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:
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- Journals:
  - IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control.
  - IEEE Transactions on Medical Imaging
  - Journal of Acoustical Society of America
Medical Ultrasound Course
(25-636)

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

Who are the smart guys?
History of Ultrasound

• A long time ago:
History of Ultrasound

• A long time ago:
History of Ultrasound

• 1822, Lake Geneva:
History of Ultrasound

• Piezoelectric effect, Pierre Curie, 1880:
History of Ultrasound

• 1954-1957:
History of Ultrasound

• 1954-1957:
History of Ultrasound

• Doppler (1842):
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

\[ t_1 = \frac{2d_1}{c_{avg}} \]

\[ d_1 = t_1 \cdot c_{avg}/2 \]

\[ d_2 = t_2 \cdot c_{avg}/2 \]

\[ d = c_{avg} \left( t_2 - t_1 \right)/2 \]
Basics
Basics

• Characteristic Impedance:

\[ Z = \rho \times c \]

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

\( c (m/s) \): Propagation Speed
Amplitude of Acoustic Wave Pressure

\[ RF = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} = \frac{P_{\text{ref}}}{P_{\text{in}}} \]
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
Scan Formats

linear

sector

curved linear

easy access

limited access

wide view

limited view

wide view

wide view
3D Ultrasound
Doppler-Mode

- Doppler Effect

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

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

\[ f_{\text{Doppler}} = f' - f_0 = \frac{v}{c}f_0 \]
Doppler Effect
Doppler-Mode

• Doppler Effect

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

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<th>CT</th>
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<td>100 هزار دلار</td>
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<td>1 میلیون دلار</td>
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<td>قابلیت حمل</td>
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Ultrasound Developments

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

• Contrast improvement:
  – Contrast agents (containing bobbles for THI and Endothelial Dysfunction measurement)
Ultrasound Developments

• Miniaturization:
  – Decreasing the weight to a few hundred grams.
  – Leads to more invasive applications
Ultrasound Developments

- 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

- Cardiology, abdominal, surgical, intravascular, ... etc.

(From www.acuson.com)
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:
  \[ f = \frac{1}{T} \text{ [Hz]} \quad \Rightarrow \quad \omega = 2\pi f \text{ [rad.s}^{-1}] \quad ; \quad \omega T = 2\pi \]

• Spatial frequency:
  \[ f = \frac{1}{\lambda} = \frac{1}{cT} = \frac{f}{c} \text{ [m}^{-1}] \quad \Rightarrow \quad k = 2\pi f \text{ [rad.m}^{-1}] \quad ; \quad k\lambda = 2\pi \]
  \[ k = 2\pi f = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} = \frac{2\pi}{cT} \]
Spatial Fourier Transform

• Non-propagating signal:

\[ p(t) = p_0 \times \cos(\omega t) \]

• Propagating signal:

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

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

\[ e^{j(\omega t-kz)} = e^{j2\pi (ft-\tilde{f} z)} = e^{j2\pi (ft-f\frac{z}{c})} = e^{j2\pi (t-\frac{z}{c})} \]
Spatial Fourier Transform

- Spatial frequency as a vector:

\[
\vec{k} = \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}, \quad \vec{f} = \begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \\ \tilde{f}_3 \end{pmatrix} = \frac{1}{2\pi} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}
\]

\[
\vec{k} = (k_1, k_2, k_3)^t, \quad \vec{k} = (k_x, k_y, k_z)^t
\]

- Spatial Fourier transform:

\[
G(\vec{f}) = \int_{-\infty}^{+\infty} g(x)e^{-j2\pi\vec{f}\cdot \vec{x}} \, dx
\]
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:

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

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

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

\[ \tilde{f} = 1/(L\sin(\theta)) \]

Increase in L and \( \theta \) compresses the spectrum
Spatial Fourier Transform

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

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