Ultrasound – Chapter 16

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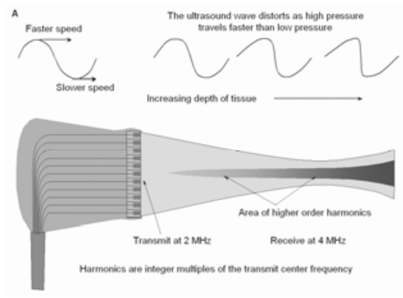
a copy of this lecture may be found at:
http://courses.washington.edu/radxphys/PhysicsCourse.html

7. Harmonic Imaging

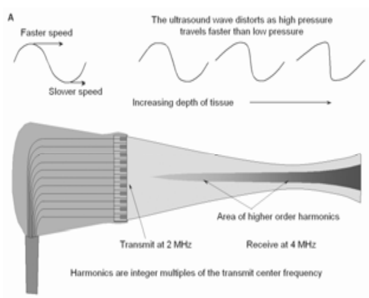
- Harmonic frequencies are integral multiples of the frequencies contained in an US pulse
  - pulse with center frequency f_0 MHz
  - upon interaction with a medium
  - will contain high-frequency harmonics of $2f_o$, $3f_o$, $4f_o$ etc.



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 518.

7. Harmonic Imaging

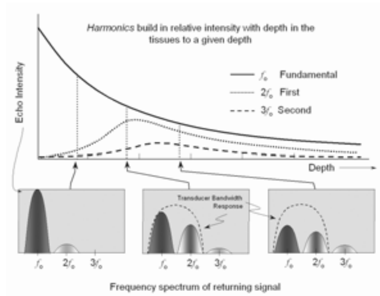
- High frequencies arise due to:
- *Nonlinear propagation of the US as it travels through tissue*
- The high-pressure component (compression) travels faster than the low-pressure component (rarefaction) of the wave causing a wave distortion in the central area of the beam
- The wave distortion increases with depth and localizes in the central area of the beam



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 518.

7. Harmonic Imaging

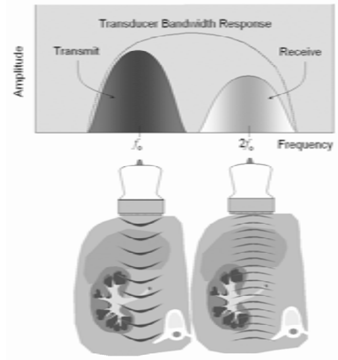
- Harmonic frequencies increase with depth
- The first harmonic ($2f_0$) is commonly used because it suffers less attenuation than higher-order harmonics
- Tuning the receiver to first harmonic spectrum filters out the lower frequency echoes



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 519.

7. Harmonic Imaging

- The transducer bandwidth response must encompass the higher harmonics
- Native tissue harmonic imaging uses a lower center frequency (e.g., 2 MHz) spectrum and receives echoes from the higher harmonics (e.g., 4 MHz)
- High transducer Q factor needed to allow easier separation of the frequency harmonics from the fundamental frequency (using multifrequency transducer)

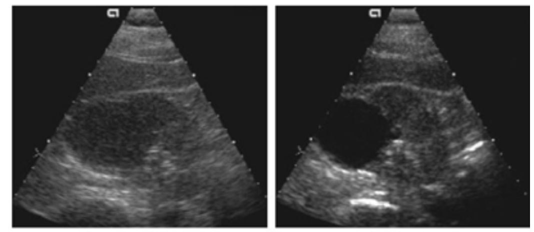


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 519.

Kanal 5

7. Harmonic Imaging

- Degrades axial resolution
- Improved lateral spatial resolution
- Best used in abdominal imaging, use lower frequency to begin with, then switch to higher frequency harmonics for better image quality and less clutter adjacent to the transducer



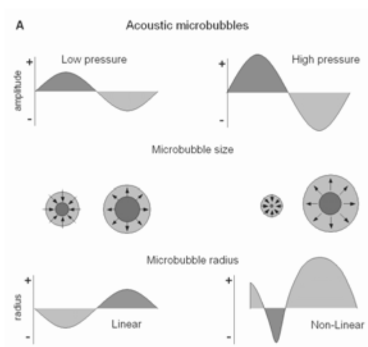
a. b.

