Northeastern University
College *of* Engineering

Biomedical Imaging
Ultrasound

Charles A. DiMarzio
EECE–4649
Northeastern University

May 2018

Ultrasound Agenda

- Ultrasound Waves
- Interactions with Materials
- Pulses and Transit Time
- A–Scans
- B–Scans
- More Scans
- Sources and Detectors
- Doppler Ultrasound
- Mixed Modalities: PAT, UOT, *etc.*
- Ultrasound Therapy

A Wave is a Wave. . .

- Pressure Difference Causes Acceleration

$$-\nabla P = \rho a = \rho \frac{\partial \mathbf{v}}{\partial t}$$

- Convergence Increases Pressure

$$K \nabla \mathbf{v} = \frac{\partial P}{\partial t}$$

- Solve for Pressure

$$\nabla^2 P = \frac{\rho}{K} \frac{\partial^2 P}{\partial t^2}$$

- Plane Wave Solution

$$P = P_0 e^{-j(\omega t - kz)}$$

Plane Waves

- Plane Wave (Previous Page)

$$P = P_0 e^{-j(\omega t - kz)}$$

- Speed

$$c = \frac{K}{\rho}$$

- Impedance

$$Z = \rho c$$

- Reflection

$$R = \frac{\frac{\rho'}{\rho}\cos\theta - n\sqrt{1 - \frac{\sin^2\theta}{n^2}}}{\frac{\rho'}{\rho}\cos\theta + n\sqrt{1 - \frac{\sin^2\theta}{n^2}}} = \frac{\cos\theta - \frac{Z}{Z'}\sqrt{1 - \frac{\sin^2\theta}{n^2}}}{\cos\theta + \frac{Z}{Z'}\sqrt{1 - \frac{\sin^2\theta}{n^2}}}$$

