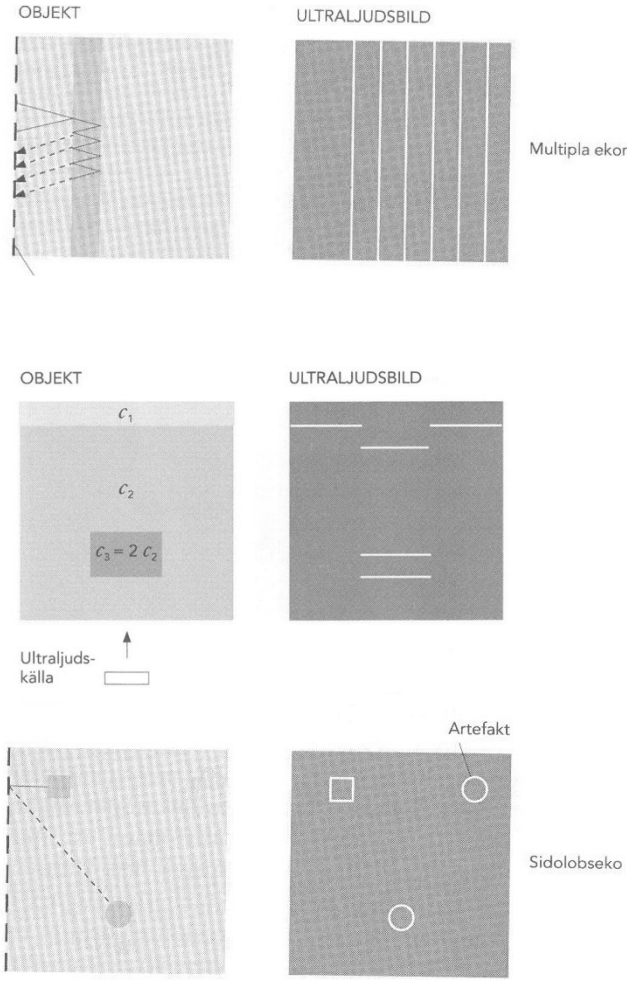
UiO : Department of Physics
University of Oslo

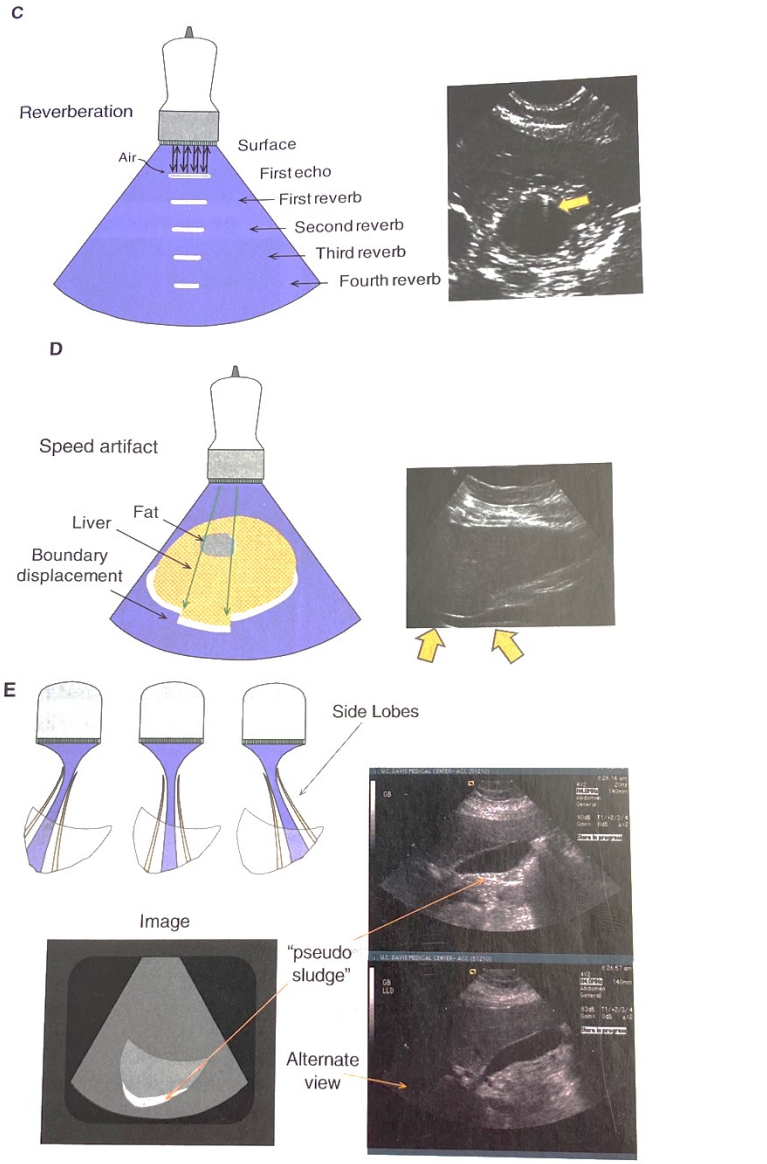
Refraction



■ **FIGURE 14-52** **A.** Refraction is a change in the direction of the ultrasound beam that results from nonperpendicular incidence at a boundary where the two tissues do not have the same speed of sound. During a scan, anatomy can be missed and/or dislocated from the true position. **B.** Attenuation and reflection of the ultrasound beam cause intensity changes. Enhancement occurs distal to objects of low attenuation, manifested by a hyperintense signal, while shadowing occurs distal to objects of high attenuation, resulting in a hypointense signal. At the curved edges of an organ boundary or mass, nonperpendicular reflection can cause distal hypointense streaks and shadowing. Clinical images show through transmission (top) of a low attenuation cyst and shadowing (bottom), caused by high attenuation gallstones. **C.** Reverberation commonly occurs between to strong reflectors, such as an air pocket and the transducer array (left diagram) or with calcium deposits and internal reflections (right image). The echoes bounce back and forth between the two boundaries and produce equally spaced signals of diminishing amplitude in the image. This is often called a "comet-tail" artifact.