Figure 14. Fundamental **(a)** and harmonic **(b)** US images of a renal cyst show the benefits of harmonic imaging. The cyst in the harmonic image **(b)** appears much more anechoic and exhibits sharper, better-delineated margins. (Courtesy of Siemens Medical Solutions, Mountain View, Calif.)

Kanal c.f. Radiographics 2003; 23:1019-1033 6

7. Harmonic Imaging – Contrast Agents

- High frequencies also arise due to:
- *The vibration of encapsulated gas bubbles used as contrast agents*
- The responses of microbubble contrast agents under low and high pressure reveal nonlinear compression and expansion of the bubble radius

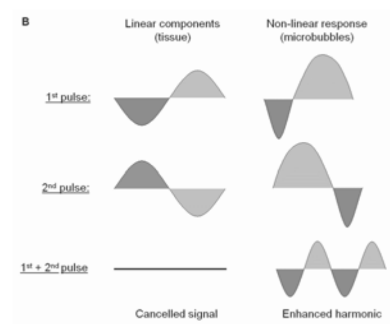


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 520.

Kanal 7

7. Harmonic Imaging – Contrast Agents

- Pulse inversion harmonic imaging:
- A standard pulse is followed by an inverted (pulse-reversed) pulse along the same beam direction
- When added, linear responses (soft tissue) are canceled while an enhanced harmonic signal remains, chiefly due to the microbubble contrast agent



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 521.

Kanal 8

7. Harmonic Imaging – Contrast Agents

- Pulse inversion harmonic imaging
- Elimination of competing signals from the soft tissues enhances the sensitivity to contrast agents and provides an ability to detect tissue perfusion by microbubble uptake
- Disadvantages include motion artifacts and frame rate penalty (at least 2 times slower than a standard scan)

Pulse Inversion Harmonic Image

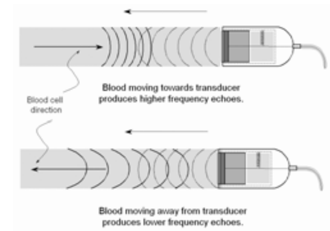
Color Doppler Image

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 521.

Kanal 9

9. Doppler Ultrasound

- Doppler ultrasound
  - Based on shift in frequency in an US wave caused by a moving reflector (blood cells)
  - Objects moving toward the transducer - higher frequency and shorter wavelength
  - Objects moving away from the transducer - lower frequency and longer wavelength
  - If object moving perpendicular to the transducer, no change in the observed frequency or wavelength

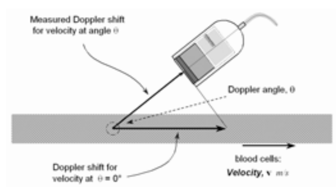


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 532.

Kanal 10

9. Doppler Frequency Shift

- The Doppler shift is the difference between the incident frequency and reflected frequency
- f_d = Doppler frequency shift
- f_i = transducer frequency
- f_r = reflected frequency
- v = blood velocity
- c_t = speed of sound in tissue
- As the angle of incidence increases with respect to the long axis of the blood vessel, the Doppler shift decreases
- Cos 0 = 1, cos 30 = 0.87, cos 45 = 0.707, cos 60 = 0.5, cos 90 = 0



$$f_d = f_i - f_r = \frac{2v\cos(\theta)}{c_t} f_i$$

$$v = \frac{f_d\, c_t}{2 f_i \cos(\theta)}$$

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 532.

Kanal 11

9. Doppler Frequency Shift

- Frequency shifts are in the audible range
  - Human audible spectrum: 15 Hz – 20 kHz
- Preferred Doppler angle is from 30-60 degrees
- At >60 deg, minor errors in angle accuracy can result in large errors in velocity
- At <20 deg, refraction and aliasing problems can occur

$$f_d = f_i - f_r = \frac{2v\cos(\theta)}{c_t} f_i$$

TABLE 16-7. DOPPLER ANGLE AND ERROR ESTIMATES OF BLOOD VELOCITY FOR A +3-DEGREE ANGLE ACCURACY ERROR

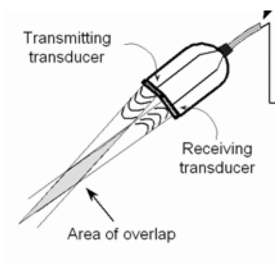
Angle (degrees)	Set Angle (degree)	Actual Velocity (cm/sec)	Estimated Velocity (cm/sec)	Error (%)
0	3°	100	100.1	0.14
25	28°	100	102.6	2.65
45	48°	100	105.7	5.68
60	63°	100	110.1	10.1
80	83°	100	142.5	42.5

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 533.

