Medical Imaging (EL582/BE620/GA4426)

Ultrasound Imaging

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Reference

Prince and Links, Medical Imaging Signals and Systems, Chap. 10 (Math derivations in section 10.5 not required),11.2,11.3

Acknowledgement

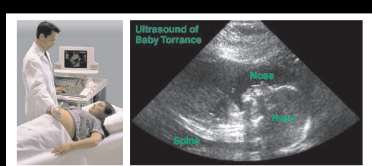
Thanks to Professor Yao Wang for use of her course materials!

Ultrasound Imaging

- Measure the reflectivity of tissue to sound waves
- Can also measure velocity of moving objects, e.g. blood flow (Doppler imaging)
- No radiation exposure, completely non-invasive and safe (*)
- Fast
- Inexpensive (relatively)

Medical Ultrasound Imaging

- Medical applications: fetus, heart, abdominal,…
- 3-10 MHz
- ≤ 1 mm resolution (limited contrast)
- ≥ 60 images per second



In vivo microimaging in mice

Ultrasound Biomicroscopy (UBM)

- 40-50 MHz ultrasound
- 50-80 μm lateral resolution, better axial
- up to 1000 images/s

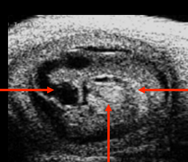
E10.5 embryo

E12.5 heart

1 mm

UBM of Mouse Embryos

APPLICATIONS



- Brain imaging
- Image-guided injections

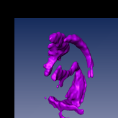
- Vascular imaging
- Blood flow (Doppler)
- Tumors

- Cardiac imaging
- (Image-guided injections)

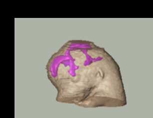
Ultrasound biomicroscopy enables in utero volumetric brain analysis

E13.5 Mouse Embryo

In utero UBM



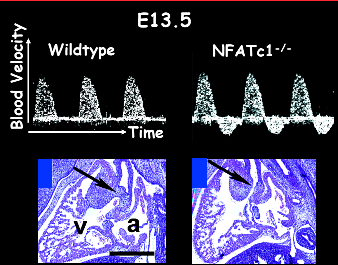
Ventricle Segmentation



3D rendering

Aristizábal et al, Ultrasound Med Biol, 2006

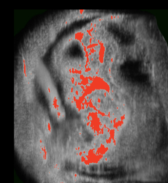
UBM-Doppler provides sensitive analysis of cardiovascular function



Phoon et al, Circ Res, 2004

Molecular imaging with ultrasound: targeted microbubbles

Microbubbles targeted to vascular endothelial cells in E11.5 mouse embryos

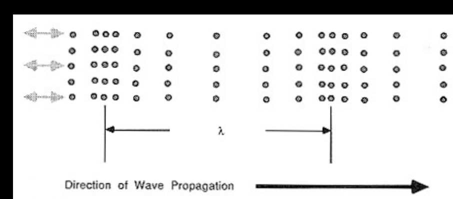


Bartelle et al, Circ Res, 2012

Acoustic Waves

- Pressure waves that propagate through matter via compression and expansion of the material
  - Generated by compressing and releasing a small volume of tissue
- Longitudinal wave
  - Particles in the medium move back and force in the same direction that the wave is traveling
- Shear Wave
  - Particles move at right angles to the direction of the wave
  - Not used for medical ultrasound imaging

Longitudinal Wave



EM vs Acoustic Waves

- **Electromagnetic**
  - Self propagating, consisting of electric and magnetic components oscillating at right angles to each other, and to propagation direction
  - Does not *require* a material medium through which to propagate
  - Classification (increasing in frequency, decreasing in wavelength):
    - radio, microwave, infrared, visible light, ultraviolet, x-ray, gamma ray
- **Acoustic**
  - Pressure waves that propagate through matter via compression and expansion of the material
  - Requires a material medium through which to propagate
  - Classification (increasing in frequency, decreasing in wavelength):
    - Infra sound, audible sound, ultrasound

Transfer / Transformation of Energy

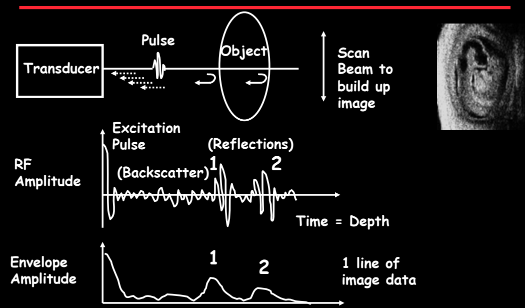
- Light becomes sound — photoacoustic phenomena
- Sound becomes light — sonoluminescence
- Absorbed electromagnetic (EM) and acoustic energy both become heat
- Nevertheless, EM and acoustic energy are FUNDAMENTALLY DISTINCT PHENOMENA!