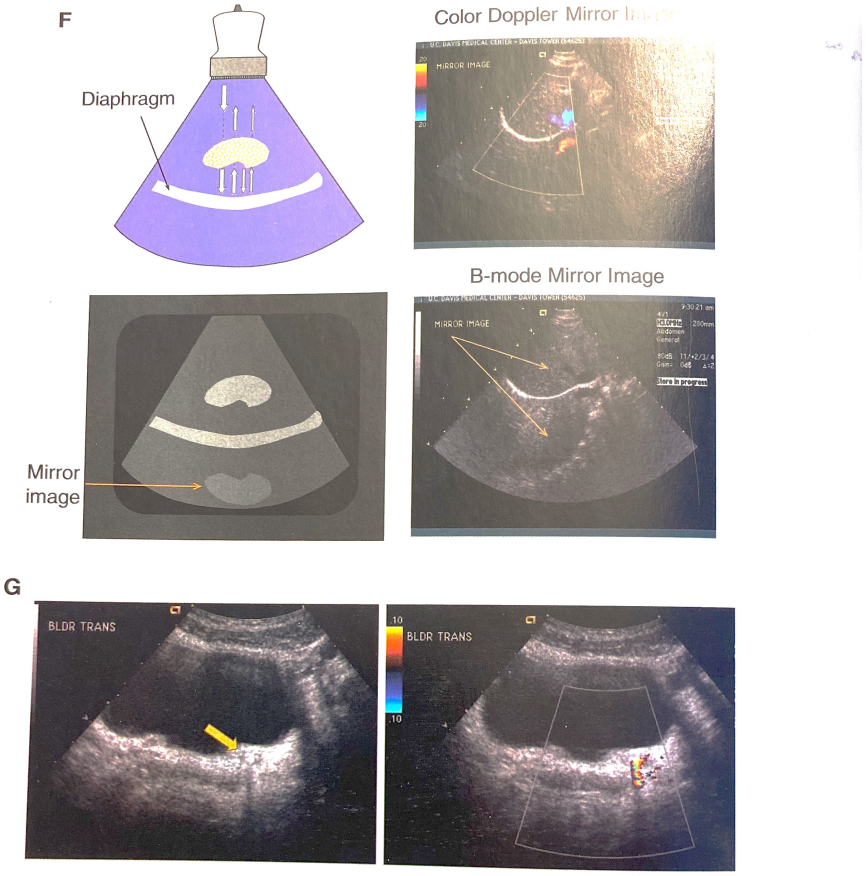
Reverberation





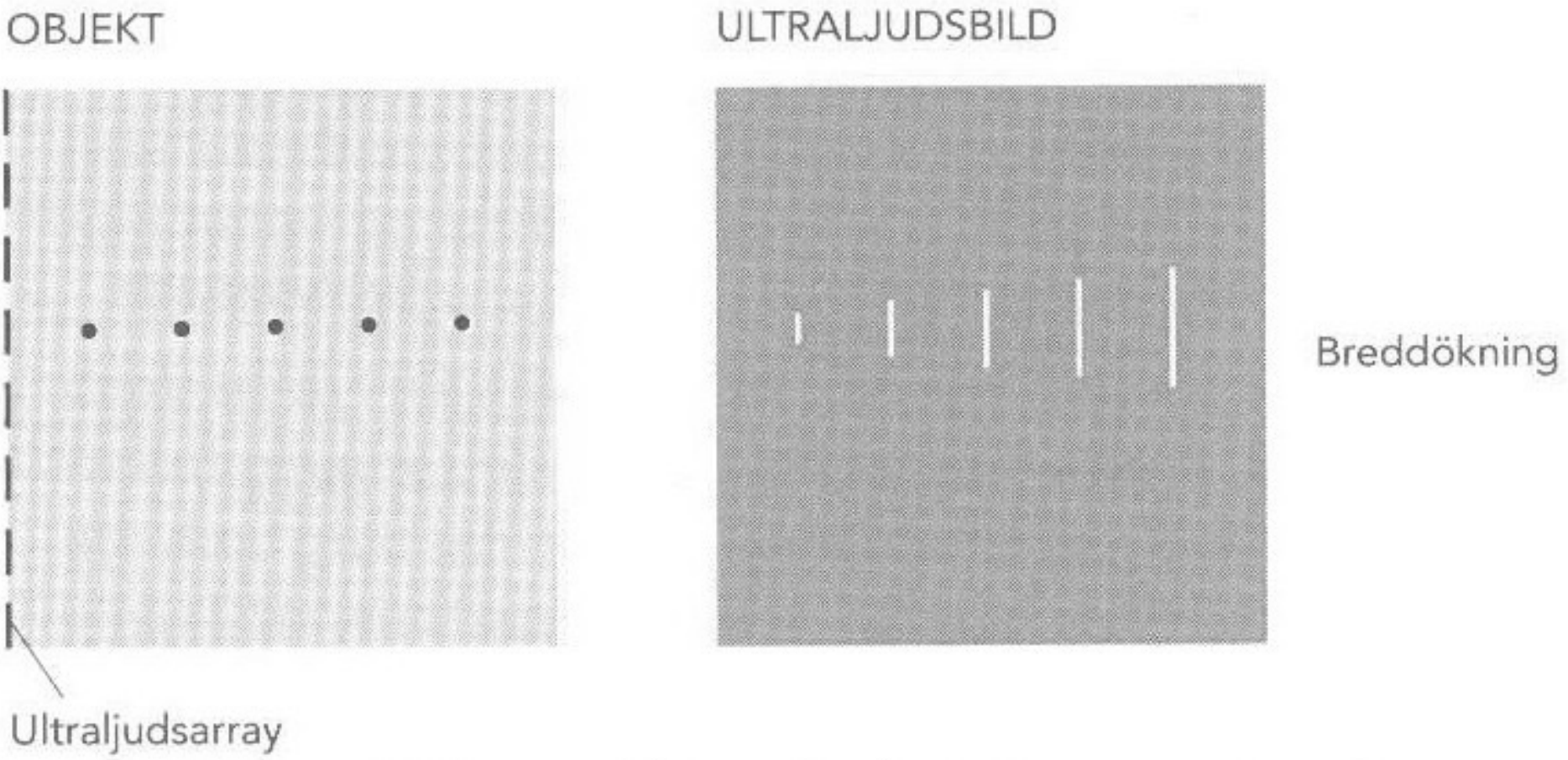
■ **FIGURE 14-52** (*Continued*) **D.** Speed of sound variation in the tissues can cause a mismapping of anatomy. In the case of fatty tissues, the slower speed of sound in fat (1,450 m/s) results in a displacement of the returning echoes from distal anatomy by about 6% of the distance traveled through the mass. **E.** Side lobe energy emissions in transducer arrays can cause anatomy outside of the main beam to be mapped into the main beam. For a curved boundary, such as the gallbladder, side lobe interactions can be remapped and produce findings such as "pseudo" sludge that is not apparent with other scanning angles. Clinical images (top) show pseudosludge, which is not evident after repositioning the transducer assembly (bottom).

