Principles of Medical Ultrasound

Zahra Kavehvash

Medical Ultrasound Course (25-636)

- Introduction
- Acoustic wave propagation
- Attenuation, scattering and speckle
- Transducers
  - Generation and detection of ultrasound
  - Equivalent circuit
  - Piezoelectric materials
- Beam forming and Diffraction
  - Array beam forming
- Image formation
- Doppler modes
  - Ultrasound flow imaging
- Contrast and resolution
- Ultrasound bioeffects and safety
- Emerging technologies and trends (If time permits)
- Acousto-optic (Photo-Acoustic) imaging (If time permits)

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- Reference:
  - Thomas L. Szabo , *Diagnostic Ultrasound Imaging: Inside Out* , Elsevier , Academic Press Series in BME , 2004.
  - Haim Azhari, *Basics of Biomedical Ultrasound for Engineers*, IEEE , Wiley, 2010.
  - K. Kirk Shung and Gray A. Thieme, *Ultrasonic Scattering in Biological Tissues*, CRC Press, 1993.
  - B. D. Steinberg, *Principles of Aperture and Array System Design*, John Wiley and Sons, 1976.
  - D. H. Evans, W. N. McDicken, R. Skidmore, and J. P. Woodcock, *Doppler Ultrasound*, John Wiley and Sons, 1989.
  - J.W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, 1968.

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- Journals:
  - IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control.
  - IEEE Transactions on Medical Imaging
  - Journal of Acoustical Society of America

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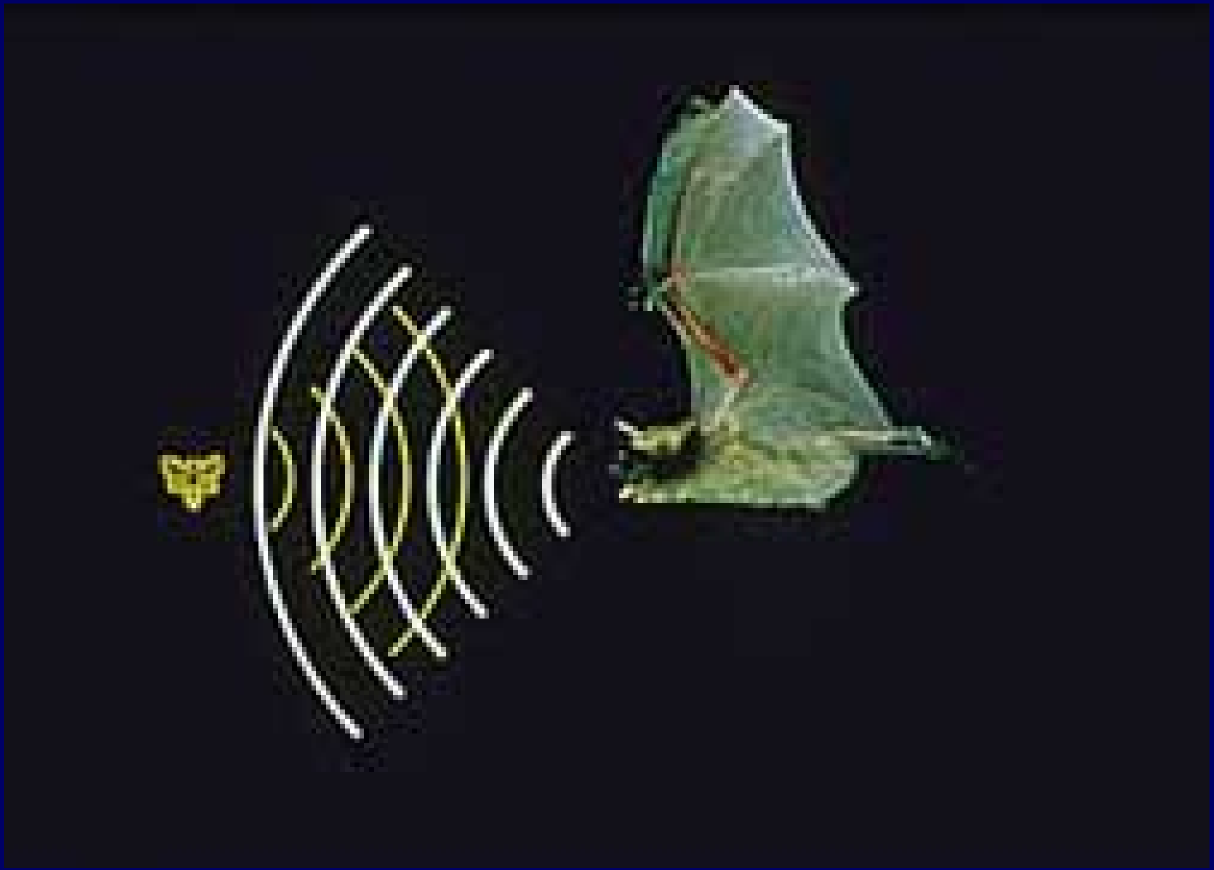
- Grading:
  - Homework: 20 %
  - Project: 10 %
  - Mid Term: 30 %
  - Final: 40 %

History of Ultrasound

<u>Who are the smart guys?</u>

History of Ultrasound

- A long time ago:



History of Ultrasound

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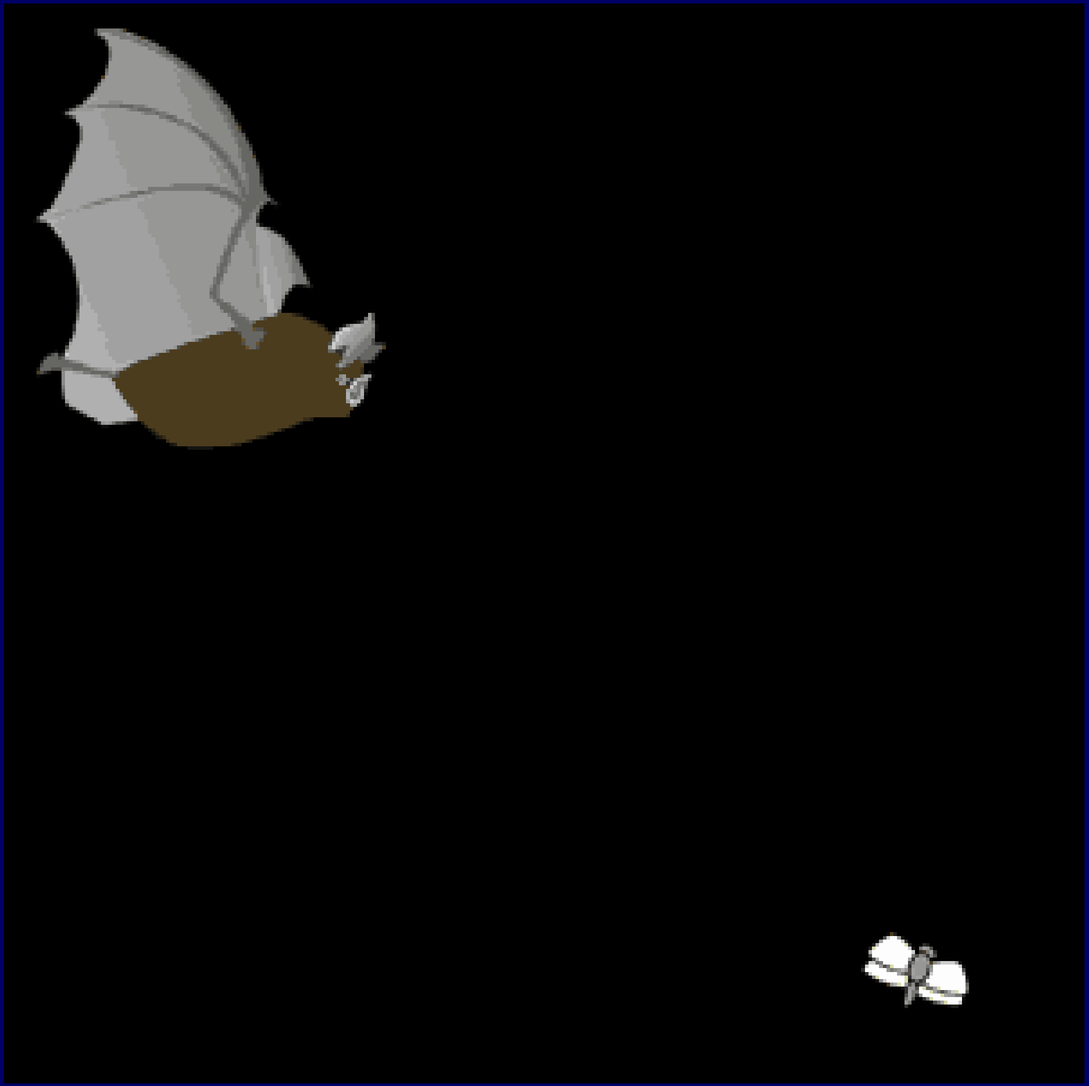
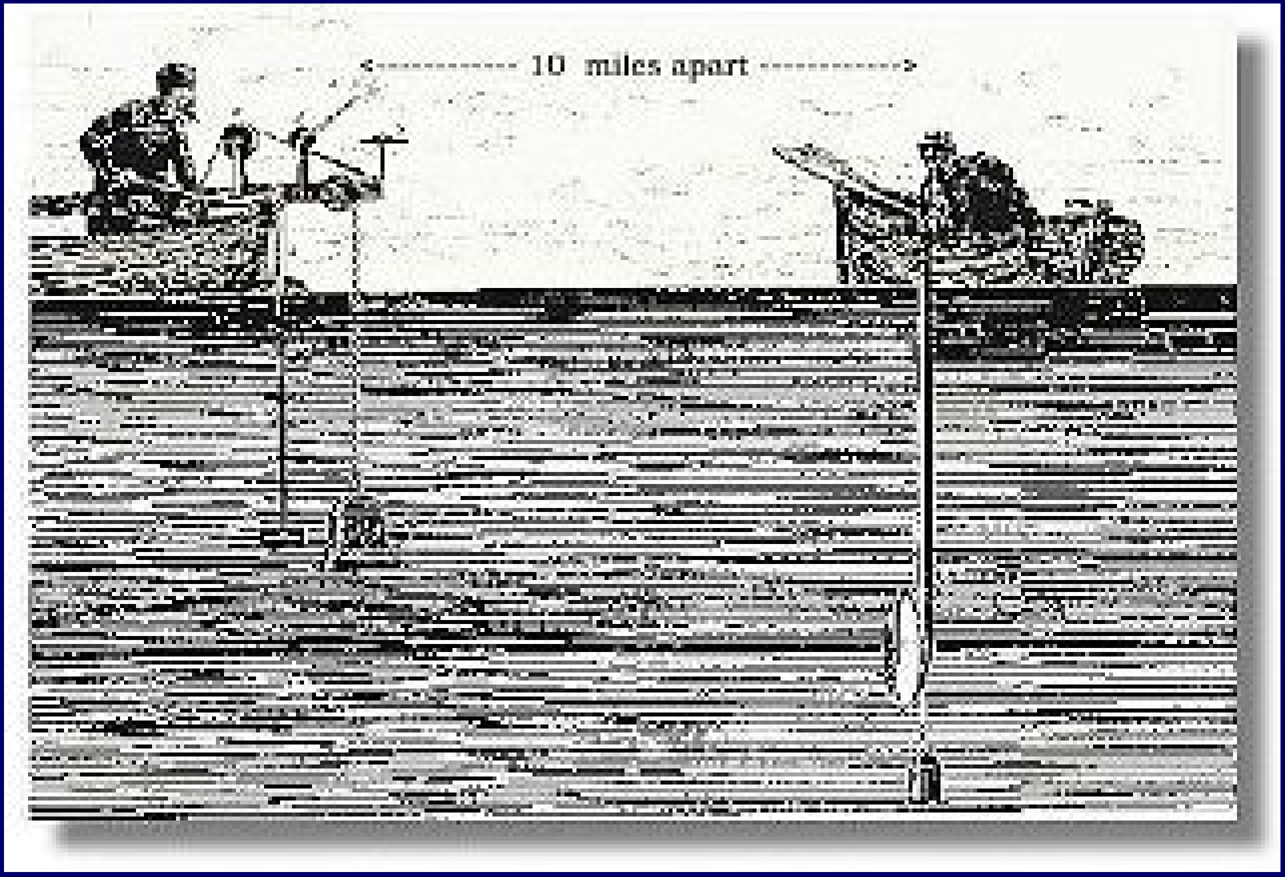


