BIOMEDICAL ULTRASOUND

Goals:
To become familiar with:

- Ultrasound wave
- Wave propagation and Scattering
- Mechanisms of Tissue Damage
- Biomedical Ultrasound Transducers
Biomedical Ultrasound Imaging

Ultrasonic nondestructive evaluation (NDE)

Any other applications?
Background

- Ultrasound is a mechanical vibration of matter with a frequency above the audible range (>20 kHz).
- The wave is propagating through the medium as a disturbance of the particles in the medium supporting the wave.
- Particles will oscillate around their mean positions in 3D manner.

- Particle Oscillations
  - along the wave propagation direction termed “Longitudinal waves”.
  - transverse to the wave propagation direction termed “Shear waves”.
In general, Liquids, soft tissue, gas produce only Longitudinal (Dilational or pressure) waves

Where solids can produce both shear and longitudinal waves, each is traveling with different speed.

Pressure wave speed in Fluids is given by:

\[ c = \sqrt{\frac{1}{\rho \kappa}} \]

where,

\( \kappa \) is the fluid compressibility coefficient
\( \rho \) the mass density
Wave Motion

The acoustic pressure of the harmonic plane wave is described by:

\[ P(t, z) = p_0 e^{i(kz - \omega t)} \]

where,

\( \omega \) is the angular frequency of the wave

\( k \) the wave number given by \( k = \omega / c \)
The acoustic impedance ($Z$) defined as the ratio of the acoustic pressure at a point in the medium to the particle speed at the same point.

For plane wave:

$$Z = \frac{p}{u}$$

$$Z = \rho c$$

The acoustic impedance is of considerable importance in characterizing the propagation of plane waves.
Reflection & Transmission

- A propagating wave will be partly reflected when encountered a medium with dissimilar acoustic properties ($Z$).

- Reflection coefficient:

- Transmission coefficient:

- Snell’s Law:
Table 1. Density, Speed of Sounds and Acoustics Impedance of human tissue (Goss et al 1978;1980)

<table>
<thead>
<tr>
<th>Medium</th>
<th>Density (kg/m$^3$)</th>
<th>Speed of Sound (m/s)</th>
<th>Acoustic Impedance (kg/m$^2$.s) x10$^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.2</td>
<td>333</td>
<td>0.0004</td>
</tr>
<tr>
<td>Blood</td>
<td>1060</td>
<td>1566</td>
<td>1.66</td>
</tr>
<tr>
<td>Bone</td>
<td>1380-1810</td>
<td>2070-5350</td>
<td>3.75-7.38</td>
</tr>
<tr>
<td>Brain</td>
<td>1030</td>
<td>1505-1612</td>
<td>1.55-1.66</td>
</tr>
<tr>
<td>Fat</td>
<td>920</td>
<td>1446</td>
<td>1.33</td>
</tr>
<tr>
<td>Kidney</td>
<td>1040</td>
<td>1567</td>
<td>1.62</td>
</tr>
<tr>
<td>Lung</td>
<td>400</td>
<td>650</td>
<td>0.26</td>
</tr>
<tr>
<td>Liver</td>
<td>1060</td>
<td>1566</td>
<td>1.66</td>
</tr>
<tr>
<td>Muscle</td>
<td>1070</td>
<td>1542-1626</td>
<td>1.65-1.74</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>1480</td>
<td>1.48</td>
</tr>
</tbody>
</table>
Ultrasound Intensity

- Acoustic intensity of a wave is the time average flow of energy through a unit area.

\[ I = \frac{1}{T} \int_{0}^{T} p u \, dt \]

- We know that

\[ p(t) = p_0 e^{i(kz-\omega t)} \],  and  \[ u(t) = \frac{p(t)}{Z} \]

thus,

\[ I = \frac{p_0^2}{2Z} \]
Example: A plane wave with an intensity of 50 mW/cm² and a frequency of 3 MHz is propagating in connective tissue (blood). What is the pressure, particle displacement, and velocity for this continuous wave?

Solution:  
Intensity is given by: \( I = \frac{P_0^2}{2Z} \), \( Z_{\text{blood}} = 1.66 \times 10^6 \text{ kg/m}^2\cdot\text{s} \)

\[ p = \sqrt{2IZ} = 40.74 \text{ kPa} \]

The particle velocity is

\[ u = \frac{p}{Z} = 24.5 \text{ mm/sec} \]

Particle displacement:

\[ z_0 = \frac{u}{\omega} = 1.31 \text{ nm} \]

Is it safe?
Home Work

Use Excel spread sheet, or any other convenient programming tool to compute the pressure, particle displacement, and velocity for continuous wave with Intensity (= 50 mW/cm$^2$) and wave frequency (= 3MHz) propagating in tissue, using the acoustic properties illustrated in Table 1. Discuss your results.
Scattering

- Reflected waves play a role in scattering and thus imaging.
- Small changes in density, compressibility, and absorption give rise to a scattered wave.
- Ultrasound scanners are optimized to detect very small scattered signals.
Wave scattering magnitude $P_{sc}$ is usually measured by the scattering cross-section $\sigma_{sc}$

$$P_s = I_i \sigma_{sc}$$

The scattering intensity is given by:

$$I_s = \frac{\sigma_{sc}}{4\pi R^2} I_i$$

where $R$ is the distance.

Ultrasound wave propagating in tissue will be attenuated because of absorption and scattering.

Attenuation is linearly dependent on frequency (*most materials*)

Commonly used unit for attenuation: dB/MHz.cm

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**Table 3. Attenuation values for human tissue (Haney and O’Brien 1986)**

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Attenuation (dB/MHz.cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td>Kidney</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>Fat</td>
<td>1.0-2.0</td>
</tr>
<tr>
<td>Blood</td>
<td>0.17-0.24</td>
</tr>
<tr>
<td>Bone</td>
<td>16.0-23.0</td>
</tr>
</tbody>
</table>
Mechanisms of Tissue Damage

- **Thermal Effect**
  - Local heating produced by ultrasound wave is directly related to the intensity of ultrasound wave at any point in the medium.
  - The rate of increase in temperature has a direct relationship with ultrasound intensity and degree of absorption and is inversely proportional to tissue density and specific heat, *i.e.*
    \[
    \frac{dT}{dt} = \frac{2\alpha I}{\rho C_m}
    \]
  - Studies show that absorption are primarily related to the concentration of proteins.
  - In general, muscles (dense media) do not heat as fat.
Mechanisms of Tissue Damage

- **Cavitation Effect:**
  - Cavitation describe the formation, growth, and dynamic behavior of gas bubble irradiated by ultrasound.
  - In pure liquid, cavitation occur when the local pressure falls below the vapor pressure of a fluid and gas “boils”
  - Sound-induced oscillations of microbubbles causes gas to diffuse inward and outward during each cycle, because of pressure change inside the bubbles.
  - In water, a bubble resonating at 1 MHz with 100 mW/cm\(^2\) can take 60 µW (90% of which convert to heat!)
  - It is estimated that 1 µm cavity collapsing in solid can create a local pressure of 1000 atm!
  - The internal temperature of a bubble could reach 1000 °C.
  - But, however, tissue viscosity is 100 times greater than water, and therefore, bubble motion is greatly limited.
American Institute of Ultrasound in Medicine (AIUM 1988) recommendations:

“In the low megahertz range there have been (as of this date) no independent confirmed significant biological effects in mammalian tissues exposed in vivo to unfocused ultrasound with intensities below 100 mW/cm². Furthermore, for exposure time greater than 1 second and less than 500 seconds (for focused ultrasound) such effect have not been demonstrated even at higher intensities, when the product of intensity and exposure time is less than 50 joules/cm²”
The spatial peak average intensity ($I_{sppa}$) is a measure of ultrasound intensity for medical safety approved by FDA:

$$I_{sppa} = \frac{\int p^2(t) \, dt}{\rho c \cdot PD}$$

$PD$ is the pulse duration

Table 2. Maximum known acoustic field emissions for commercial scanners as stated by FDA

<table>
<thead>
<tr>
<th>USE</th>
<th>$I_{sppa}$ (W/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac</td>
<td>65</td>
</tr>
<tr>
<td>Peripheral</td>
<td>65</td>
</tr>
<tr>
<td>Ophthalmic</td>
<td>28</td>
</tr>
<tr>
<td>Fetal Imaging</td>
<td>65</td>
</tr>
</tbody>
</table>
Ultrasound transducers generate acoustic waves by converting electrical energy to mechanical energy.

Most common technique for medical ultrasound uses the piezoelectric effect.

Piezoelectric transducers convert an oscillating signal into acoustic wave, and vice versa.

Real-time imaging would provide an instantaneous feedback with steering and focusing features.

Steering and focusing would be achieved by applying variable delay time.
TYPES OF ARRAY ELEMENTS

- **Linear Sequential Array**
  - Has as many as 512 elements
  - Acoustic beam can be focused but not steered
  - Adv: High sensitivity when the array is directed straight ahead
  - Disadv: Field of view is limited.

- **Curvilinear (Convex) Array**
  - Similar to linear arrays, but scans a wider field of view.
TYPES OF ARRAY ELEMENTS

- Linear Phased Array
  - Has 128 elements.
  - All elements are used to transmit and receive each line of data.
  - Typical for scanning through restricted acoustic windows
  - Ideal for cardiac imaging, since they can avoid the obstructions of the ribs (bone) and lungs (air).

- 2D Phased Array
  - A 3D imaging tool, with features similar to the linear Phase-Array transducers
ULTRASOUND TRANSDUCERS

Field II (Jensen et al., 1996)

Diagram showing the layout of ultrasound transducers with dimensions and element numbers indicated.
LINEAR ARRAY

Field II (Jensen et al, 1996)
2D LINEAR ARRAY

Field II (Jensen et al, 1996)
2D FOCUSED ARRAY

Field II (Jensen et al, 1996)
FOCUSED MULTI-ROW ARRAY

Field II (Jensen et al, 1996)
Convex Array

Field II (Jensen et al, 1996)
Capacitive Micromachined Ultrasound Transducers

Sensant, Inc.
SPATIAL RESOLUTION

- **Axial Resolution**

\[
\theta_z = \frac{\lambda}{2} = \frac{c}{2f}
\]

- **Lateral Resolution**

\[
\theta_x = \sin^{-1} \left( \frac{\lambda}{D} \right)
\]
DESIGNING A PHASED-ARRAY TRANSDUCER

- Choosing Array Dimensions:
  - Element Thickness ($t$):
    \[ t = \frac{\lambda_t}{2} = \frac{c_t}{2f} \]
    where $c_t$ = longitudinal speed in the transducer material
  - Element width and length:
    \[ \frac{w}{t} \leq 0.6 \quad \text{and} \quad \frac{l}{t} \geq 10 \]

To avoid the lateral modes
DESIGNING A PHASED-ARRAY TRANSDUCER

- Element Spacing

\[ d = \frac{\lambda}{2} \]

To eliminate grating lobes

- Acoustic Backing and Matching Layers:
  - Improve the transducer bandwidth and sensitivity
  - A low impedance acoustic backing layer reflects the acoustic pulse toward the front side of the transducer
  - Acoustic Matching layer maintain adequate bandwidth of the propagating and scattered signals.