Impedance Matching

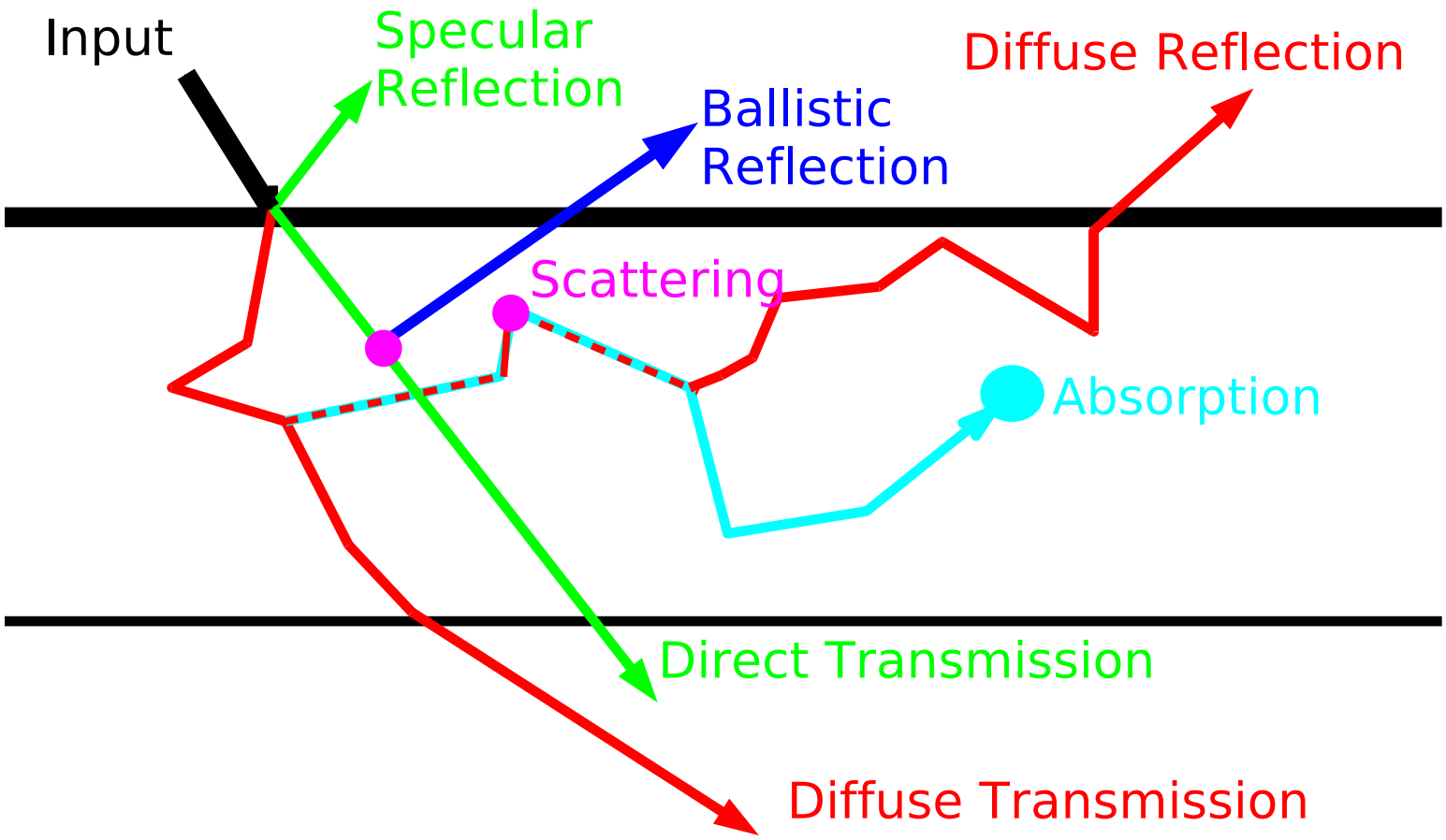
- Reflection Equation

$$R = \frac{\cos\theta - \frac{Z}{Z'}\sqrt{1 - \frac{\sin^2\theta}{n^2}}}{\cos\theta + \frac{Z}{Z'}\sqrt{1 - \frac{\sin^2\theta}{n^2}}}$$

$$Z = \rho c$$

- Match speed and density
- ρc (Rosy!) Rubber
- Acrylamide Gel (Optical Match Too)

Waves Interactions



(and reverberation, cavitation)

Impedance

Sound Speed and Impedance

Material	Velocity (mm/μs)	Impedance(MRayl)
Water	1.48	1.48
Blood	1.57	1.61
Liver	1.55	1.65
Kidney	1.56	1.62
Muscle	1.58	1.70
Fat	1.45	1.40
Soft tissue	1.54	1.63
Dense bone	4.10	7.8
Air	0.33	0.0004

S. A. Goss, et al. J. Acoust. Soc. Am. 64(2):423–457, 1978.
S. A. Goss, et al. J. Acoust. Soc. Am. . 68(1):93–108, 1980.
F. A. Duck, *Physical Properties of Tissue (Academic, New York, 1990).*

6

Thanks to Robin Cleveland, Oxford

Extinction

Attenuation

For tissue it is common to assume attenuation increases linearly with frequency $\bar{\alpha} = \alpha f$

Report α in dB/cm measured at 1 MHz and then extrapolate

1 Np/m = 0.0869 dB/cm

Typical **attenuation** in soft tissue:

Kidney	0.32 dB/cm/MHz
Fat	0.63 dB/cm/MHz
Muscle	1.3 dB/cm/MHz
Skin	3.3 dB/cm/MHz
"Average"	0.5 dB/cm/MHz