History of Ultrasound

- 1822, Lake Geneva:



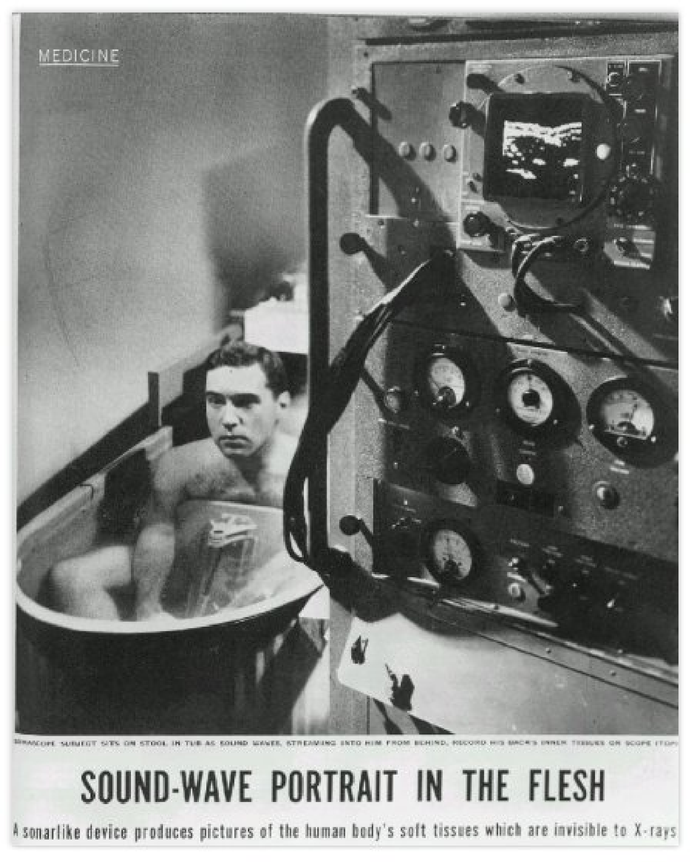
History of Ultrasound

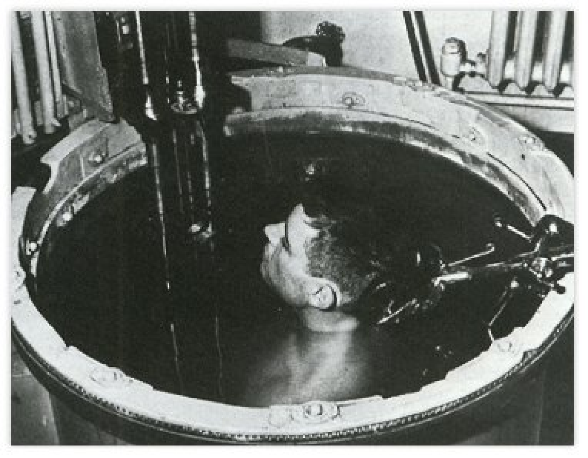
- Piezoelectric effect, Pierre Curie, 1880:

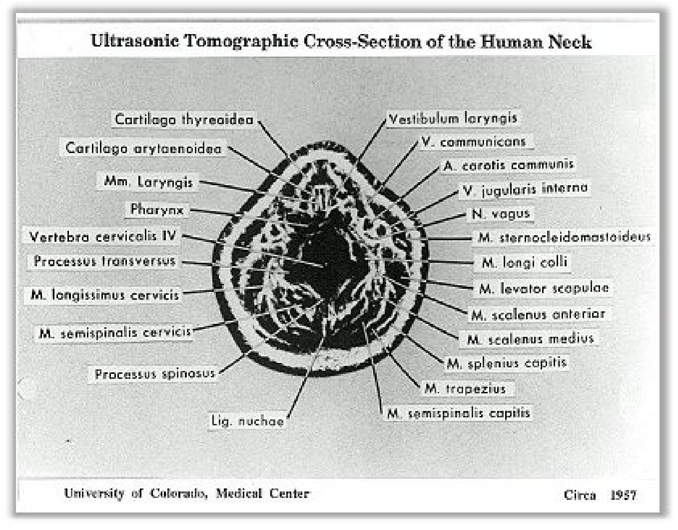
Pierre and Marie Curie in the Laboratory

History of Ultrasound

- 1954-1957:







History of Ultrasound

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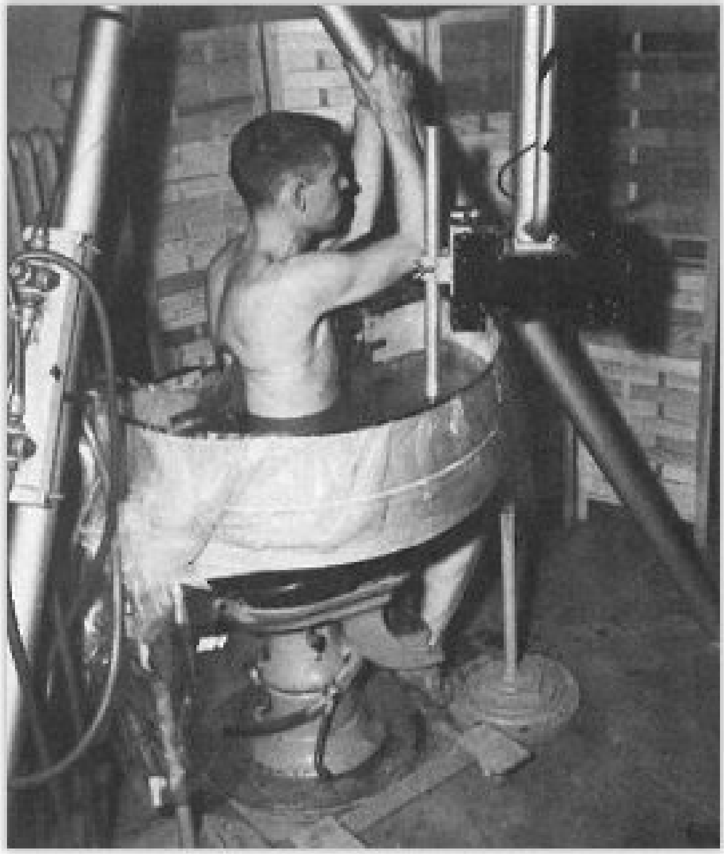
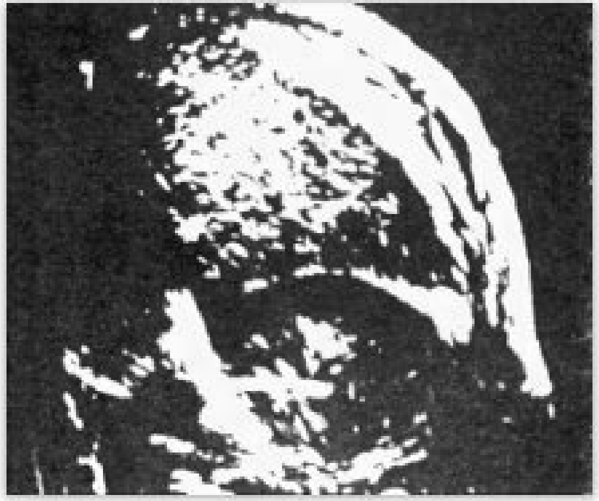