Kanal 12

9. Continuous-Wave Doppler Operation

- CW Doppler is the simplest and least expensive device for measuring blood velocity
- Continuous Wave Doppler: two transducers required, one transducer continuously transmits and one transducer continuously receives
- The area of overlap determines the position of blood velocity measurement
- The frequency of the two signals are subtracted to give the Doppler shift
- Lacks depth resolution and provides little spatial information
- Good for measuring fast flow and assessing deep lying vessels

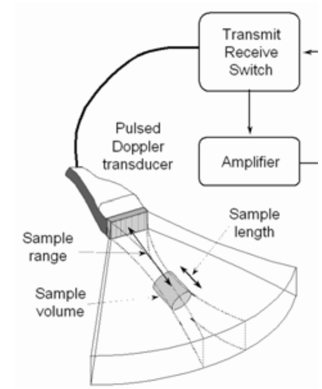


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 534.

Kanal 13

9. Pulsed Doppler Operation

- Pulsed Wave Doppler: allows both velocity and depth information to be obtained (pulse-echo)
- Single transducer used
- Depth selection is achieved with an electronic time gate circuit to reject all echo signals except those falling within the gate window, as determined by the operator

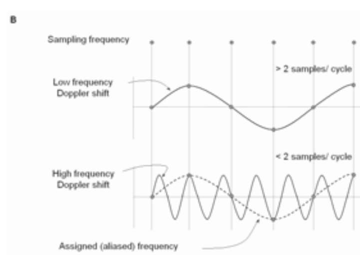


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 535.

Kanal 14

9. Aliasing

- According to sampling theory, a signal can be reconstructed as long as the true frequency (Doppler shift) is less than half the sampling rate (PRF)
- The PRF must be at least twice the maximal Doppler shift encountered in the measurement
- High blood flow causing the Doppler shift to exceed ½ PRF will result in false (aliased) velocities



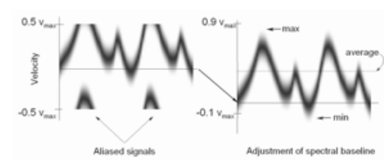
$$\Delta f_{\max} = \frac{PRF}{2}$$

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 536.

Kanal 15

9. Aliasing

- Aliasing is characterized by “wraparound” of the highest velocities to the opposite direction
- Reduce or eliminate aliasing by adjusting the velocity scale to a wider range as most instruments have the PRF linked to the scale setting

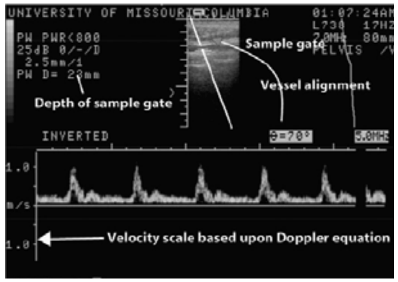


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 540.

Kanal 16

9. Duplex Scanning

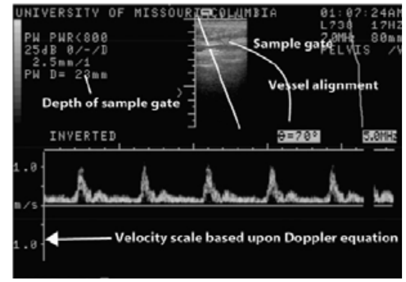
- Combination of 2D B-mode imaging (visual guidance) and pulsed Doppler data acquisition
- The 2D B-mode creates the real-time image to facilitate selecting the Doppler gate window position, and then is switched to the Doppler mode



c.f. Radiographics 2003; 23:1315-1327

9. Duplex Scanning

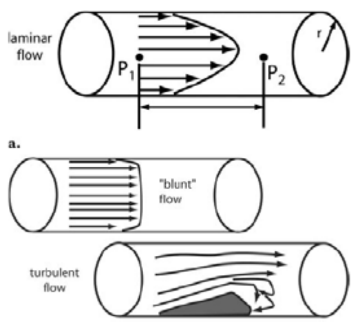
- Sample volume position (range gate) indicated by a window position cursor and a line cursor for the angle
- Errors in the flow volume may occur if
  - vessel axis not totally within scanned plane
  - vessel might be curved