Acoustic Wave Energy Ranges

Infrasound	Audible	Ultrasound
	20 Hz	20 kHz

- Just as there are infrared, visible, and ultraviolet ranges in the EM spectrum, so there are infrasound ("infra" = "below," "beneath"), audible (i.e., sound) and ultrasound ("ultra" = "beyond," "above") ranges of acoustic wave frequencies
- Note that the ratio of the highest to the lowest audible frequencies is 10^3, while the ratio of the highest to the lowest frequencies of *visible light* is a bit less than 2!

Pulse-Echo Ultrasound Imaging



Speed of Sound

- Each medium has a characteristic speed
  - c [m/s] = λ[μm] x f [MHz] = wavelength x frequency
- Approximate ultrasound speeds

Air	330 m/s
Water	1500
Muscle	1600
Fat	1480
Bone	3000

Image frame rate is determined by sound speed

- Sound speed = 1540 m/s = 1.54 mm/μs
- 256 line image / Depth = 10 mm

Propagation length = 20 mm (2-way)
Time per line = 20/1.54 ~ 13 μs

Time per image = 13 x 256 = 3300 μs = 3.3 ms

Frame rate = 1/3.3 ms ~ 300 images/s

Ultrasonic Waves

- Ultrasound imaging relies on the propagation of sound within tissue
- Mechanical (pressure) wave
- Pressure distribution

3D Wave Equation

- Acoustic pressure: $p(x, y, z, t)$
- 3-D wave equation

$$\nabla^2 p(x, y, z, t) = \frac{1}{c^2} p_{tt}(x, y, z, t)$$

where

$$\nabla^2 p = p_{xx} + p_{yy} + p_{zz}$$

and c is the speed of sound
- General solution is very complicated

Plane Wave

- Plane wave in z direction:

$$p(z,t) = p(x,y,z,t)$$

- Plane wave equation:

$$p_{zz}(z,t) = \frac{1}{c^2} p_{tt}(z,t)$$

- General solution:

Forward traveling wave **Backward**

$$p(z,t) = \phi_f(t - c^{-1}z) + \phi_b(t + c^{-1}z)$$

Harmonic Waves

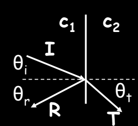
- Harmonic plane wave:
  p(z,t) = cos(k[z-ct])
- Viewed at a fixed particle, the pressure changes in time with frequency
  f_t=kc/2π (cycles/s)
- Viewed at a fixed time, the pressure changes in z with frequency
  f_z=k/2π
  - k is called wavenumber
- Wavelength is the spacing between peak or valleys of the wave at any time
  - λ=1/f_z=2π/k=c/f_t
- (approximately) Harmonic wave are widely used in ultrasound imaging
- Given f_t, the wavelength depends on c, which depends on tissue properties!
  - Wavelength determines the resolution of ultrasound imaging
  - Ex: f_t=3.5 MHz, c=1540m/s (most tissue), λ=0.44mm

Reflection/refraction: Snell's Law

- Reflection / refraction at interfaces follows Snell's law:

$$\frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{c_1}{c_2}$$

$$\theta_i = \theta_r$$



Acoustic Impedance

- Acoustic Impedance, Z [MRayl = 10^6 kg/m^2/s]

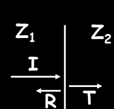
Z = density [kg/m^3] x sound speed [m/s]

- **Determines the amplitude of the reflected / transmitted waves at interface**
- **Complex scattering properties of tissues are due to acoustic impedance interfaces in microstructure of tissues**

Reflection at Interfaces

Reflection Coefficients:
(Normal Incidence)

Reflection: R = $|(Z_2-Z_1)/(Z_2+Z_1)|$

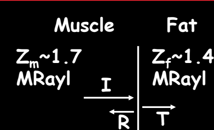


Transmission:

T = 1-R
= $2Z_2/(Z_2+Z_1)$

Reflection at Interfaces: Example

Reflected Sound Pressure:



R/I = $|(Z_f-Z_m)/(Z_f+Z_m)|$
= 0.3/3.1
~ 0.1 (10% = -20dB)

Attenuation of Ultrasound

- **Attenuation = Energy lost through interactions between ultrasound waves and soft tissues:**
  - **Absorption:**
    Power deposited in tissue (Heat)
  - **Scattering**
    Ultrasound radiated away from transducer

Attenuation of Ultrasound

- Attenuation is frequency dependent:

  $a(f) = a_o f^n$

  - a_o is the attenuation coefficient at 1 MHz
  - n ~1 for most soft tissues
- Attenuation leads to a decrease in amplitude of the ultrasound signal:

  Attenuation ~ 1 dB / cm / MHz

Attenuation: An Example

What relative amplitude of a 60 MHz ultrasound signal do you expect to receive from a depth of 5 mm?

Attenuation ~ 1 dB / cm / MHz

@ 60MHz: Attenuation ~ 60 dB/cm

Depth = 5 mm: Ultrasound propagates through 1 cm

Attenuation ~ 60 x 1 = 60 dB

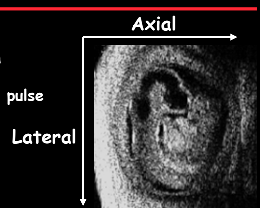
1/1000 of the transmitted signal is received!

Attenuation: Consequences

- **Consequences of frequency dependent attenuation for imaging:**
  - **Penetration of ultrasound is limited by frequency**
  - **Frequency of ultrasound decreases with increasing depth of imaging**

Resolution in Ultrasound Imaging

- **Axial Resolution:**
  - **Resolution in propagation direction**
  - **Determined by length of pulse propagating in tissue**
- **Lateral Resolution:**
  - **Resolution orthogonal to propagation direction**
  - **Determined by focusing properties of transducer**



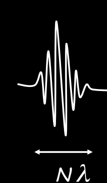
Axial Resolution

- Axial Resolution:

  Axial Resolution

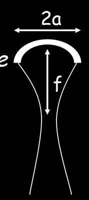
  = pulse width (s) x speed of sound (m/s) /2

  $= N\lambda/2$



Lateral Resolution

- Lateral Resolution:
  f-number = focal length/aperture
  = f/2a
  Lateral Resolution
  = wavelength x f-number
  = λf/2a



Resolution *vs* Penetration

- Resolution (axial and lateral)↑ with ↑frequency
- Penetration↓ with ↑frequency

Compromise between resolution and penetration

Doppler Ultrasound: Basic Concepts

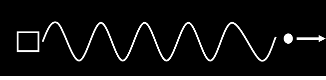
- Ultrasound wave reflected from moving targets (*Blood cells*)
- Frequency shift in received ultrasound wave compared to transmitted wave:
  Doppler Shift Frequency, f_d

Doppler Ultrasound: Basic Concepts

Target (stationary): $f_d = 0$

- Target moves towards transducer:
  - *More compressions per unit time: $f_d > 0$*

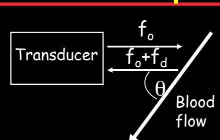
- Target moves way from transducer:
  - *Fewer compressions per unit time: $f_d < 0$*



Doppler Ultrasound: Concepts

- Doppler Equation:

$f_d = 2f_o.v.\cos\theta/c$

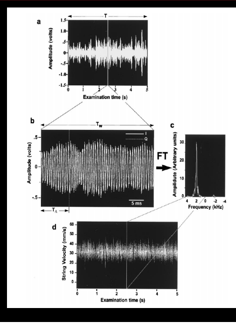


- f_o is the frequency transmitted
- v is the velocity of the moving blood
- c is the sound speed in the medium (blood, ~1600 m/s)

Doppler Equation: Consequences

- Shift frequency is proportional to blood velocity
- f_o = 2-10 MHz, v = 0-5 m/s → f_d = 0-15 kHz
  (Audio frequencies)
- f_d is maximized when blood flow is in-line with ultrasound beam (θ=0)
- f_d = 0 when flow is perpendicular to the beam

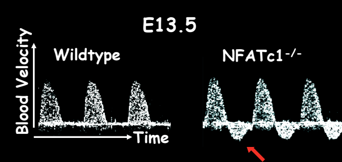
Doppler Data Processing



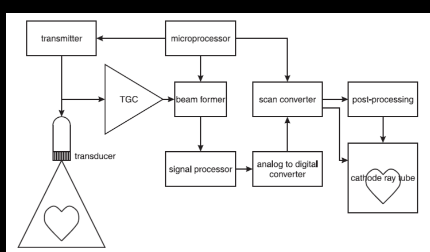
(Aristizabal, Ultrasound in Medicine & Biology 1998)

UBM-Doppler analysis is sensitive to blood flow abnormalities

Flow reversal in mouse mutants with defective cardiac valves



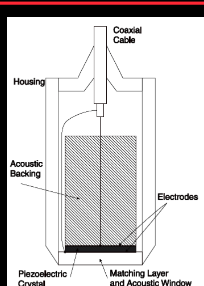
Schematic: Ultrasound Imaging System



Functions of the transducer

- Used both as Transmitter And Receiver
- Transmission mode: converts an oscillating voltage into mechanical vibrations, which causes a series of pressure waves into the body
- Receiving mode: converts backscattered pressure waves into electrical signals