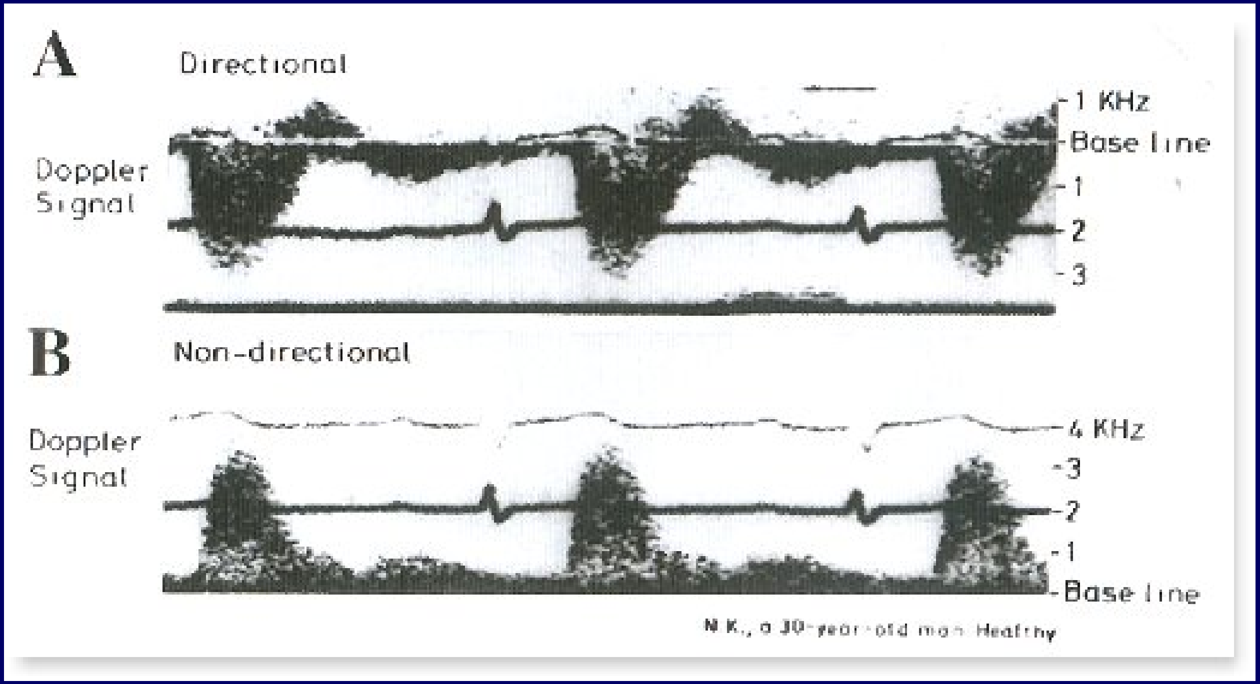
History of Ultrasound

- Doppler (1842):

Christian Andreas Doppler

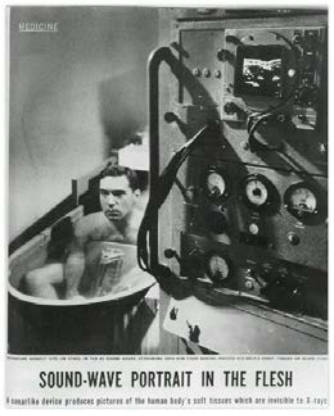
History of Ultrasound

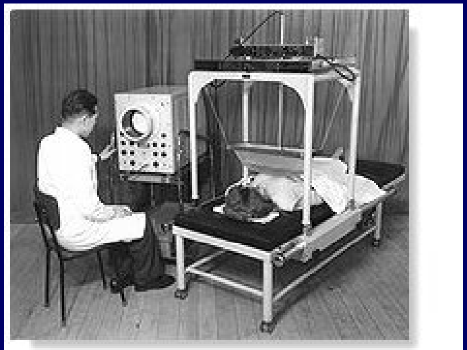
- Doppler ultrasound (1959-1960):



(1966)

History of Ultrasound




The water-bag B-mode scanning system, the SSD-1, from Aloka in 1960

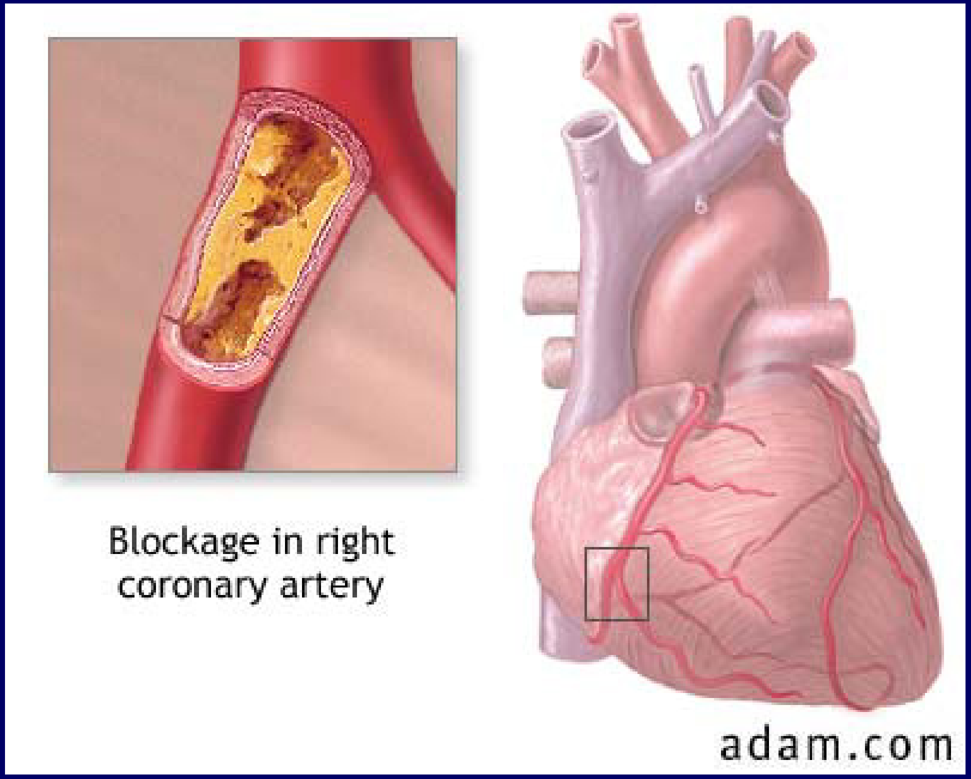
What is Medical Ultrasound?

- Prevention: actions taken to avoid diseases.
- Diagnosis: the process of identifying a disease by its signs, symptoms and results of various diagnostic procedures.
- Treatment: care by procedures or applications that are intended to relieve illness or injury.

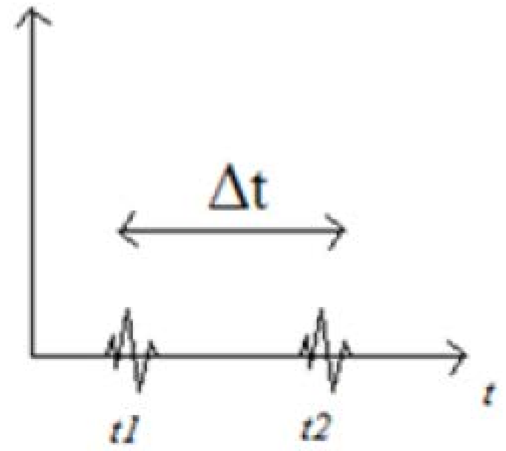
Diagnosis

Medical Diagnosis: Heart Attack as an Example

- Heart attack: Coronary artery disease, blockage of blood supply to the myocardium.



Basics



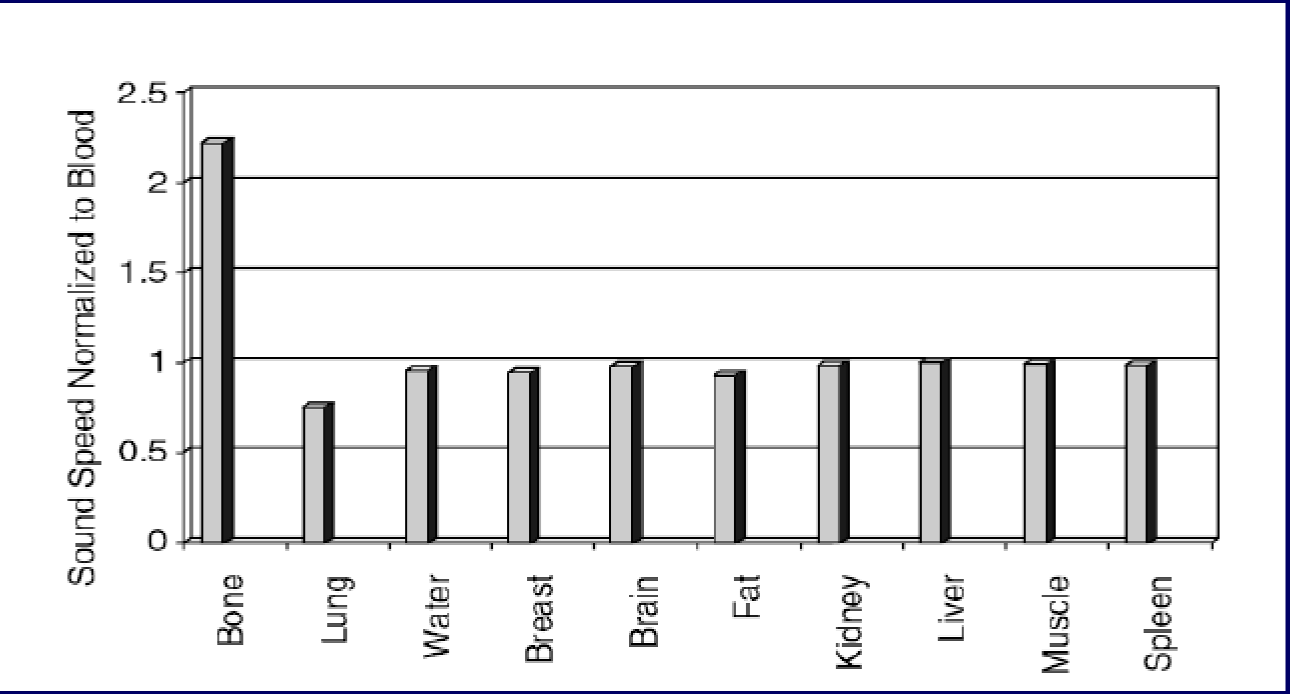
$$t_1 = \frac{2d_1}{c_{avg}}$$

$$d_1 = t_1 * c_{avg}/2$$

$$d_2 = t_2 * c_{avg}/2$$

$$d = c_{avg}(t_2 - t_1)/2$$

Basics



Sound Speed Normalized to Blood
2.5
2
1.5
1
0.5
0
Bone
Lung
Water
Breast
Brain
Fat
Kidney
Liver
Muscle
Spleen