Mirror image and twinklinng artifact



■ FIGURE 14-52 (*Continued*) **F.** A mirror image artifact arises from multiple beam reflections between a mass and a strong reflector, such as the diaphragm. Multiple echoes result in the creation of a mirror image of the mass beyond the diaphragm. Clinical images show mirror artifacts for color Doppler (**top**) and B-mode scan (**bottom**), where the lower arrow points to the artifact mirrored by the diaphragm. **G.** Twinkling artifact occurs with color flow imaging, caused by strong reflectors such as calcified stones, resulting in a changing mixture of colors indicating flow. On the left is a B-mode image of the bladder and the corresponding color flow image (***inset*** trapezoidal area) demonstrating the twinkling artifact.

Sources of error (2)



Case 13



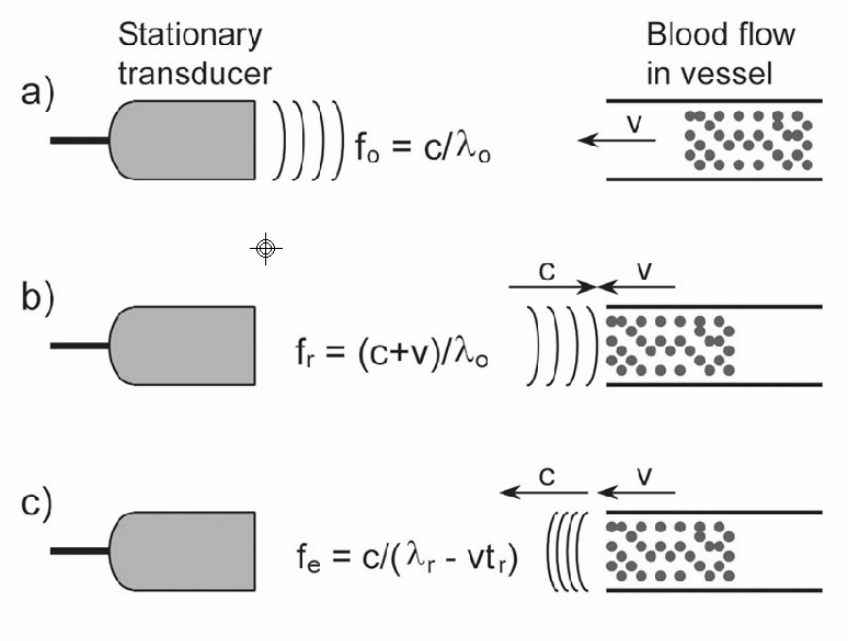
- Despite the positive hCG-test, a transvaginal ultrasound scan revealed an empty uterus, no intrauterine gestational sac, an endometrial thickness of 5.1 mm and free fluid in the pouch of Douglas. However, there was found a tumor in the left ovary, and the hCG levels had now raised to 203 IU/L. There was a need to see the vascularisation of the tumor.

What is then the next step?