c.f. Radiographics 2003; 23:1315-1327

9. Blood Flow
Laminar, Blunt and Turbulent

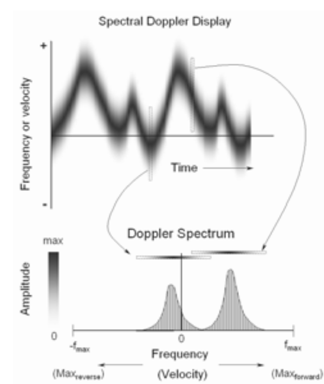
- Laminar flow – fast in center of large, smooth wall vessels
  - Slowest at vessel wall (friction)
- Blunt flow – uniform in center, falls off at vessel wall
- Turbulent flow – when stenosis is present
  - results as a separation of flow occurs downstream from the stenosis



c.f. Radiographics 2003; 23:1315-1327

9. Spectral Waveform

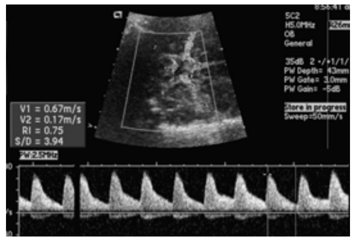
- Plot of Doppler shift frequency spectrum versus time
- Amplitude is encoded as gray-scale variation
- The spectral waveform - audible signal and provides information about
  - the **direction** of the flow
  - how fast the flow is traveling **(velocity)**
  - the **quality** of the flow (normal vs. abnormal)



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 539.

9. Spectral Waveform

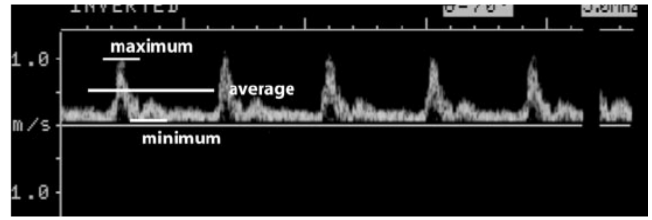
- A broad spectrum represents turbulent flow while
- A narrow spectrum represents laminar flow within the Doppler
- gate
- Figure shows a color Doppler image showing the active color area and the corresponding spectral Doppler display



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 539.

Kanal 21

9. Spectral Waveform



Pulsatility Index, PI

Resistivity Index, RI

S – Systolic

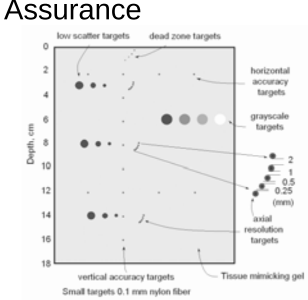
D - Diastolic

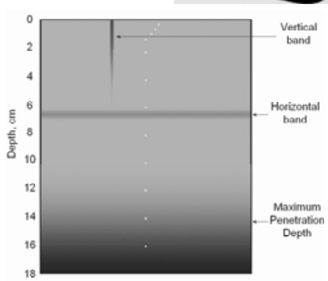
$$\mathrm{PI} = \frac{v_{\max} - v_{\min}}{v_{\text{mean}}} = \frac{S - D}{mean}.$$

$$\mathrm{RI} = \frac{v_{\max} - v_{\min}}{v_{\max}} = \frac{S - D}{S}.$$

Kanal c.f. Radiographics 2003; 23:1315-1327 22

10. System Performance and Quality Assurance





Precision multi-purpose grey scale phantom (RMI 403GS LE)

Kanal c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 545. 23

11. Acoustic Power and Bioeffects

- The intensity at a specific point during a single pulse is the spatial peak pulse average intensity (I_{SPPA}), W/cm^2
- The intensity at a specific point averaged over a long period (many pulses) is the spatial peak temporal average intensity (I_{SPTA}), W/cm^2

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 549-550

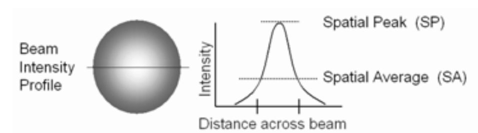
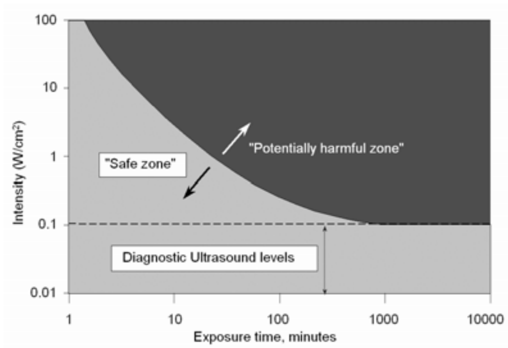