Basics

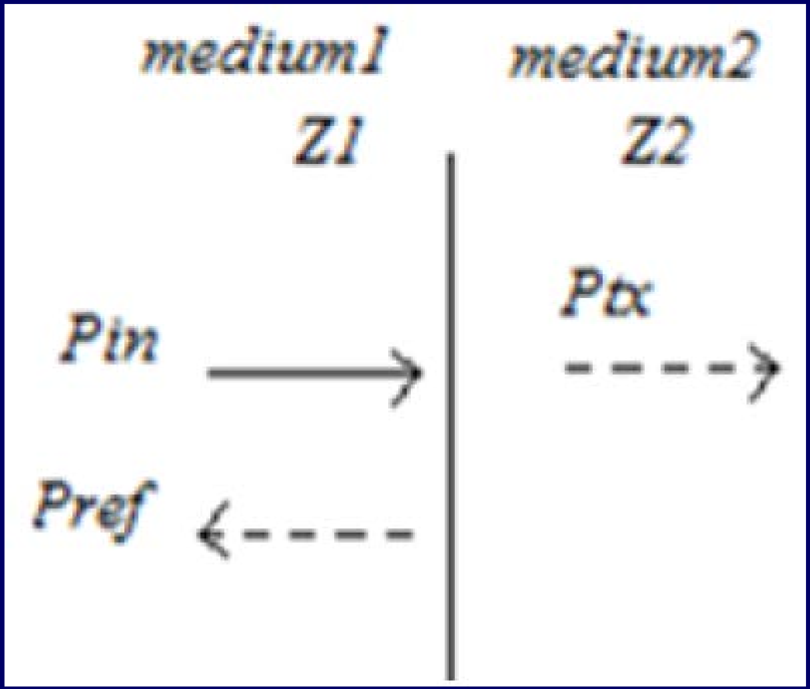
- Characteristic Impedance:

$$Z = \rho \times c$$

$$\rho(kg/m^3): Tissue \quad Density$$

$$c(m/s): \Pr opagation \quad Speed$$

Basics



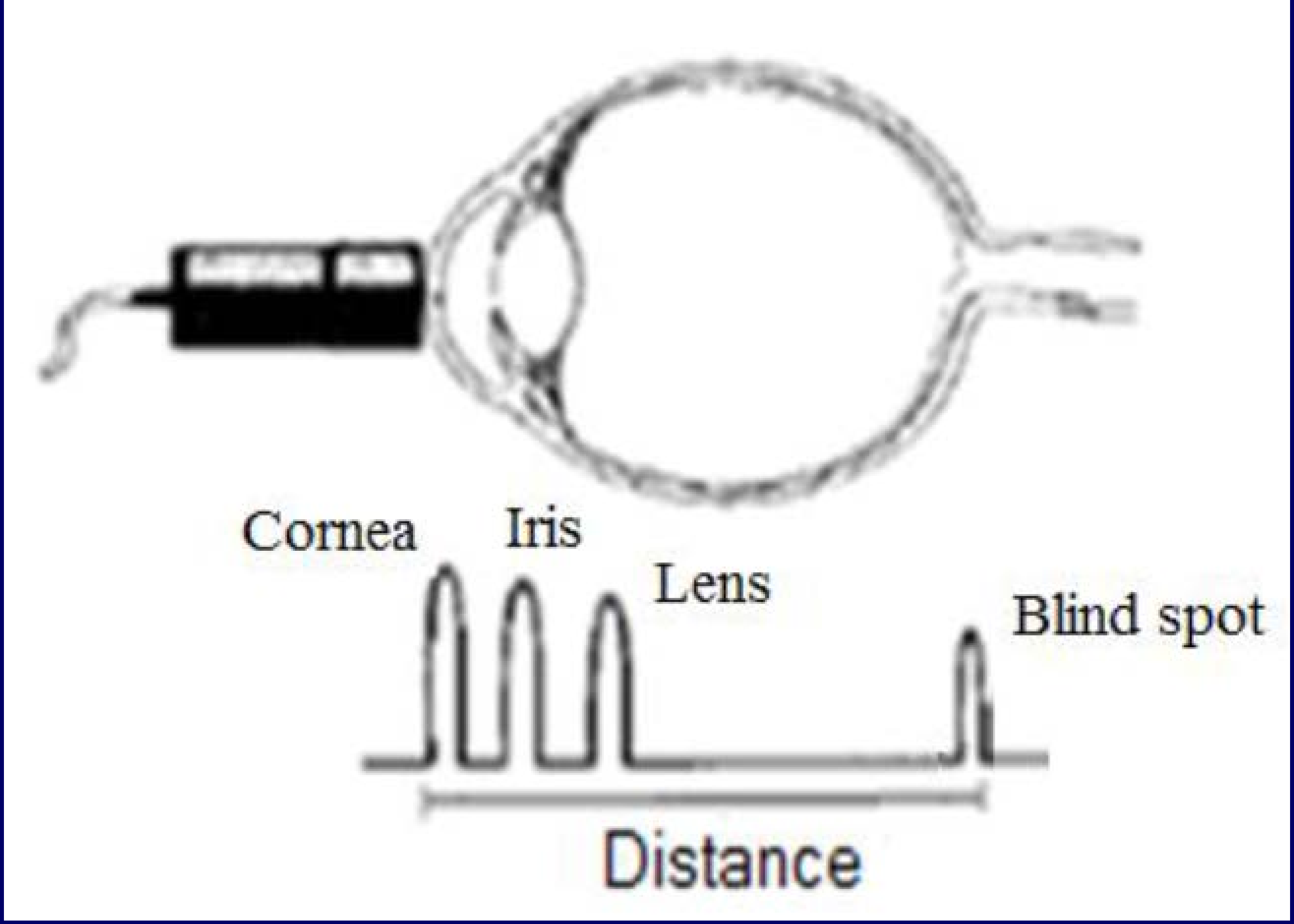
Amplitude of Acoustic Wave Pressure

$$RF = (Z_2 - Z_1)/(Z_2 + Z_1) = \frac{P_{ref}}{P_{in}}$$

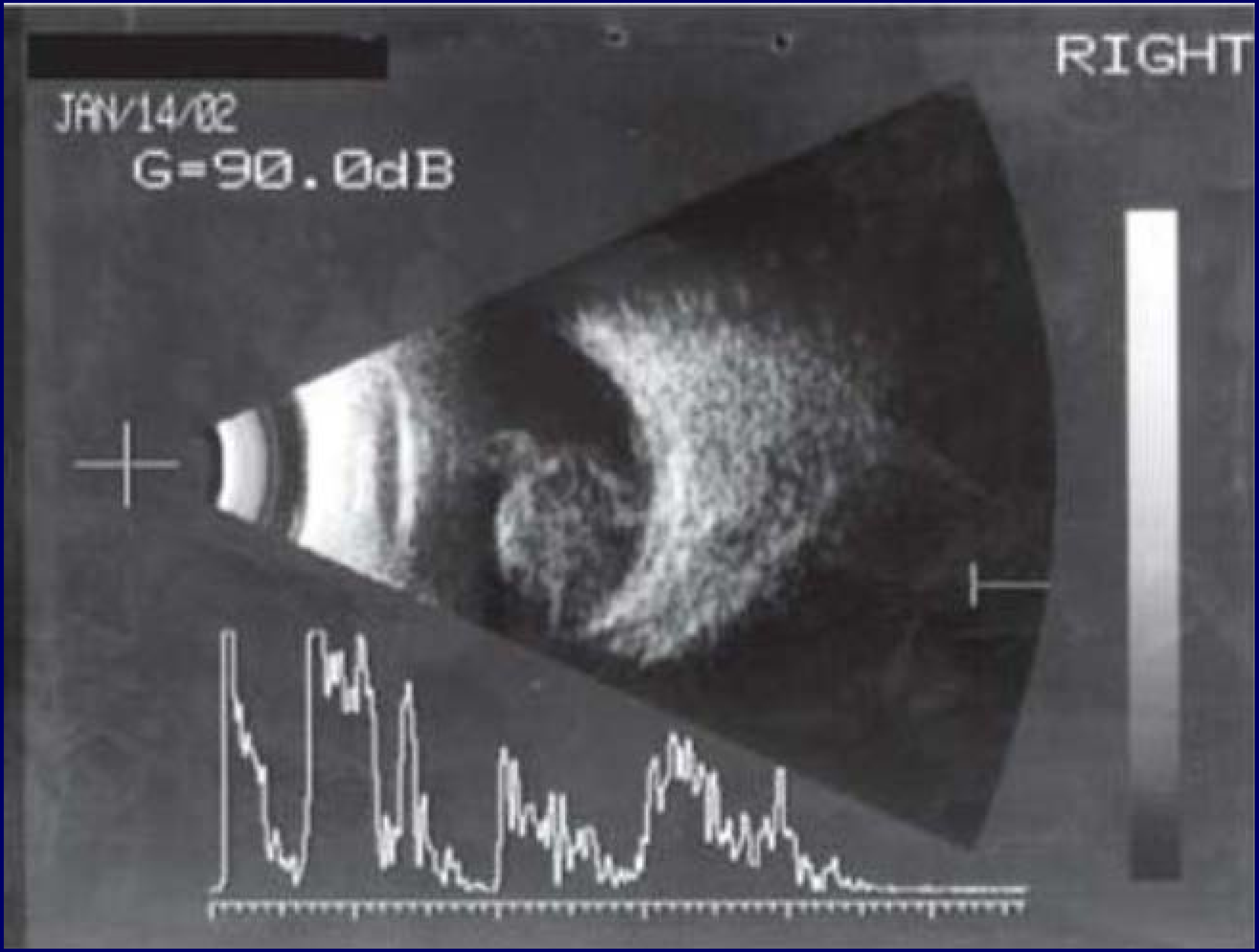
Scan Modes

- A-mode (A-scan, 1D).
- B-mode (Gray scale, 2D).
- M-mode (motion)
- Color Doppler (2D, blood flow).
- Spectral Doppler (localized, blood flow).
- Audio Doppler.

A-Scan (Amplitude, 1D)



B-Scan (Brightness, 2D)



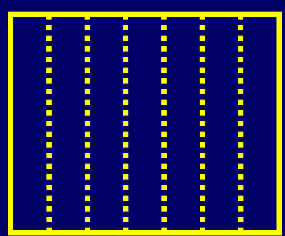
M-Mode (Brightness, 2D)

- A-Mode data in time

Normal mitral valve

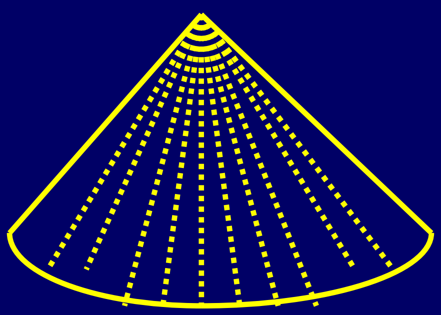
Scan Formats

linear



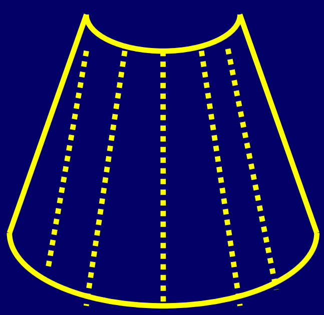
easy access
limited view

sector



limited access
wide view

curved linear

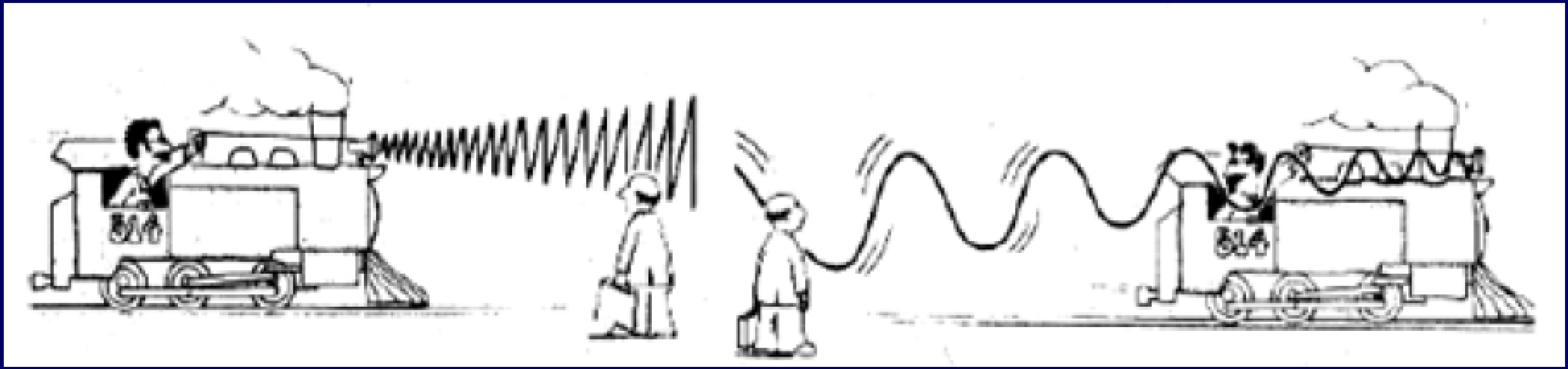


easy access
wide view

3D Ultrasound

Doppler-Mode

- Doppler Effect



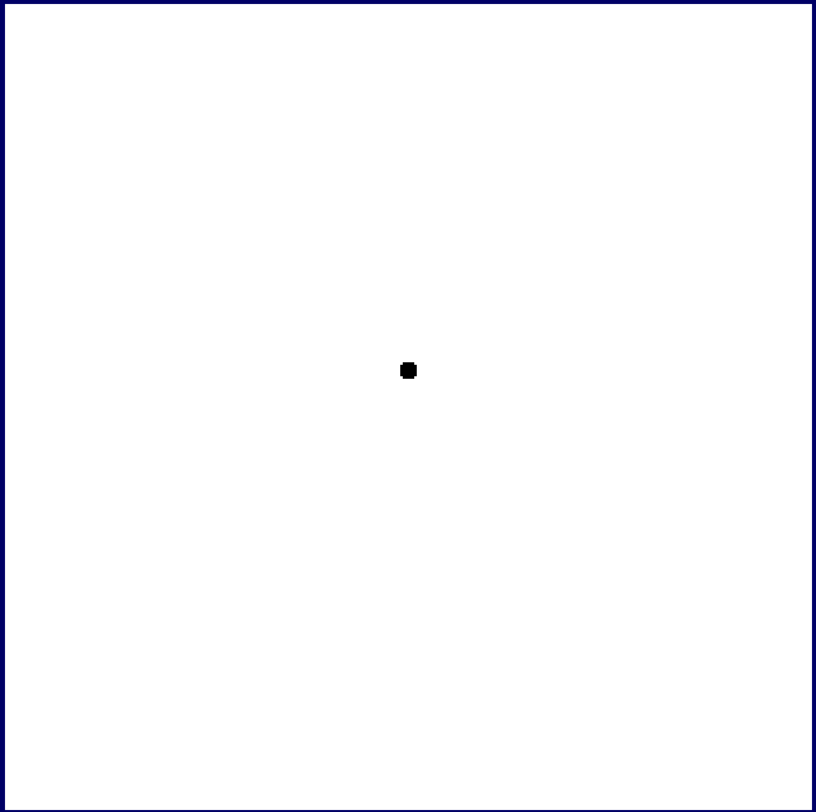
$$T' = \frac{\lambda}{c+v} = \frac{c \times T_0}{c+v} = \frac{c}{(c+v)f_0}$$

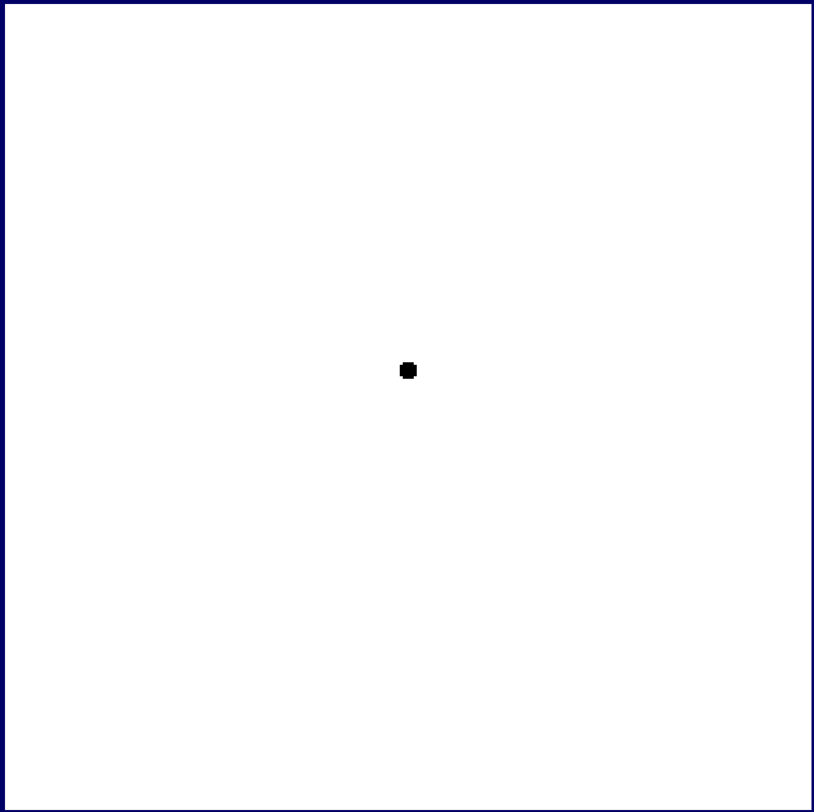
$$\frac{1}{T'} = f' = (1+\frac{v}{c})f_0$$