FDA derating: 0.3 dB/cm/MHz

9

Beer's Law; $e^{-\mu z}$ where $\mu = 10 \log 10 \alpha$

Thanks to Robin Cleveland, Oxford

Attenuation, Frequency, Depth

Attenuation - range decreases with higher frequency

Freq (MHz)	λ (mm)	Att. coeff. (dB/cm)	Imaging depth (cm)
2.0	0.75	1.0	15
3.5	0.45	1.8	8
5	0.30	2.5	6
7.5	0.20	3.8	4
10	0.15	5	3

Wavelength: $\lambda = \frac{c}{f}$

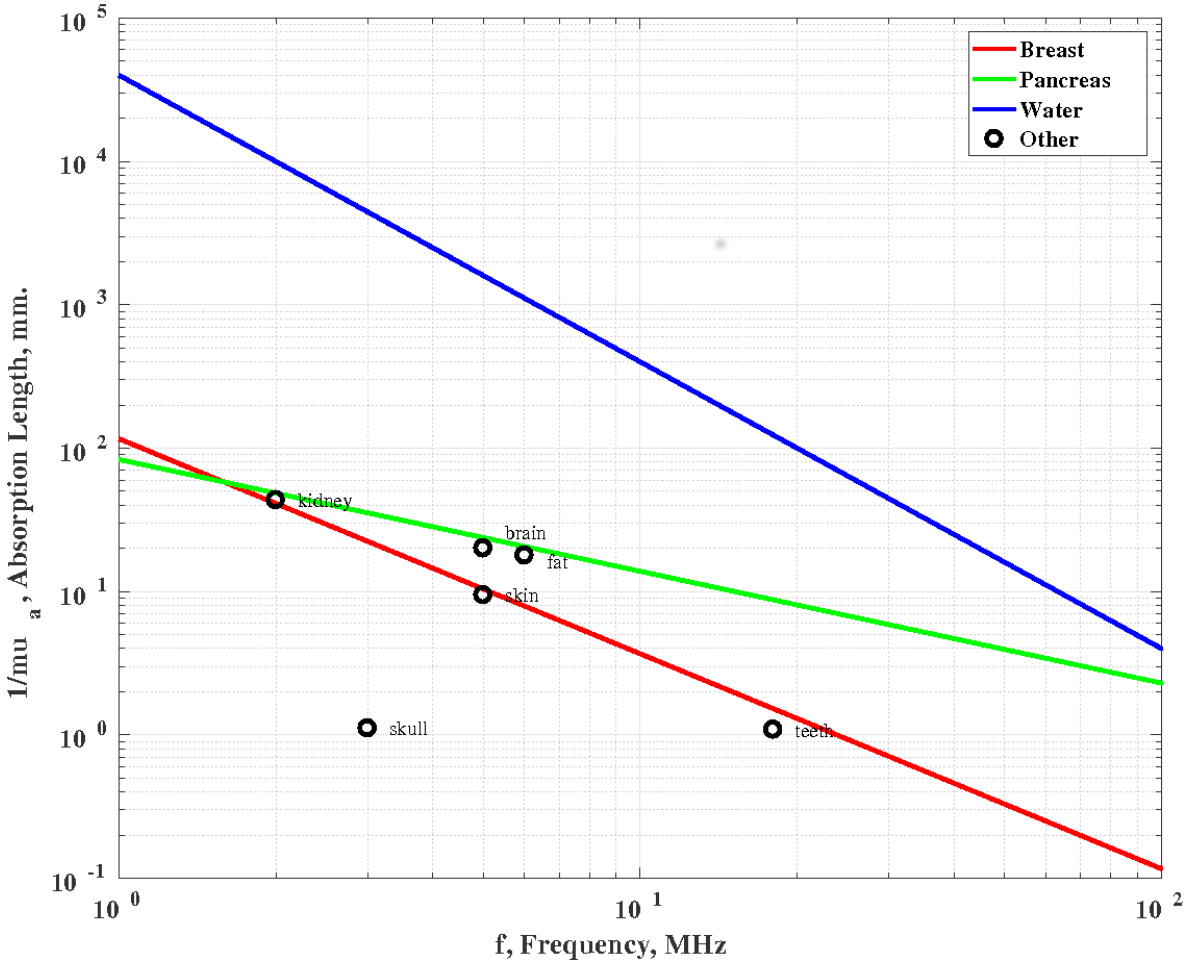
Frequency ↗ ↔ Attenuation ↗ ↔ Imaging depth ↘

Imaging depth is usually on the order of **400 wavelengths** (~ -30dB)

16

Thanks to Robin Cleveland, Oxford

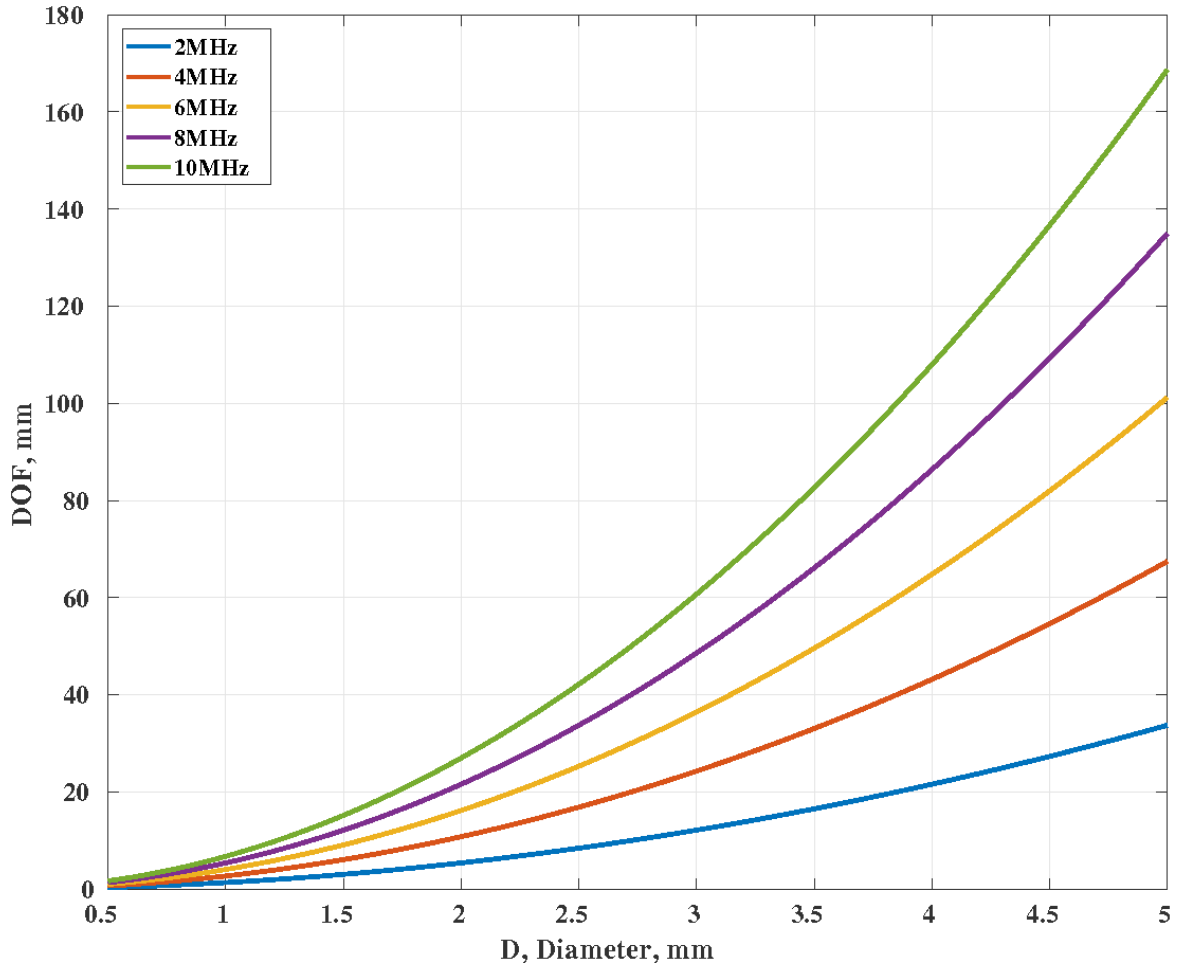
Extinction


Breast
Pancreas
Water
Other
kidney
brain
fat
skin
skull
teeth
1/mu a, Absorption Length, mm.
f, Frequency, MHz
10 5
10 4
10 3
10 2
10 1
10 0
10 -1
10 0
10 1
10 2

Resolution & Depth of Focus

Resolution: λ/NA

Depth of Focus: λ/NA^2



Speed

- In Air: $c = 344$ m/s
- In Water: $c = 1482$ m/s
- $f\lambda = c$

1	MHz	1500	μm
2		740	
5		300	
10		150	
100		15	

- Slow Enough for Time–of–Flight
  - 1482 m/s
  - 1482 mm/ms
  - 1482 μm/μs
- Round Trip: $2z = ct$

A–Scan

- One Pulse
- Signal *vs.* Depth
- Assume Known c

$$2z = ct$$

- Transverse Resolution λ/NA
- Axial Resolution for Pulse Length τ

$$2z = c\tau$$

- Avoid Ambiguity (Pulse Repetition Frequency)

B–Scan

Thanks to Robin Cleveland, Oxford

Sources and Detectors

- Piezoelectric Transducer (PZT)
  - Usually Resonant, Moderate Q
  - Focused or Not
  - Arrays or Not
- Transmit / Receive Switch
- Maybe Dynamic Focus on Receiver

Doppler Ultrasound

- "Color Doppler"
- Principles

$$f_{doppler} = \frac{2v_{\|}}{\lambda}$$

- 100s to 1000s of Hz.
- Pulsed or CW? (Resolution and Ambiguity?)

Miscellaneous

- C–Scans
- Microbubbles
- Elastography
- Photoacoustic Tomography
- Ultrasound Modulated Optical Tomography

Speckle

- Intereference Effect
- Most Noticable with Highly Coherent Sources
  - Ultrasound
  - Optical Imaging with Laser Sources
- Random, High–Contrast Pattern
- Normally Unwanted

Image Time

- A–Scan Limited by Depth (wait for return)
- B–Scan Limited by Transverse Resolution Requirement
- Example
  - 20–cm Depth (260 μs for A–Scan)
  - 128 A–Scans per B–Scan
  - Total 24 ms (29 Hz Frame Rate)

Safety

- Mechanical Index
- Thermal Index

High Power Focused Ultrasound (HIFU)

Lesion

US beam direction

Heat Diffusion Equation

Heat Deposition

$$\rho C \frac{\partial T}{\partial t} = \kappa \nabla^2 T + 2\alpha I$$

24

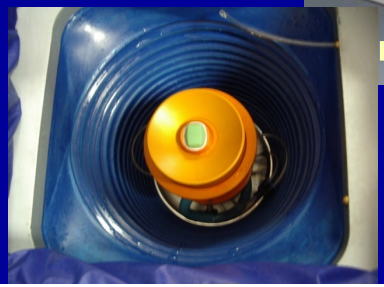
Thanks to Robin Cleveland, Oxford

HIFU Applications

Applications of HIFU

- Opthamology
  - FDA approval 1985
- Cancer
  - Liver, kidney, prostate, breast, brain, skin…
- Non Cancer
  - Uterine fibroids, liver surgery, BPH, …
- Trauma Care
  - Acoustic hemostasis through vessel occlusion
    - Transcutaneous
    - Intraoperative

FU 'JC-Tumor Therapy System'



25

Thanks to Robin Cleveland, Oxford