TABLE 16-9. TYPICAL INTENSITY MEASURES FOR ULTRASOUND DATA COLLECTION MODES

Mode	Pressure Amplitude (MPa)	I_{SPTA} (mW/cm^2)	I_{SPPA} (W/cm^2)	Power (mW
B-scan	1.68	19	174	18
M-mode	1.68	73	174	4
Pulsed doppler	2.48	1,140	288	31
Color flow	2.59	234	325	81

Kanal 24

11. Bioeffects



No bioeffects have been shown below an I_{SPTA} of 100 mW/cm^2

Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 553.

Kanal 25

11. Acoustic Power and Bioeffects

- At high power levels, ultrasound can cause:
  - *Likelihood of Cavitation (Mechanical Index, MI)*- the creation and collapse of microscopic bubbles
  - Small-scale fluid motions called microstreaming
- Tissue heating occurs as a result of energy absorption and is the basis of using ultrasound for hyperthermia treatment
- *Thermal Index, TI* is the ratio of the acoustic power produced by the transducer to the power required to raise tissue in the beam area by 1 deg C

Kanal 26

9. Color Flow Imaging

- Color flow imaging provides a 2D visual display of moving blood in the vessels, superimposed on the conventional gray-scale image
- Typically, flow toward the transducer is assigned red and flow away from the transducer blue
- Turbulent flow can be displayed as green or yellow

Figure courtesy: Brent Stewart, Ph.D.

Kanal 27

9. Color Flow Imaging

- The color intensity varies with flow intensity
- Color Doppler can detect flow in vessels too small to be seen by imaging alone
- One limitation of color scanning is that clutter of slow-moving solid structures and noise can overwhelm the smaller echoes from moving blood
- Spatial resolution of the color image is much lower than that of gray-scale image

Figure courtesy: Brent Stewart, Ph.D.

Kanal 28

9. Power Doppler

- PD permits detection and interpretation of slow blood flow but sacrifices directional and quantitative flow information
- It uses the return Doppler signal strength alone
- It is more sensitive than standard color flow imaging
- The image signal does not vary with the direction of flow

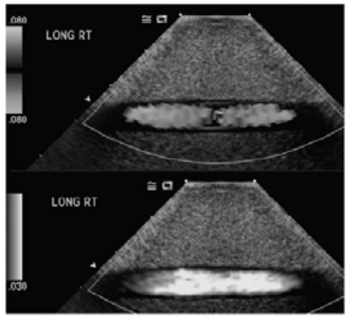


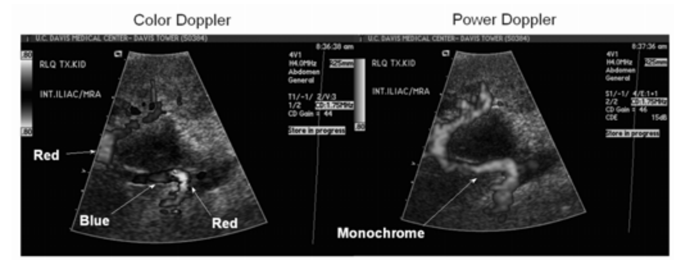
Figure 10. Color flow (top) and power Doppler (bottom) images of the same phantom under the same conditions. The directions of flow toward and away from the transducer are seen in the color flow image (top). The power Doppler image (bottom) displays only the intensity of the Doppler shift.

c.f. Radiographics 2003; 23:1315-1327

Kanal 29

9. Power Doppler

- Enchanced sensitivity in the PD acquisition – in areas perpendicular to the beam direction, where the signal is lost in in the color Doppler image
- Flow directionality is lost in the PW image

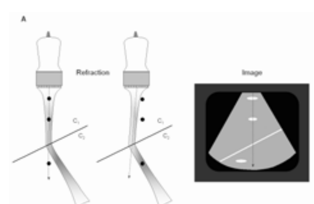


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 544.

Kanal 30

8. Ultrasound Artifacts

- Artifacts arise from the incorrect display of anatomy or noise during imaging
- Refraction - misplaced anatomic position in the image

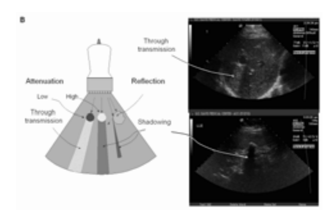


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 527.

Kanal 31

8. Ultrasound Artifacts

- Shadowing and Enhancement
  - Shadowing - reduced echo intensity behind a highly attenuating or reflecting object, such as a stone creating a “shadow”
  - Nonperpendicular reflection near a curved edge of a mass can also cause shadowing
  - Enhancement - increased echo intensity behind a minimally attenuating object such as a fluid filled cyst

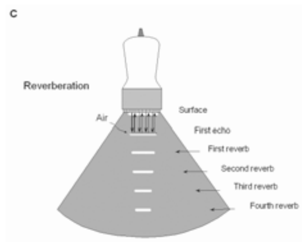


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 527.

Kanal 32

8. Ultrasound Artifacts

- Reverberation artifacts commonly occurs between two strong reflectors, such as an air pocket and the transducer array at the skin surface
  - 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

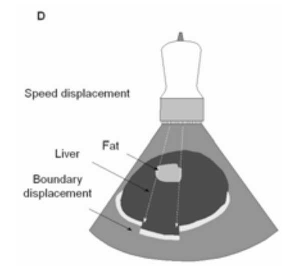


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 528.

Kanal 33

8. Ultrasound Artifacts

- Speed displacement artifacts are caused by the variability of the speed of sound in various tissues
  - In the case of fatty tissues, the slower speed of sound in fat (1,450 m/sec) results in a displacement of the returning echoes from distal anatomy by about 6% of the distance traveled through the mass

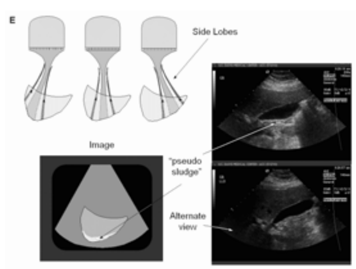


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 528.

Kanal 34

8. Ultrasound Artifacts

- Side Lobes, Grating Lobes
  - Side lobe - cause anatomy outside the main beam to be mapped into the main beam
  - Side lobes redirect diffuse echoes from adjacent soft tissues into an organ that is normally hypoechoic.
    - gallbladder - "pseudo-sludge"
  - Grating Lobes - create ghost images of off-axis high-contrast objects

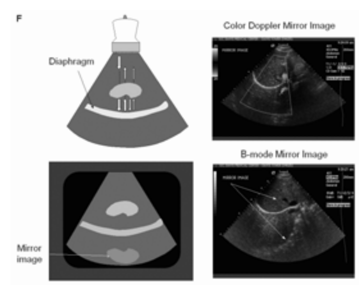


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 528.

Kanal 35

8. Ultrasound Artifacts

- A mirror image artifact arises from multiple beam reflections between a mass and a strong reflector, such as a diaphragm
  - Multiple echoes result in the creation of a mirror image beyond the diaphragm of the mass



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 529.

Kanal 36

7-11. Harmonic Imaging, Artifacts, Doppler – Key Points

- Harmonic frequencies are integral multiples of the frequencies contained in an US pulse
- The first harmonic ($2f_0$) is commonly used
- Artifacts arise from the incorrect display of anatomy or noise during imaging – several different types in US
- Doppler ultrasound is based on shift in frequency in an US wave caused by a moving blood cells
- Preferred Doppler angle is from 30-60 degrees

$$v = \frac{f_d \, c_t}{2 \, f_i \cos(\theta)}$$

- CW Doppler lacks depth resolution and provides little spatial information
- PW Doppler allows both velocity and depth information to be obtained (pulse-echo)

Kanal 37

7-11. Harmonic Imaging, Artifacts, Doppler – Key Points

- The PRF must be at least twice the maximal Doppler shift encountered in the measurement
- Laminar, Blunt and Turbulent blood flow
- Typically, flow toward the transducer is assigned red and flow away from the transducer blue
- Spectral waveform, PI, RI
- *Cavitation (Mechanical Index, MI)*- the creation and collapse of microscopic bubbles
- *Thermal Index, TI* is the ratio of the acoustic power produced by the transducer to the power required to raise tissue in the beam area by 1 deg C
- No bioeffects have been shown below an ISPTA of 100 mW/cm2

Kanal 38