→

$$f_{Doppler} = f' - f_0 = \frac{v}{c} f_0$$

Doppler Effect

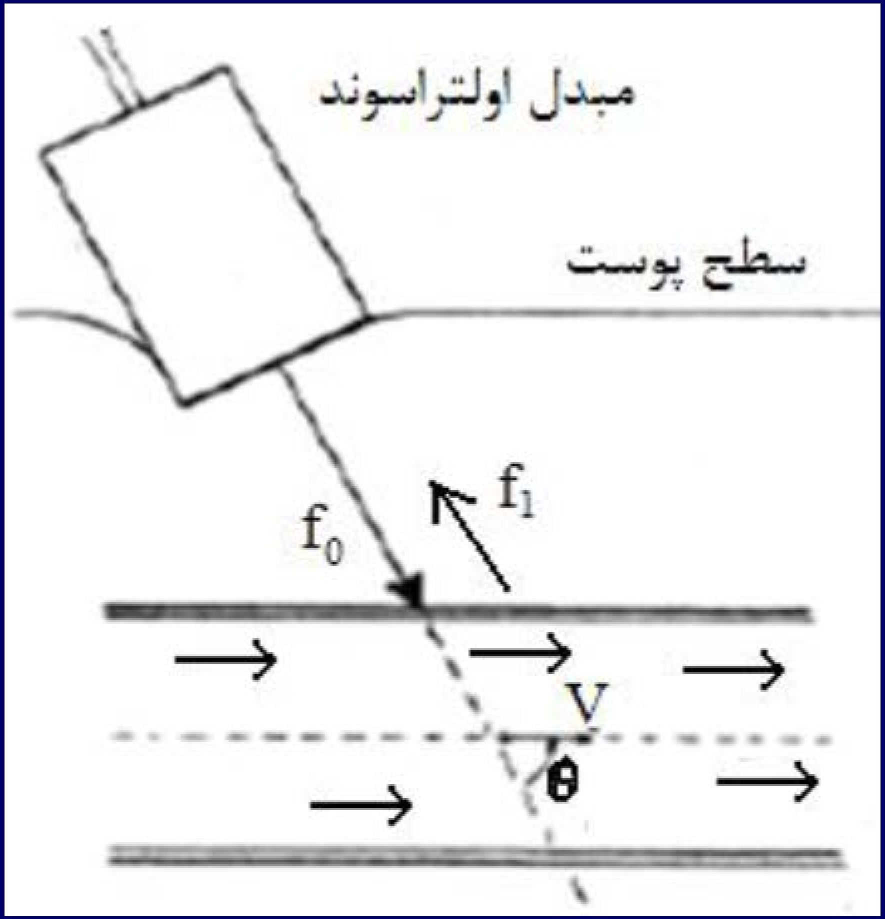




Doppler-Mode

- Doppler Effect

$$f_d = 2 f_0 \frac{V}{c} \cos\theta$$



Doppler-Mode

- Doppler Systems:
  - Continuous Doppler
  - Pulse Doppler

Doppler-Mode

- Continuous Doppler:
  - Just records the change in frequency
  - Display the changes in color or sound
- Pulse Doppler:
  - Records the reflection depth along with the Doppler frequency

Ultrasound vs. Other Imaging Systems

Ultrasound	X-ray	MRI	CT	
خواص مکانیکی	متوسط جذب بافت در طول مسیر	بیوشیمی(T_1 و T_2)	جذب ناحیه‌ای بافت	**خاصیت فیزیکی مورد کاوش**
وابسته به فرکانس عمقی و محوری 0/3 – 3 mm	~1 mm	~1 mm	~1 mm	**قدرت تفکیک فضایی**[1]
وابسته به فرکانس (حداکثر 25 cm)	عالی	عالی	عالی	**عمق نفوذ**[2]
خیلی خوب	خطر یونیزه شدن	خیلی خوب	خطر یونیزه شدن	**ایمنی**
تا 100 frames/sec	دقیقه	تا 10 frames/sec	دقیقه	**سرعت تصویر سازی**
50 هزار دلار	100 هزار دلار	1/5 میلیون دلار	1 میلیون دلار	**قیمت**
خیلی راحت	راحت	دشوار	دشوار	**قابلیت حمل**

Ultrasound Developements

- Harmonic imaging
- 2D Transducers for 3D imaging
- Increasing the Number of Transducer Elements
- Intra Vascular Ultrasound

Ultrasound Developements

- Contrast improvement:
  - Contrast agents (containing bobbles for THI and Endothelial Dysfunction measurement)

Ultrasound Developements

- Miniaturization:
  - Decreasing the weight to a few hundred grams.
  - Leads to more invasive applications

Ultrasound Developements

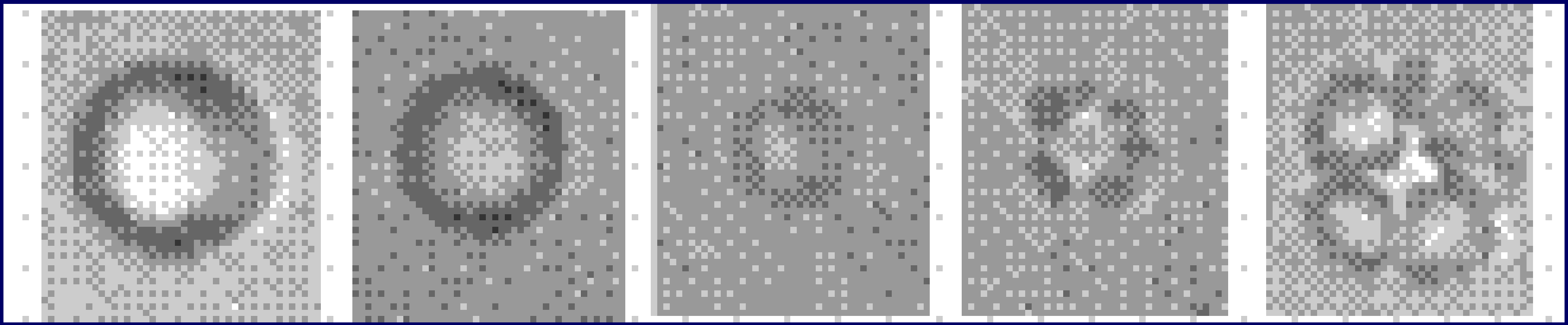
- Immunity:
- Appropriate power dose for different diagnostic and therapeutic applications

Bio-Effects

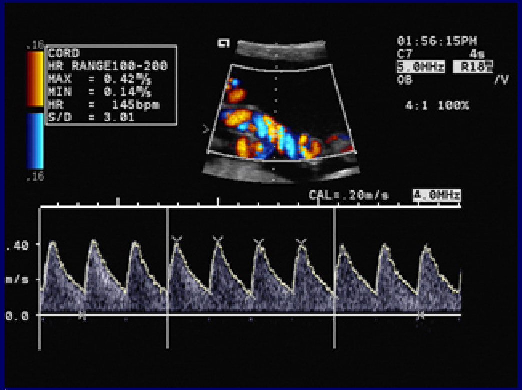
- Heating
- Cavitation

Cavitation

- Formation and behavior of gas bubbles in acoustic fields.
- Transient cavitation: sudden growth and collapse of bubbles, resulting shock waves and very high temperatures.



Clinical Applications



(From www.acuson.com)

- Cardiology, abdominal, surgical, intra-vascular, …etc.

Characteristics of Diagnostic Ultrasound

- Non-invasive.
- Safe (under regulations).
- Real-time.
- Reflection mode (similar to RADAR).
- Blood flow imaging.
- Portable.
- Body type dependent.

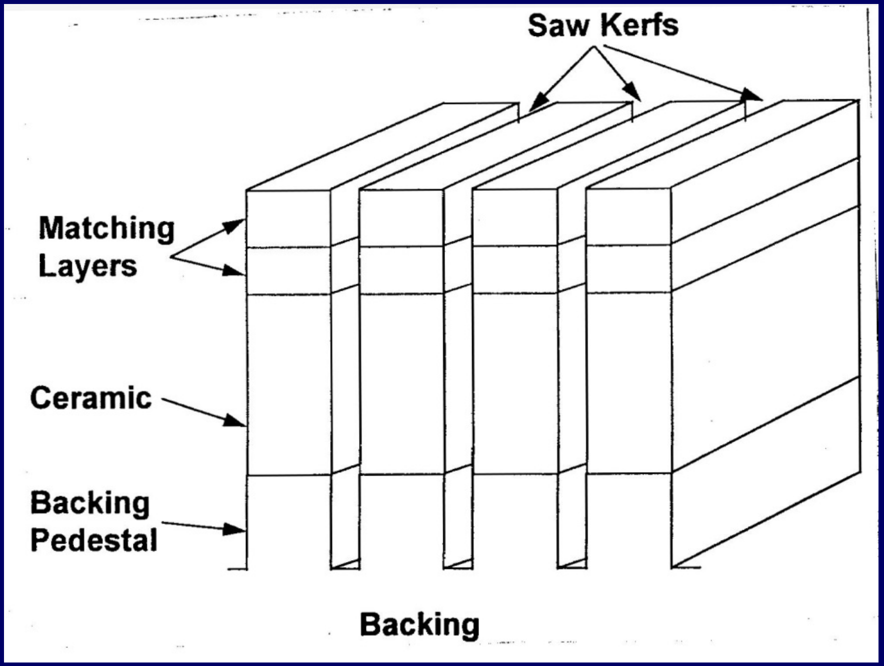
Characteristics of Diagnostic Ultrasound

- Spatial resolution:
  - Lateral and elevational: diffraction limited.
  - Axial: transducer and system bandwidth, pulse energy.
- Contrast resolution: spatial resolution and speckle brightness variations.
- Temporal resolution: speed of sound in tissue.

Ultrasonic Transducers

Ultrasonic Array Transducers

(From www.acuson.com)



Generic Ultrasonic Imaging System

- Receiver:
  - Programmable apodization, delay control and frequency control.
  - Arbitrary receive direction.
- Image processing:
  - Pre-detection filtering.
  - Post-detection filtering.
- Scan converter: various scan format.