Doppler ultrasound

Higher frequency = blood towards the transducer

Lower frequency = blood away from the transducer

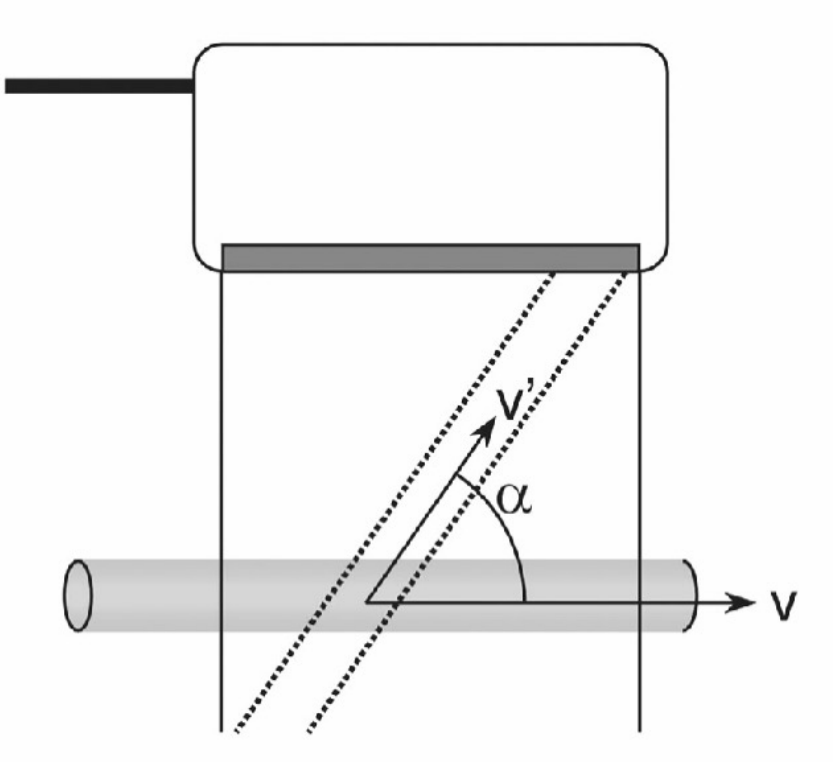


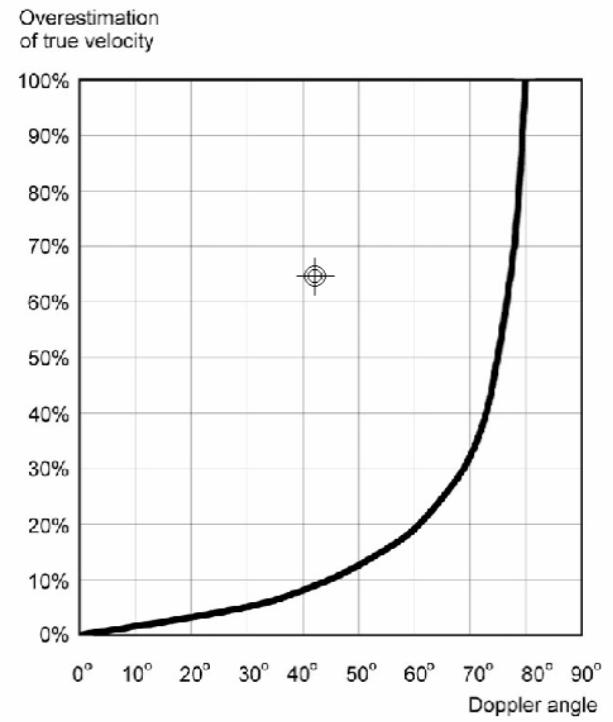
$$f_D = f_e - f_0 = 2 f_0 \frac{v \cdot \cos\alpha}{c}$$

Kilde: Alejandro Frangi

Doppler ultrasound

$$f_D = f_e - f_0 = 2 f_0 \frac{v \cdot \cos\alpha}{c}$$





Doppler image/velocity

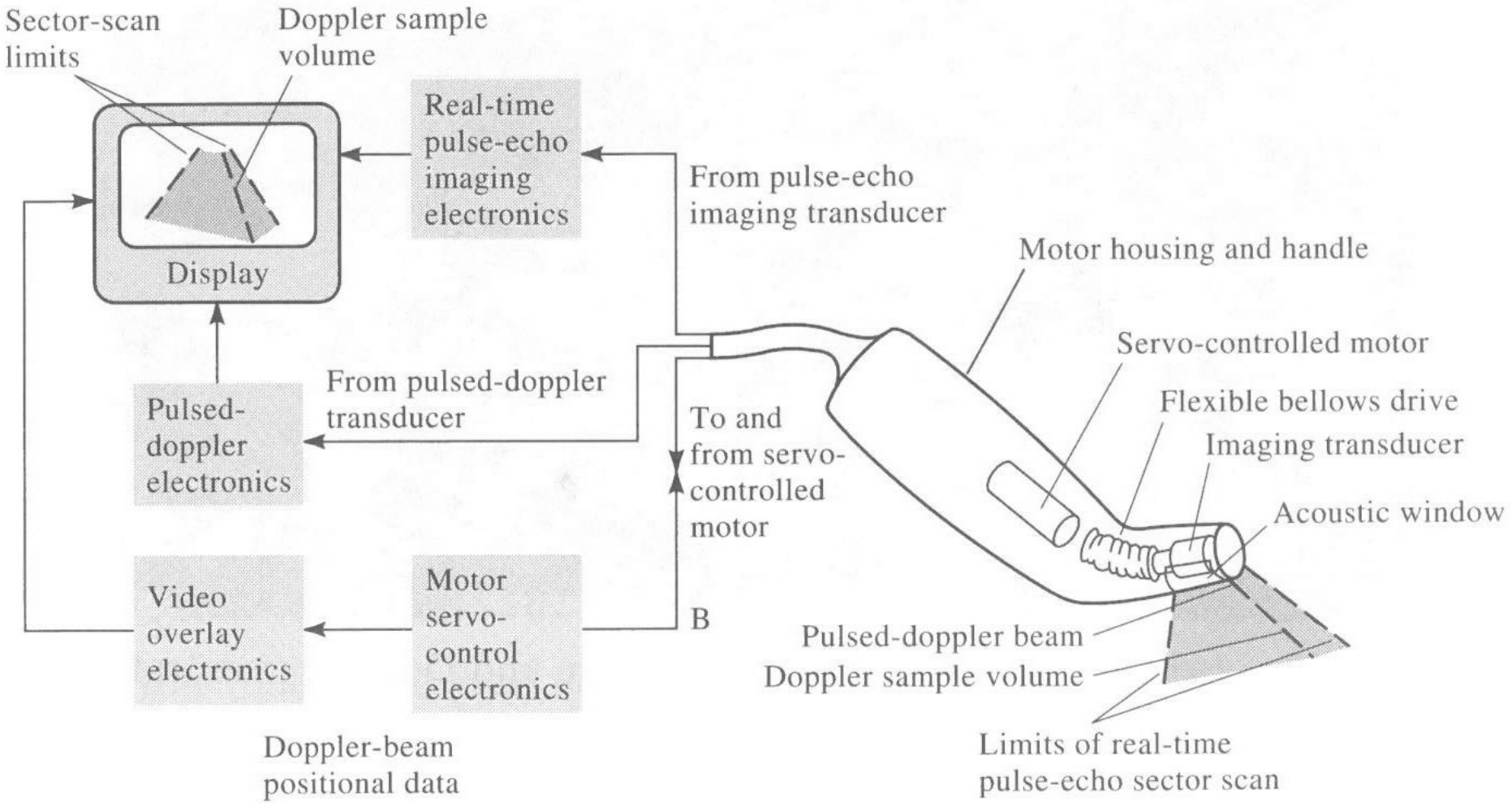
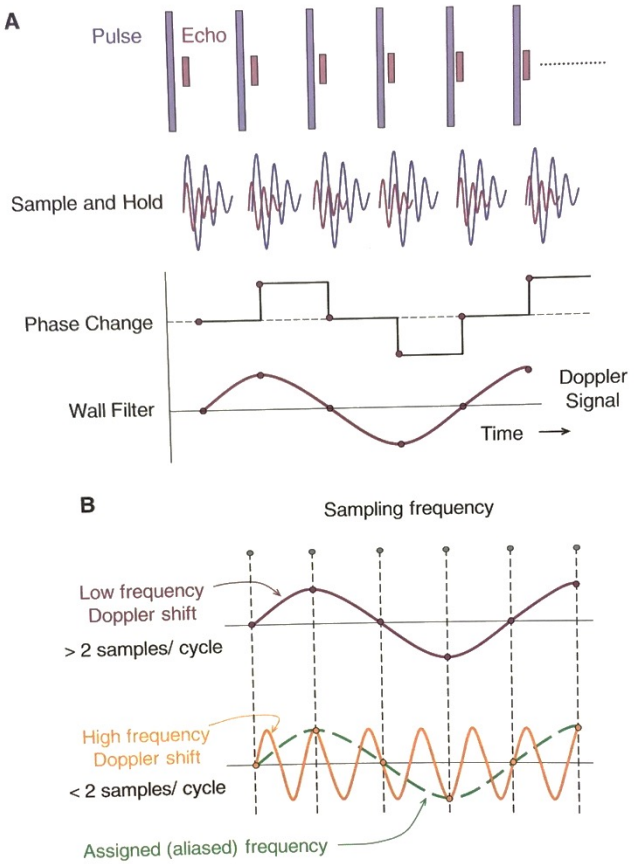


Figure 12.32 The duplex scanner contains a mechanical real-time sector scanner that generates a fan-shaped two-dimensional pulse-echo image. Signals from a selected range along a selected path are processed by pulsed Doppler electronics to yield blood velocity (from Wells, 1984).

Doppler Ultrasound Aliasing



■ FIGURE 14-40 **A.** The returning ultrasound pulses from the Doppler gate are sampled over several pulse-echo cycles (in this example, six times), in order to estimate Doppler shifts (if any) caused by moving blood cells. A sample and hold circuit measures a variation of signal with time (note that the echo [***purple line***] and the pulse [***blue line***] vary in phase, which are recorded and analyzed by Fourier transform methods to determine the Doppler shift frequencies). The wall filter removes the low-frequency degradations caused by transducer and patient motion. **B.** Aliasing occurs when the frequencies in the sampled signal are greater than ½ the PRF (sampling frequency). In this example, a signal of twice the frequency is analyzed as if it were the lower frequency and thus mimics (aliases) the lower frequency.

Bushberg et al, The essential physics of medical imaging

Color doppler

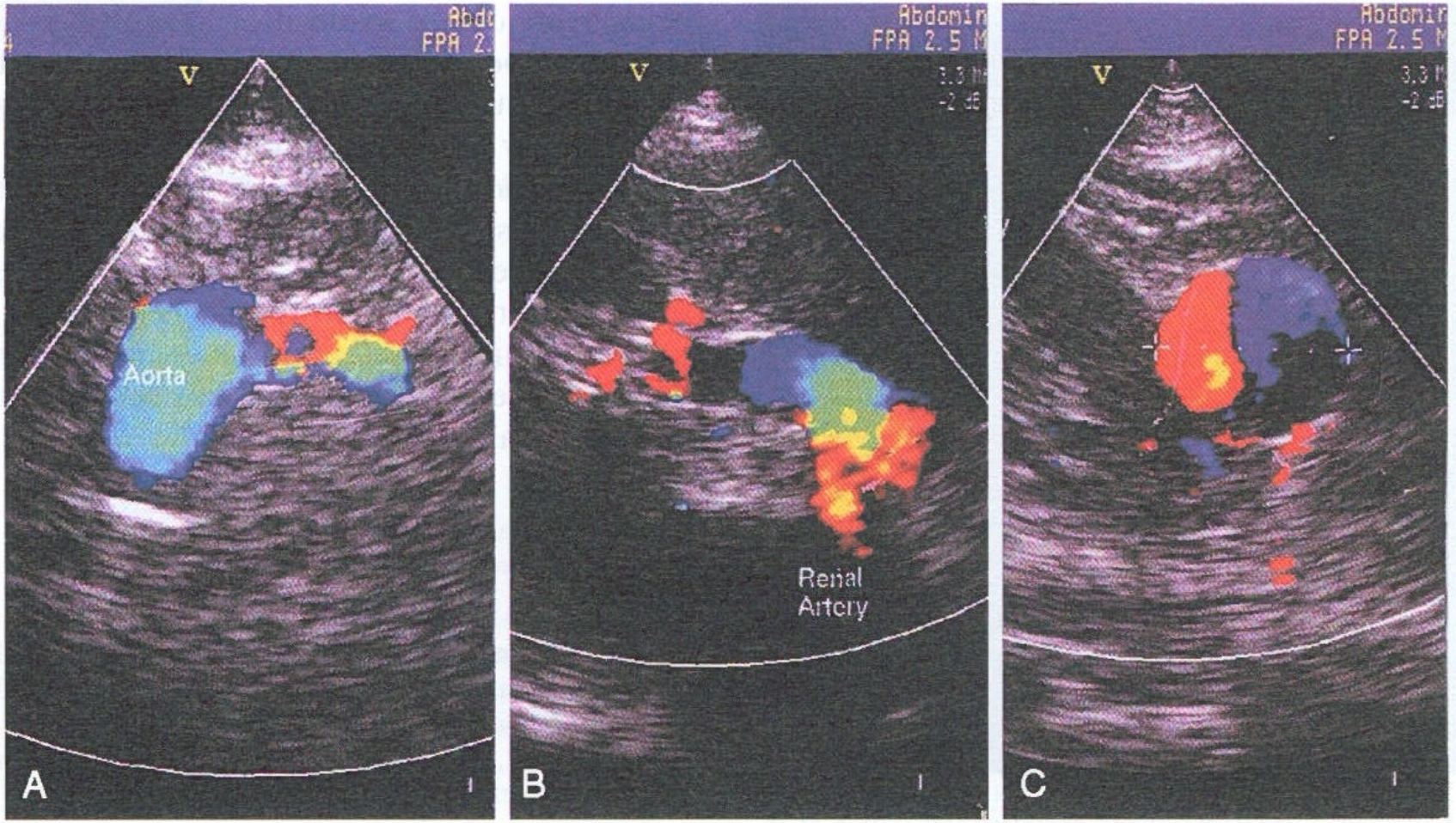


Fig. 1. A–C. Colour ultrasonography examination shows the dilated, tortuous left renal artery. A large aneurysm, partially exophytic, can be seen at the lower pole of the kidney. There is coexistence of both arterial and venous blood flow.