Single Element Transducer

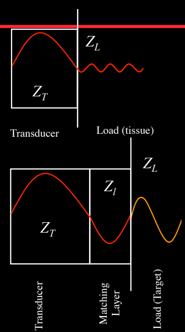


Piezoelectric Material

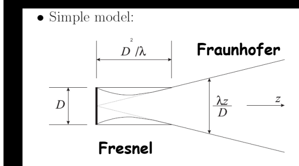
- Converts electrical voltage to mechanical vibration and vice versa
- The thickness of the crystal varies with the applied voltage
- When an AC voltage is applied across the crystal, the thickness oscillates at the same frequency of the voltage
- Examples of piezoelectric Materials:
  - Crystalline (quartz), Ceramic (PZT, lead zirconium titanate), Polymers (PVDF), Composite materials
  - PZT is the most efficient material
- The crystal vibrates sinusoidally after electrical excitation has ended (resonate)
  - Resonant frequency $f=c/2d$ (d=thickness)
  - The damping material damps the vibration after 3-5 cycles
- When the diameter D of the surface is much larger than d, longitudinal waves are transmitted into the body
- The crystal is shaped into a disk or rectangle, with either flat or concave surface

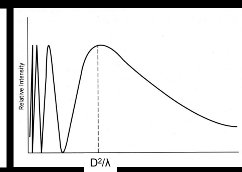
Matching Layer(s)

- To provide acoustic coupling between the crystal and patient skin and to protect surface of the crystal
- Z of PZT (Z_T) is ~15 times greater than Z of tissue (Z_L)
  - Placing crystal directly over skin would result a large amount of energy be reflected back from the boundary
    - » $R = |(Z_L - Z_T)/(Z_L + Z_T)| \sim 1$
- Matching layer
  - layer thickness = $\lambda/4$
  - $Z_I = \sqrt{(Z_T Z_L)}$
  - Maximize energy transfer into the body
  - Show as a homework(*)
- Problems: Finding material with exact Z_l value



Flat (Piston) Plate Transducer



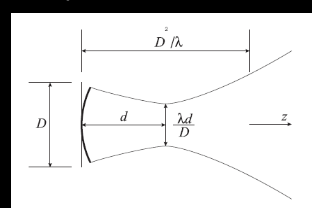


Beam Properties of a Piston Transducer

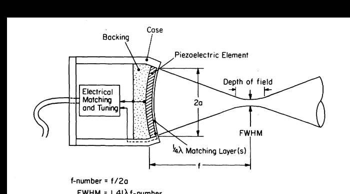
- At border of the beam width, the signal strength drops by a factor of 2, compared to the strength on the z-axis
- Beam width determines the imaging resolution (lateral resolution).
- Smaller D is good only before far field
- D=1~5 cm in practice, very poor lateral resolution
- Focused plate is used to produce narrow beam

Focused Transducer

- Beam focusing can be accomplished by
  - Using a crystal with a curved surface
  - Placing a concave lens in front of the crystal



Single Element Transducer



From: Hunt *et al*, IEEE Trans BME, 1983

Transducer Array

- With a single crystal, manual or mechanical steering of the beam is needed to produce a two-dimensional image
- Practical systems today use an array of small piezoelectric crystals
  - Allow electronic steering of the beam to optimize the lateral resolution

Array types

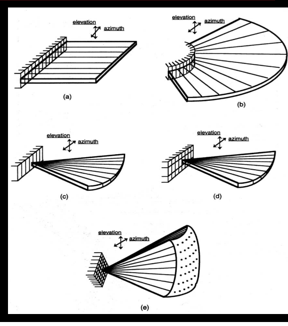
a) Linear Sequential (switched)
~1 cm x 10-15 cm, up to 512 elements

b) Curvilinear
similar to (a), wider field of view

c) Linear Phased
up to 128 elements, small footprint → cardiac imaging

d) 1.5D Array
3-9 elements in elevation allow for focusing

e) 2D Phased
Focusing, steering in both dimensions



Homework

- **Reading:**
  - Prince and Links, Medical Imaging Signals and Systems, Chap. 10 (Sec. 10.5 not required),11.2,11.3
- **Problems:**
  - P10.1
  - P10.3
  - P10.6
  - P10.8
  - P10.12
  - P10.13
  - Considering the (λ/4) matching layer in a transducer. Show that the transmitted energy into the tissue is maximized with an impedance of $\sqrt{(Z_T Z_L)}$