Spatial Fourier Transform

- Temporal frequency:

$$f = \frac{1}{T}\,[Hz] \quad \rightarrow \quad \omega = 2\pi f\ [\text{rad.s}^{-1}] \quad ; \quad \omega T = 2\pi$$

- Spatial frequency:

$$\tilde{f} = \frac{|1}{\lambda} = \frac{1}{cT} = \frac{f}{c}\ [\text{m}^{-1}] \quad \rightarrow \quad k = 2\pi\tilde{f}\ \ [\text{rad.m}^{-1}] \quad ; \quad k\lambda = 2\pi$$

$$k = 2\pi\tilde{f} = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} = \frac{2\pi}{cT}$$

Spatial Fourier Transform

- Non-propagating signal:

$$p(t) = p_0 \times \cos(\omega t)$$

- Propagating signal:

$$p(t,z) = p_0 \times \cos(\omega(t - z/c)) = p_0 \times \cos(2\pi f(t - z/c))$$

$$= p_0 \times \cos[2\pi(ft - \tilde{f} z)] = p_0 \times \cos(\omega t - kz)$$

$$e^{j(\omega t - kz)} = e^{j2\pi(ft - \tilde{f}z)} = e^{j2\pi(ft - f\frac{z}{c})} = e^{j2\pi f(t - \frac{z}{c})}$$

Spatial Fourier Transform

- Spatial frequency as a vector:

$$\vec{k} = \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix} \qquad \tilde{f} = \begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \\ \tilde{f}_3 \end{pmatrix} = \frac{1}{2\pi} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}$$

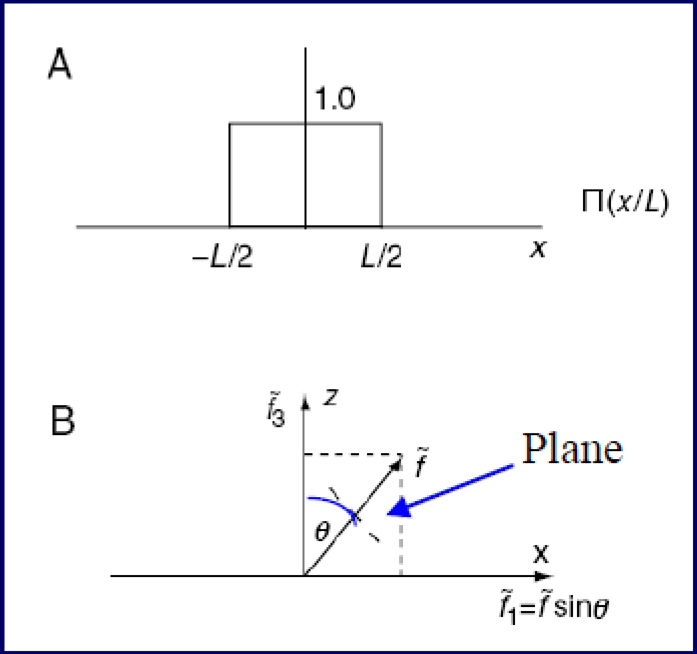
$$\vec{k} = (k_1, k_2, k_3)^t \qquad \vec{k} = (k_x, k_y, k_z)^t$$

- Spatial Fourier transform:

$$G(\tilde{f}) = \int_{-\infty}^{+\infty} g(x) e^{-j2\pi\tilde{f}x} dx$$

Spatial Fourier Transform

- Spatial FT for a linear source in x-z plane:



$$k_1 = k\sin(\theta)$$

$$k_3 = k\sqrt{1-\sin^2\theta}$$

$$k_3 = \sqrt{k^2 - k_1^{\,2}}$$

Spatial Fourier Transform

- Spatial FT for a linear source in x-z plane:

$$G(\tilde{f}_1) = \int_{-\infty}^{+\infty} \Pi(\frac{x}{L}) e^{j2\pi \tilde{f}_1 x} dx = L \sin c(-L\tilde{f}_1)$$

$$= L \sin c(L\tilde{f}_1) = L \sin c(L\tilde{f} \sin(\theta))$$

Zeros at $L\tilde{f} \sin(\theta)$ = integer

$\tilde{f} = 1/(L \sin(\theta))$ →

Increase in L and θ compresses the spectrum

Spatial Fourier Transform

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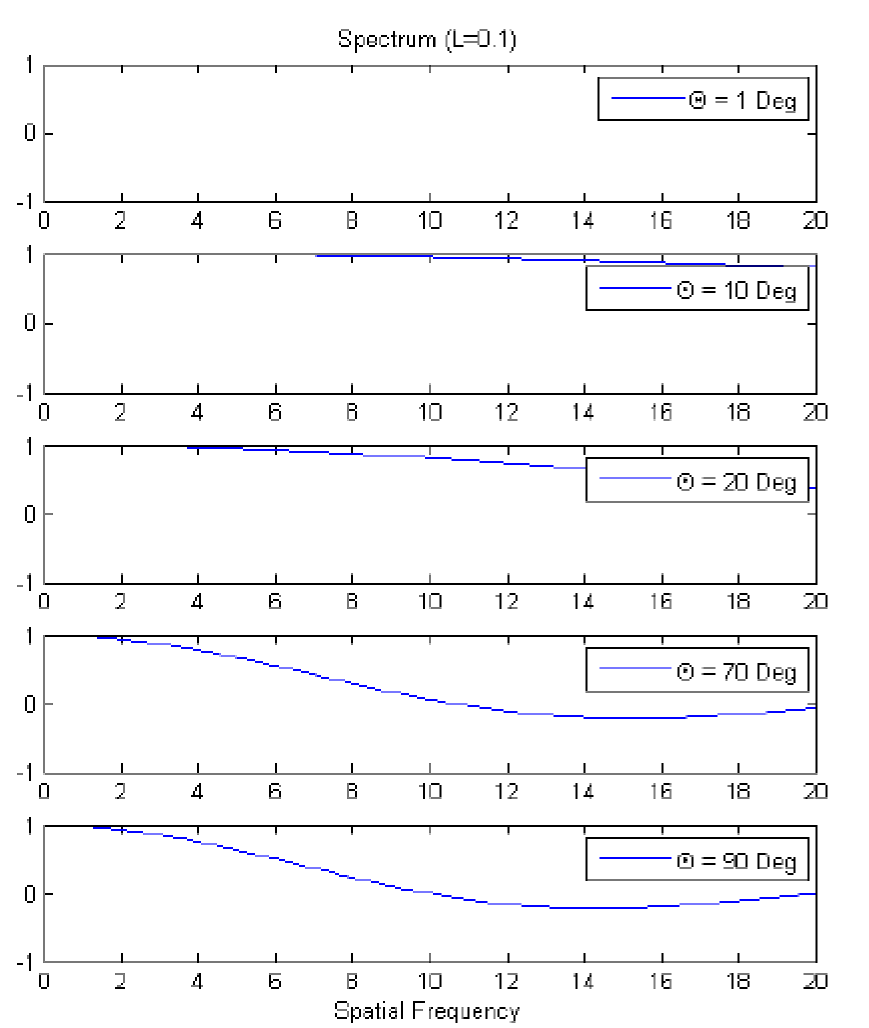

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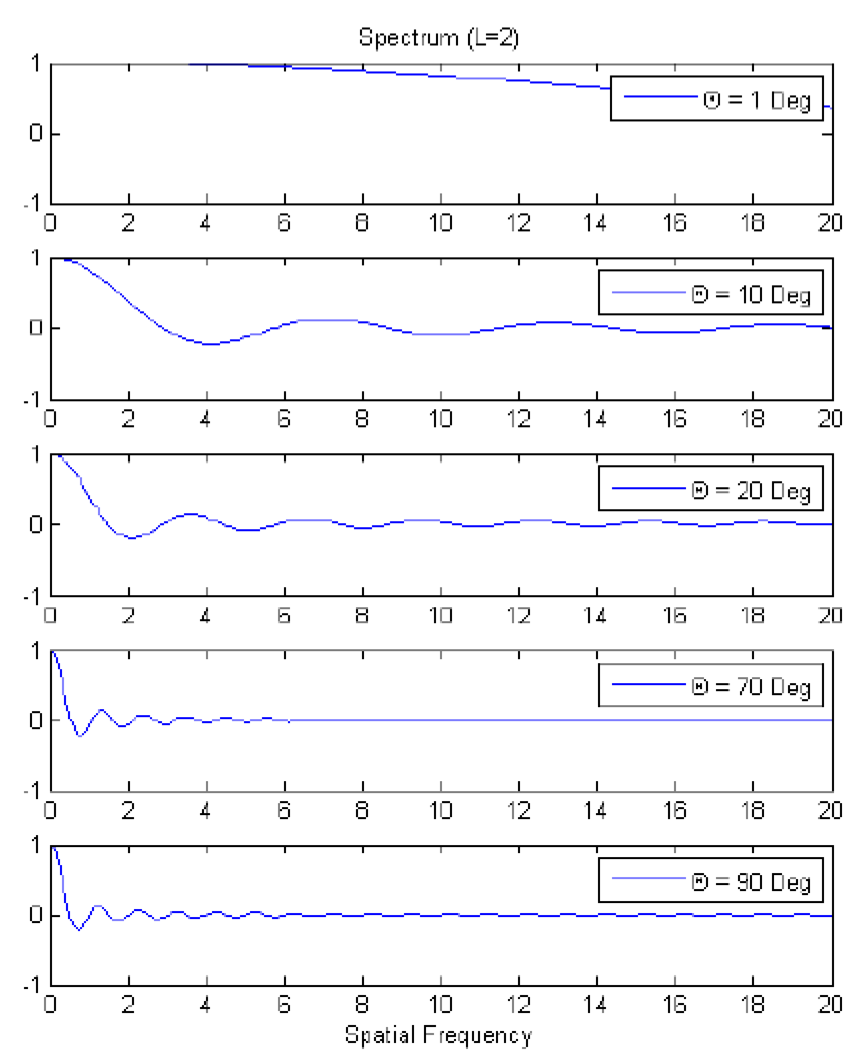