Ultrasound advantages

- Muscles and soft tissue are suitable for US-imaging, especially transitions between solid substances and liquid filled areas.
- Real time images = fast diagnosis. Can also be used to biopsy-guiding
- Shows the organ structure
- No well-known side effects, not unpleasant for the patient
- Small scanners compared to other image modalities
- Inexpensive compared to other image modalities
- Spatial resolution is better at high-frequency US than most of the other modalities

Ultrasound disadvantages

- Unable to penetrate bone tissue
- Poor performance where gas is present
- Limited operating range, dependent on the frequency
- High requrements for the operator, can be difficult to interpret
- Difficult to track back a scanned volume, as soon as the pictures are aquired no exact anchor-pile is available to navigate in the volume

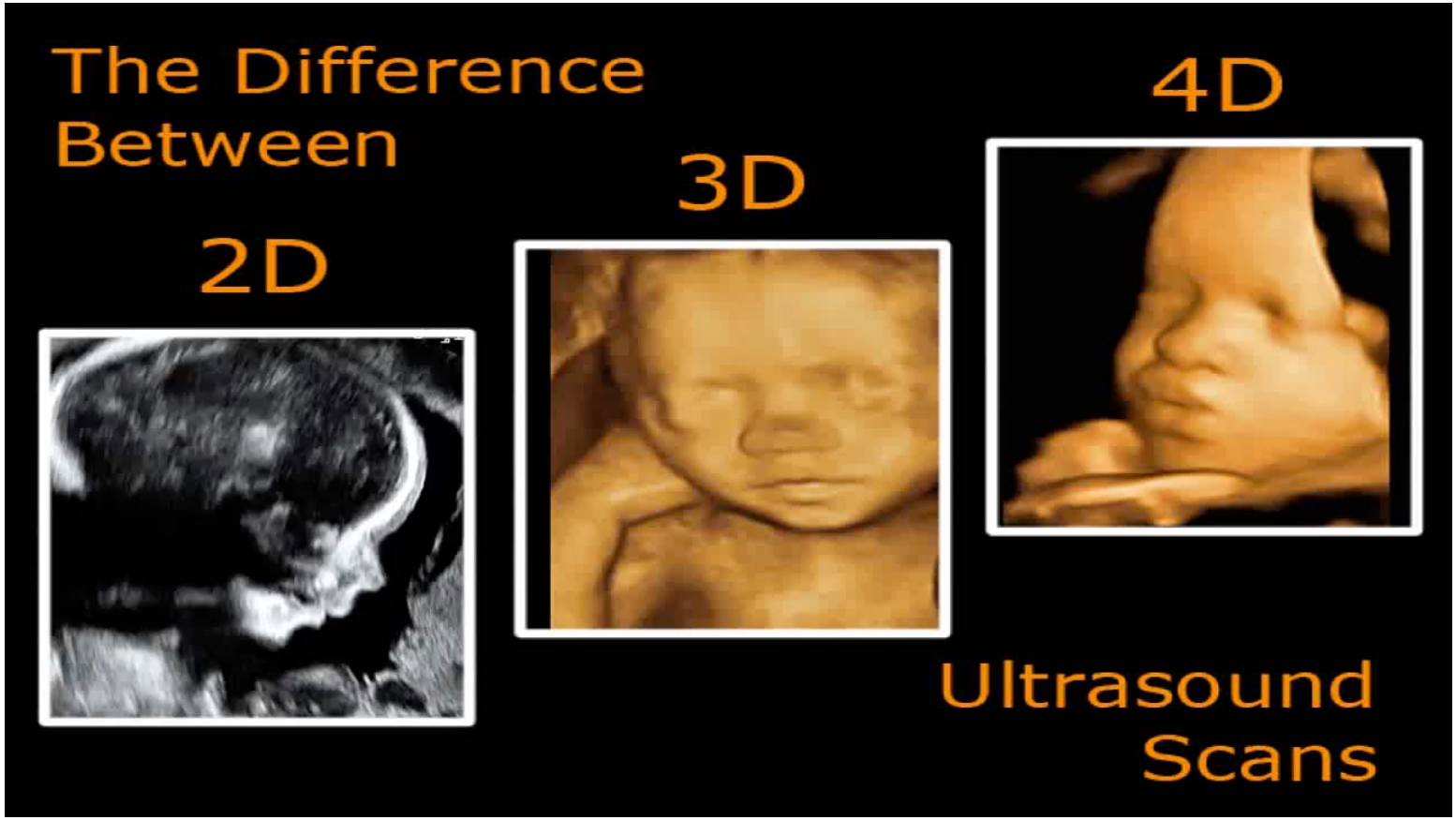
Miniaturization (Vscan)



Source: General Electric. The next stethoscope for the medical doctor?

UiO : Department of Physics
University of Oslo




The Difference Between
2D
3D
4D
Ultrasound Scans

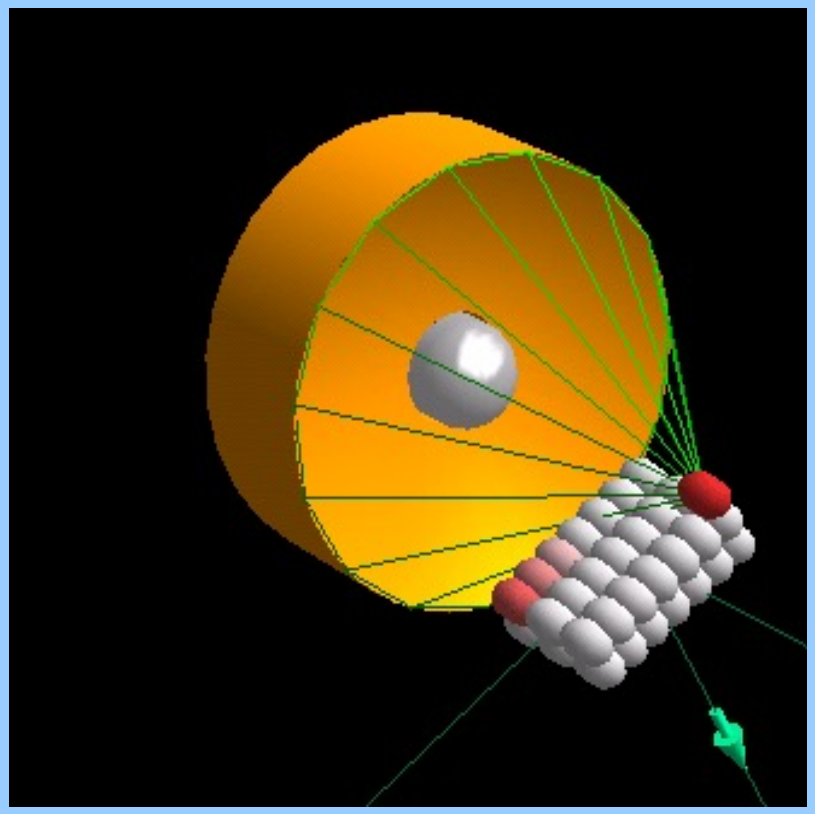
Case 13

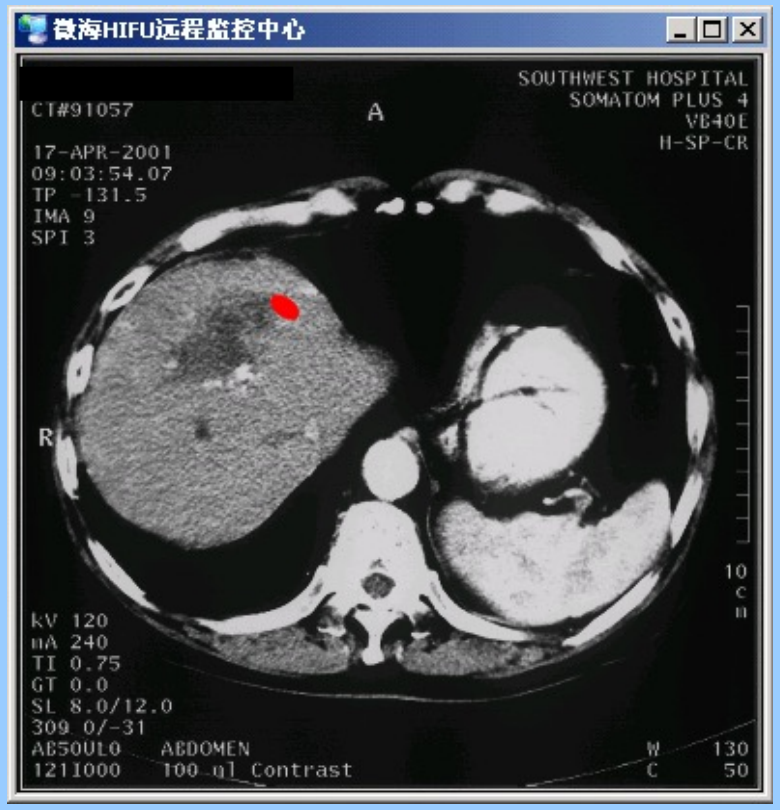


- Color doppler demonstrated high vascularity, and a germ cell tumor of the left ovary was found plausible. This was confirmed after a biopsy of the tumor. She was now scheduled for a left ophorectomy the following week, preferably with focused ultrasound.

Focused ultrasound

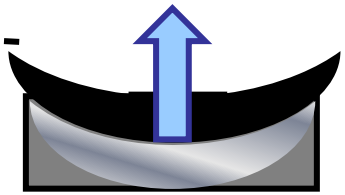
- Volume ablation animation and MR image courtesy of Feng Wu

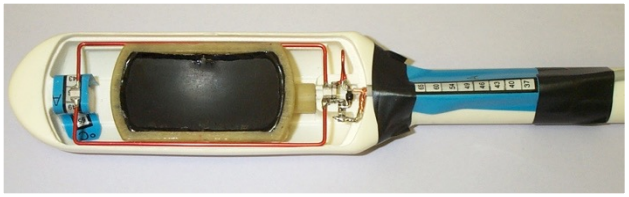




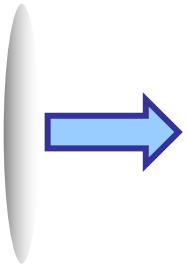
Kennedy JE (2005) Nature Reviews Cancer 18 March 321-327

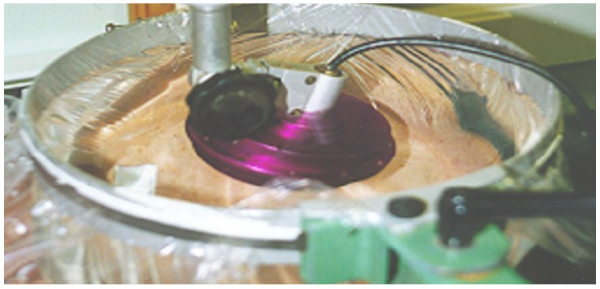
Focused ultrasound



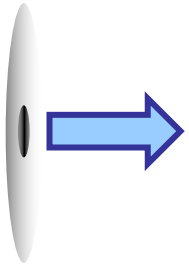


Integrated therapy & MR imaging device for treatment of prostate tumours





Single-element 1.7 MHz extra-corporeal transducer





Single-element HIFU transducer with central aperture for imaging transducer

Frequenses from 0.5 to 4 MHz, intensity up to 20 kWcm^2

Focal length from 3 to 15 cm, Fasearray allows multiple simultaneous foci

Kilde: http://www.maths.bath.ac.uk/~masigg/Godden.ppt#10

Advantages focused ultrasound

- High accuracy (diameter of a few cells)
- Destroyed tissue will be re-absorbed of the body
- Rapid heating of the tissue will destroy the tumor
- Non-invasive or minimal invasive
- No blood loss
- Repeatable
- Rapid convalescence

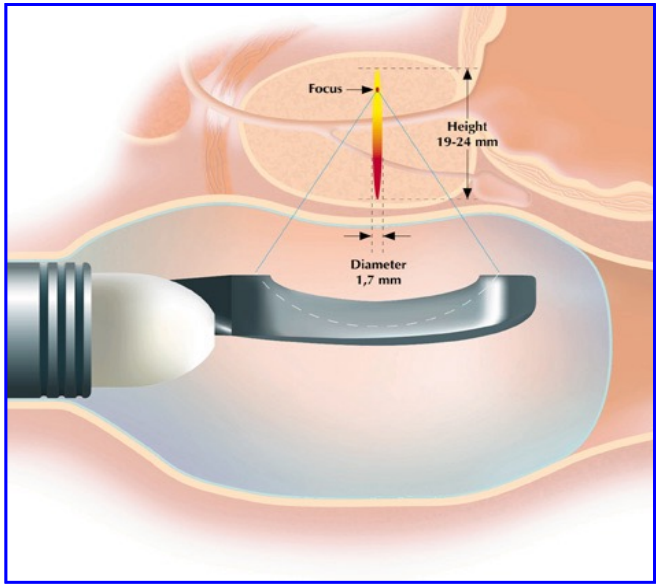
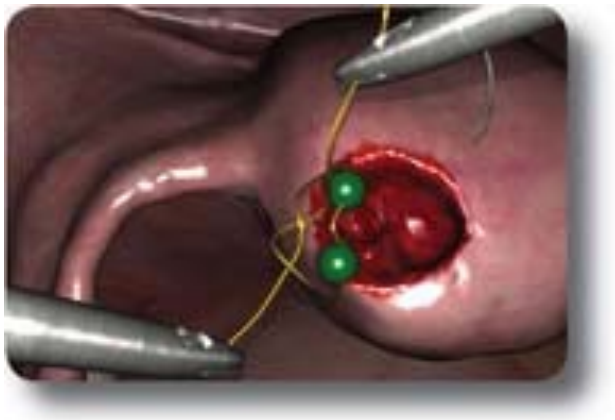


Image: Trans-rectal probe (EDAP)

Disadvantages focused ultrasound

- Capacity problems with large tumors
- New and not established procedure
- Needs direct acoustic access to tumor
- The tumor must be well defined
- The surgeon will not have direct vision of the tissue with the tumor
- Possible side effects of high energetic ultrasound is not clarified (10^4 of the energy of imaging ultrasound)
- Require normally MR-monitoring to verify necrosis



Case 13



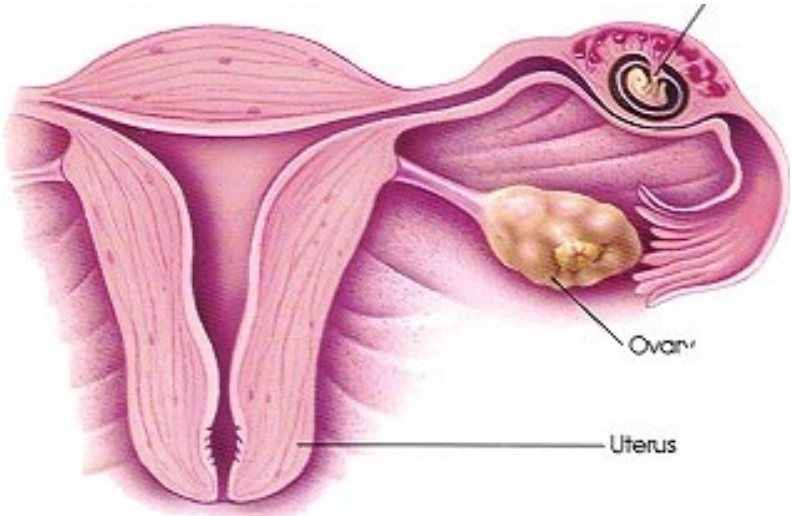
- Despite the fact that the left ophorectomy with a high focused ultrasound was a success, the serum hCG levels seems to refuse to decline. She was monitored closely, and 14 days later, it was still more than 134 IU/L, even if the level had plateaued since the previous tests.

What is wrong?

Case 13



- Answer: There are several types of tumors that are able to produce false positive pregnancy tests because of their ability to produce hCG. As the young lady expected to be pregnant, the presence of high levels of hCG was immediately interpreted as a pregnancy. The ultrasound scan revealed no in-uterine fetus, and the finding of the ovarian tumor explained the elevated hCG levels. However, the continuously elevated levels of hCG even after tumor recession aims for another explanation. More ultrasound scans were performed, and an ectopic pregnancy was discovered

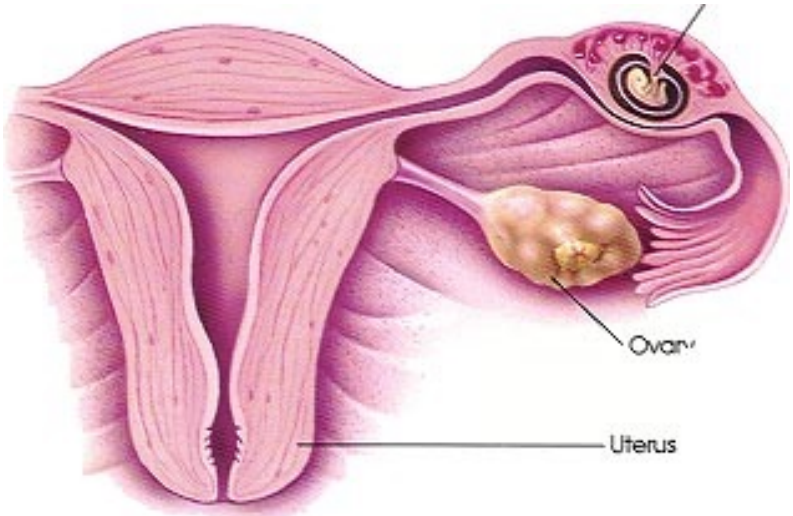


http://www.soc.ucsb.edu/sexinfo/sites/default/files/files/styles/large/public/field/image/ectopic_preg.jpeg

Case 13



- Answer: The fetus localized in the fallopian tube was not viable and represented a serious health condition for the mother because it can rupture the fallopian tube with excessive bleeding as a result. For that reason, the fetus was removed surgically. Most ectopic pregnancies are caused by a blockage in the fallopian tube, typically because of a scar from surgery or an inflammation like chlamydia or gonorrhea. The woman recovered quickly after surgery and gave birth to a child a few years later after artificial insemination



http://www.soc.ucsb.edu/sexinfo/sites/default/files/files/styles/large/public/field/image/ectopic_preg.jpeg