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Biomedical Imaging
Ultrasound

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EECE–4649 Dialogues of Civilization
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May 2023

Thanks to Robin Cleveland, Oxford University

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

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

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Plane Waves

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- Plane Wave (Previous Page)

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

- Speed

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

- Impedance

$$Z = \rho c$$

-

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

Speed

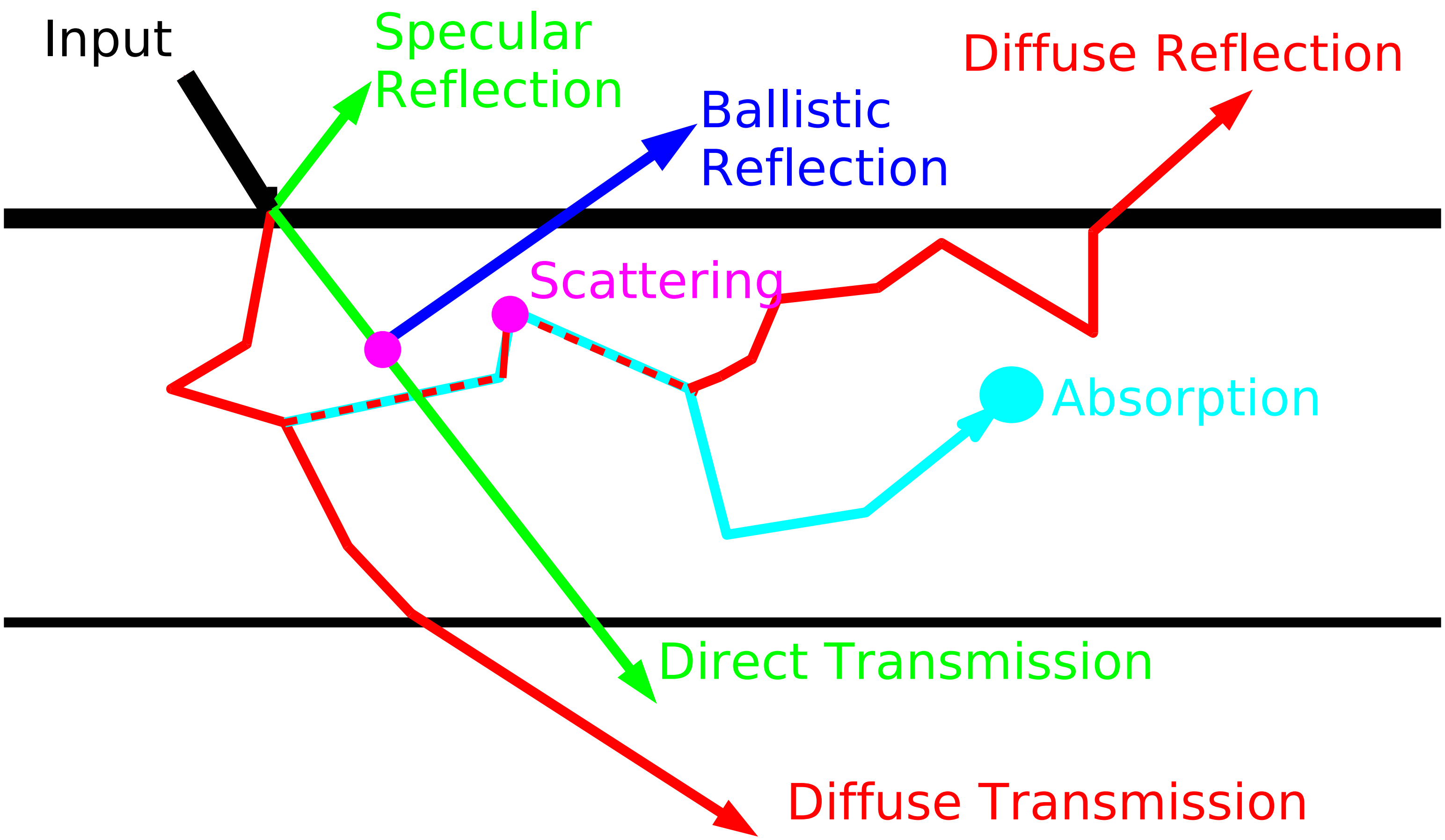
- In Air: $c = 344$ m/s
- In Water: $c = 1482$ m/s
- $f\lambda = c$

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: $2z = ct$

Echo from ρc Contrast

Waves Interactions



(and reverberation, cavitation)

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Impedance Matching

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- Reflection Equation

$$R = \frac{\cos\theta - \frac{Z}{Z'}\sqrt{1 - \frac{\sin^2\theta}{(c/c')^2}}}{\cos\theta + \frac{Z}{Z'}\sqrt{1 - \frac{\sin^2\theta}{(c/c')^2}}}$$

$$Z = \rho c \qquad \frac{\text{kg}}{\text{m}^2\text{s}} = \text{Rayl}$$

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

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).*

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Note: Air to Soft Tissue, $R = 0.999$

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

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

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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)

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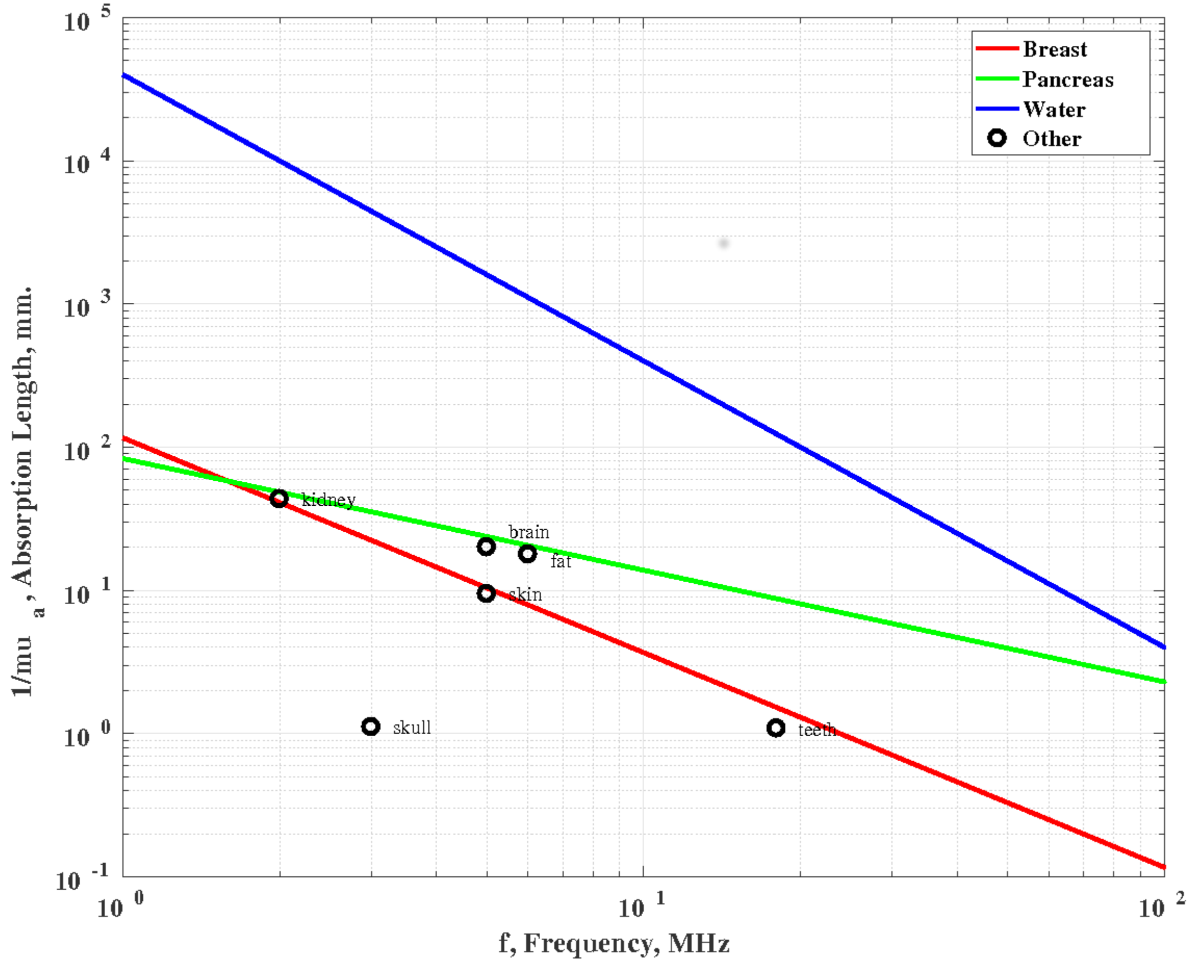
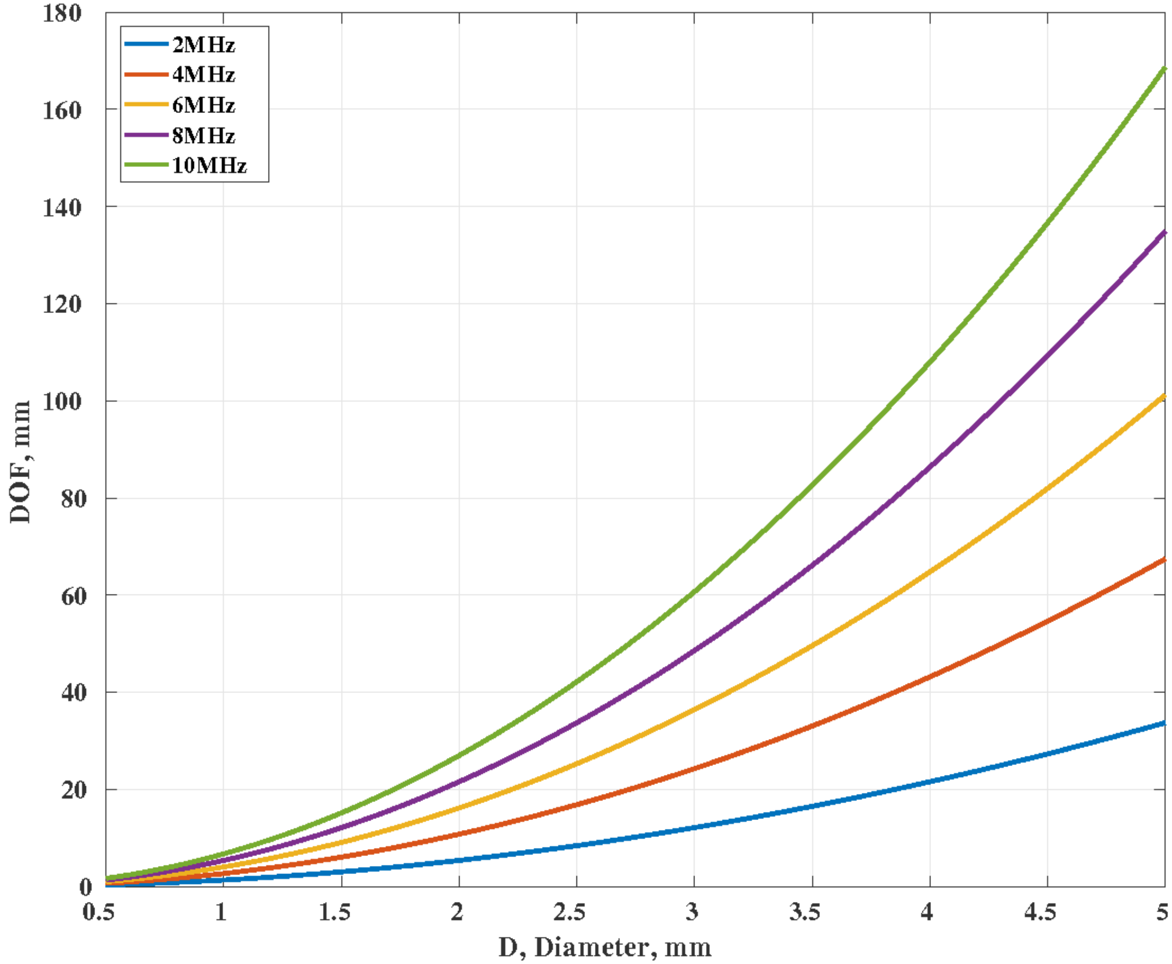
Extinction


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

Resolution & Depth of Focus

Resolution: λ/NA

Depth of Focus: λ/NA^2



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

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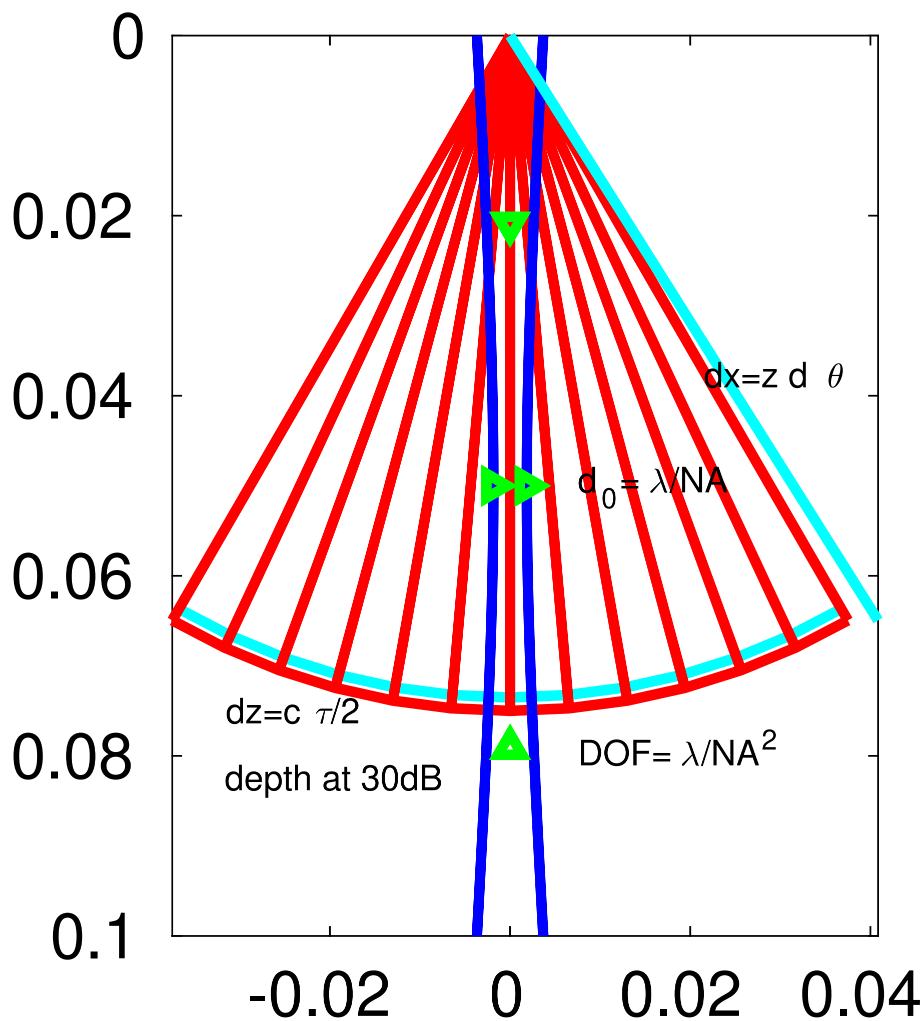
Ultrasound Distances



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

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

- 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
  Cavitation

- Thermal Index
  Heating

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High Power Focused Ultrasound (HIFU)

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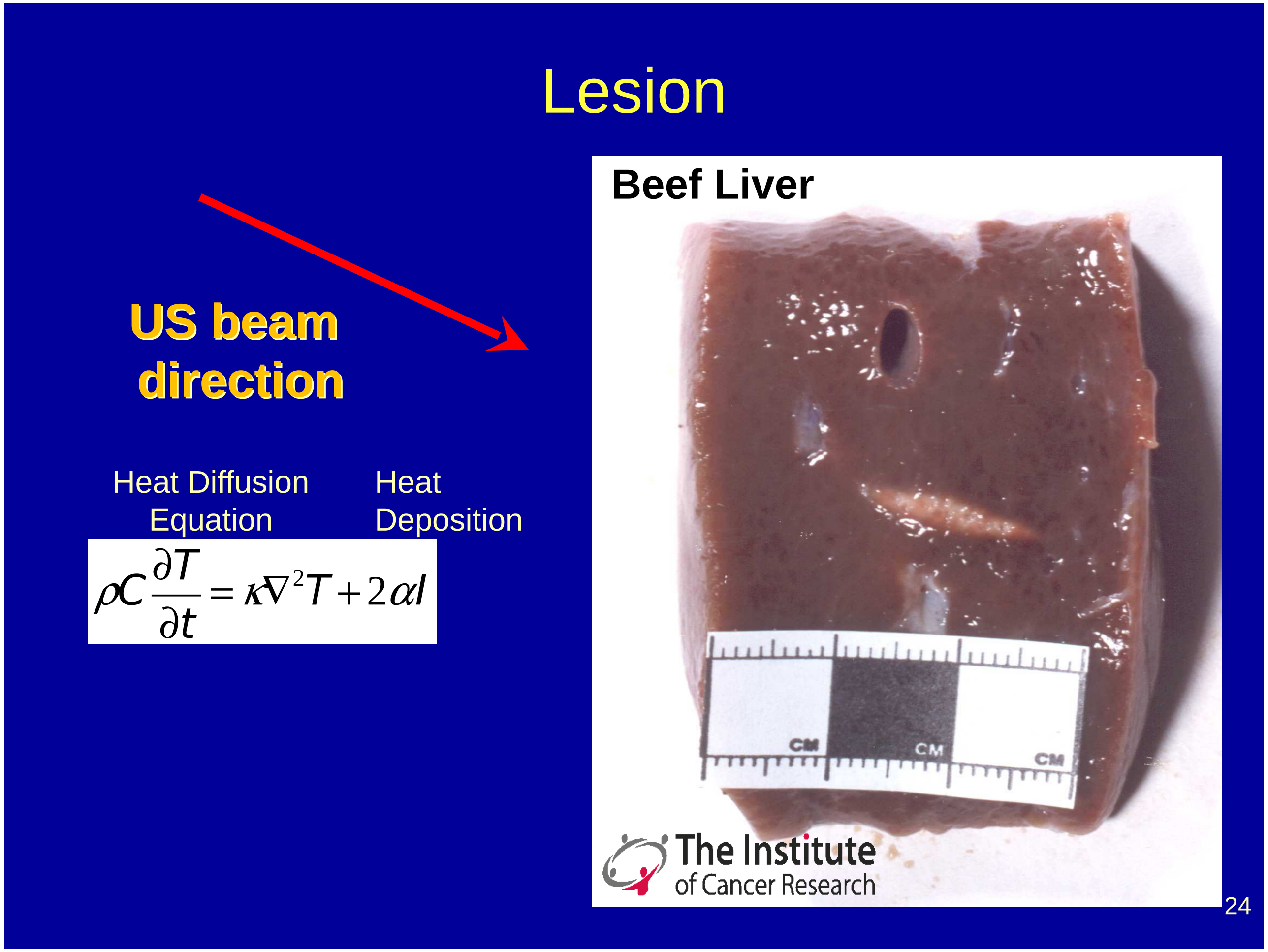

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HIFU Applications

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'

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