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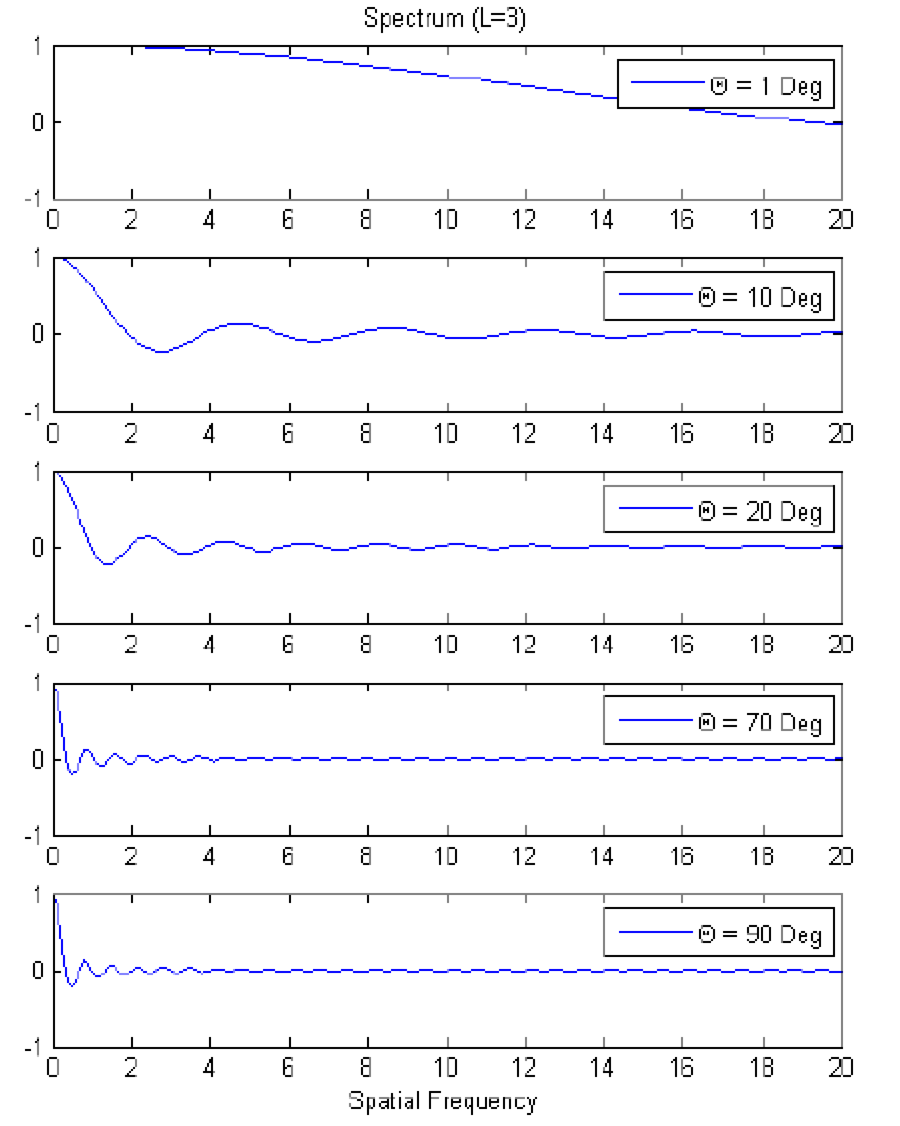

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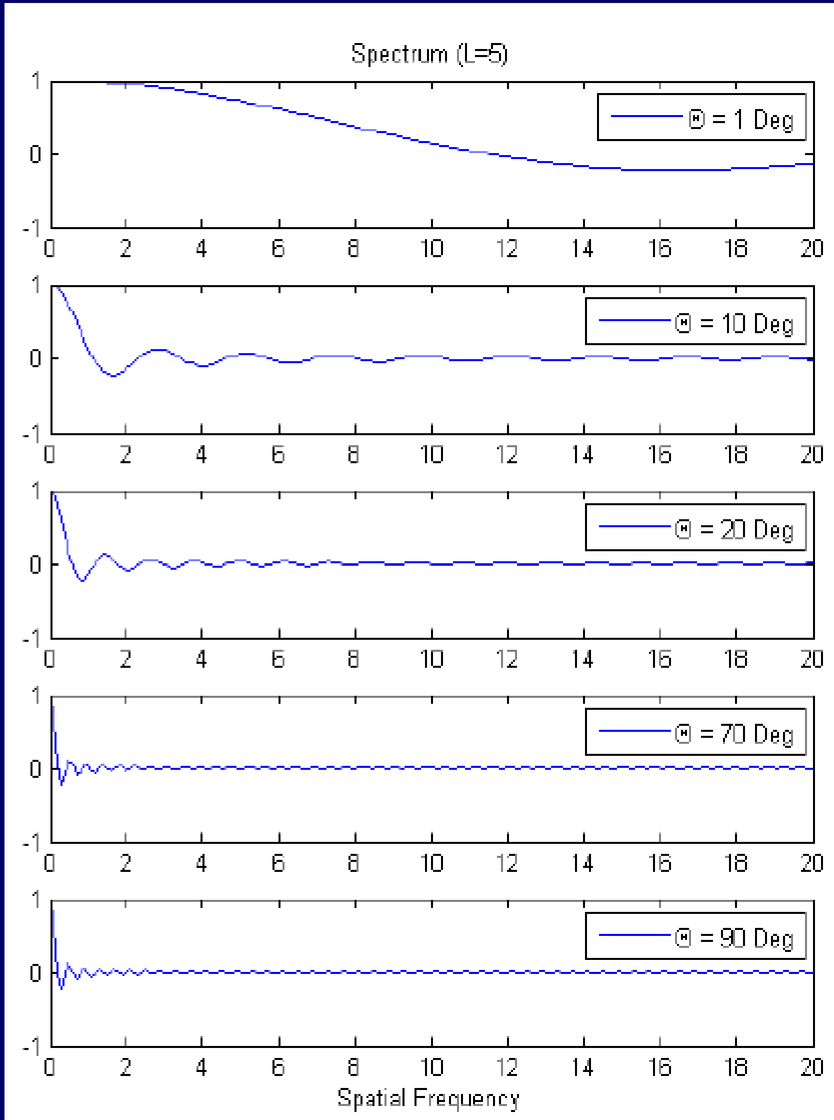

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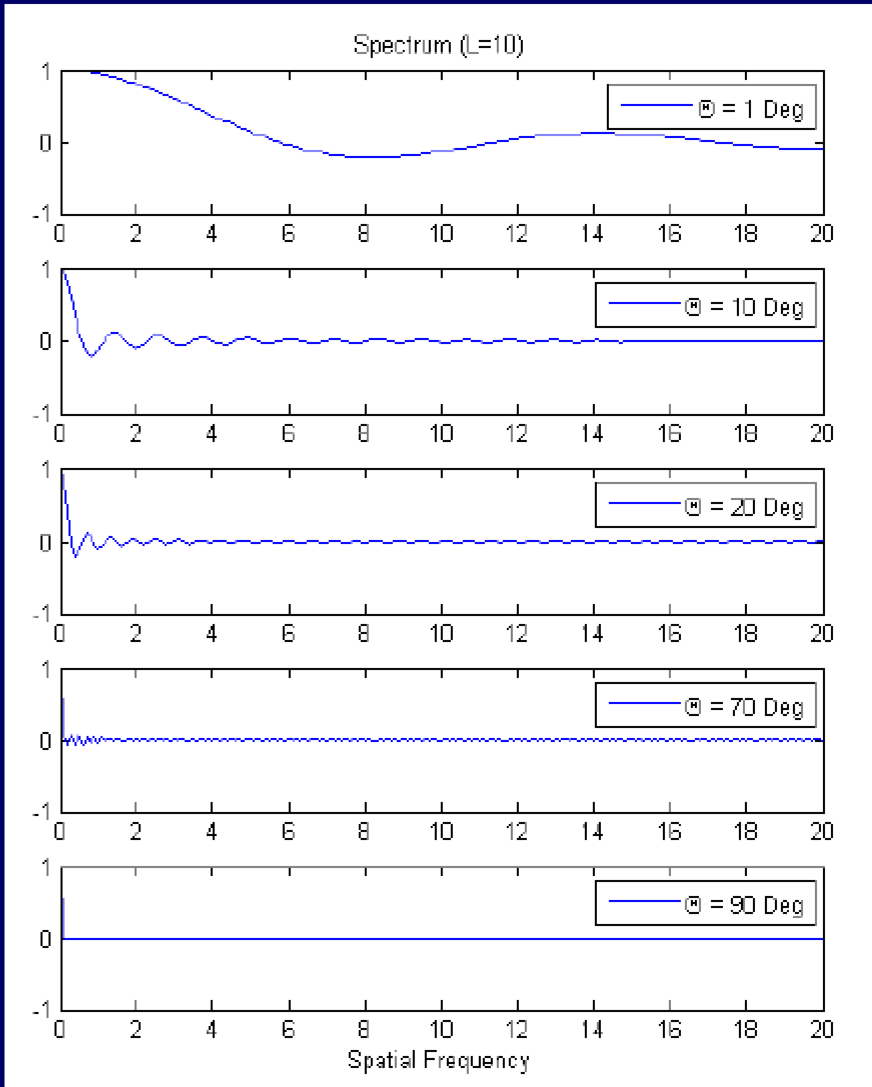

Spatial Fourier Transform

- Spatial FT for a linear source in x-z plane: