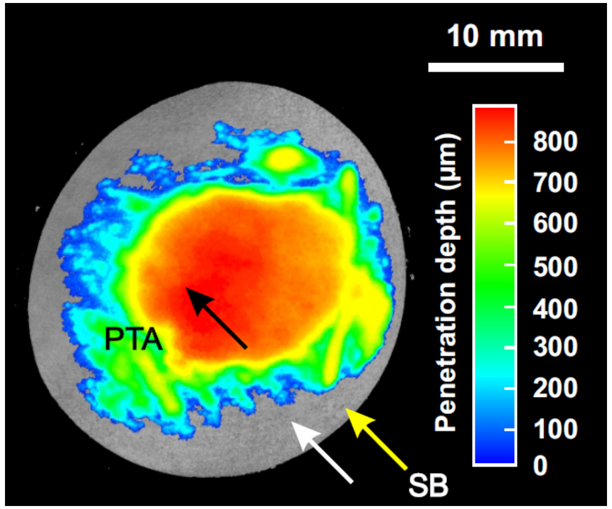
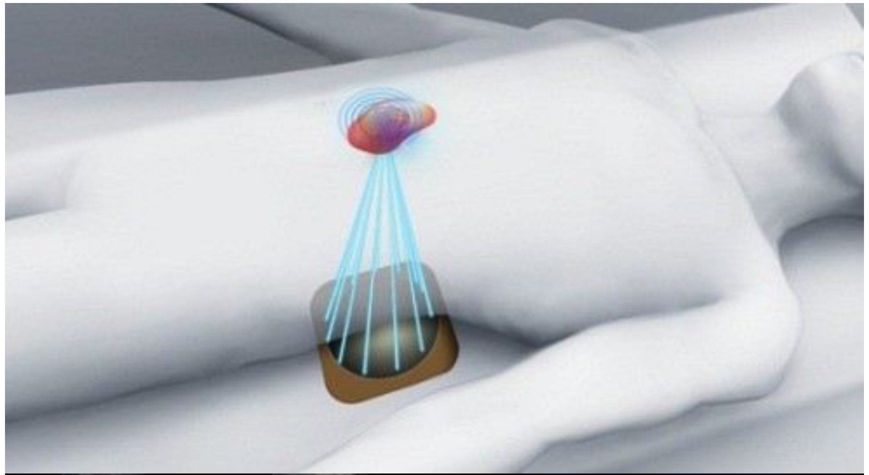
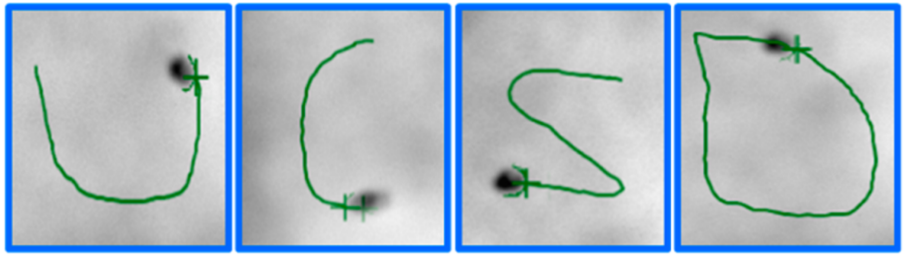
Biomedical Ultrasonics, 5 cr

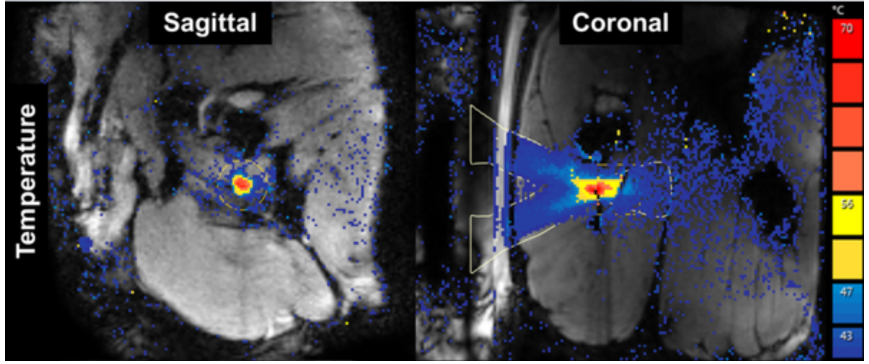
Heikki Nieminen

7.1.-31.5.2019









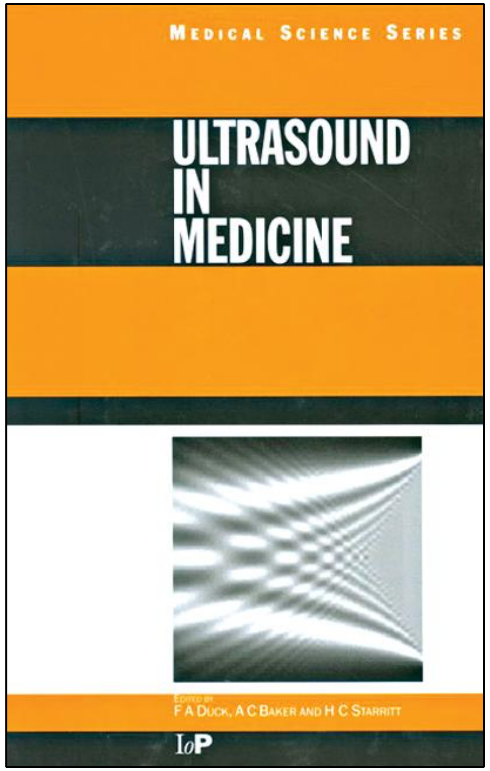
General information

- Lectures: Heikki Nieminen
  - heikki.j.nieminen@aalto.fi, 050-3389932
- Course assistants:
  - Exercises: Emanuele Perra, emanuele.perra@aalto.fi
  - Workshops: Yohann le Bourlout, yohann.lebourlout@aalto.fi
- Contact: primarily through Discussion forum
- Course web-site:
  - Sign-up: https://oodi.aalto.fi/a/etusivu.html (NBE-E4310)
  - Course website: https://mycourses.aalto.fi/course/view.php?id=22208

    The course materials will appear there.

General information

- Course dates: 7.1.-31.5.2019
- Course materials:
  - Lecture slides
  - Articles discussed during the lectures
    - Slides contain hyperlinks to the original article that you should be able to access inside Aalto. If article is for some reason not accessible, it can be provided separately on request.
    - Lecture notes will appear on course website
  - **Book: Duck et al: *Ultrasound in Medicine, 1998***
- Further reading:
  - Kinsler et al: *Fundamentals of Acoustics*, 4th ed
  - Dowsett et al.: *The Physics of Diagnostic Imaging,* 2nd ed



Evaluation

- 5 credits course
- Evaluation is based on the following:
  - Excercises (0.40) (50% = 1, 100% = 5)
  - Presentation (0.20)
  - Report (0.40) (includes material generated in workshops in the lab)
- Each evaluated on scale 1-5 points and using the weights
- To pass the course, one needs to pass each sub-category
- There will be no final exam

Goals of the course

Learning outcomes:

- **After taking the course, the student is able to explain in writing and calculations:**
  - basic linear and non-linear ultrasound–matter interactions (acoustic radiation force, acoustic streaming, cavitation, shock waves)
  - physics of biomedical ultrasonic applications, e.g., ultrasound imaging, quantitative ultrasonics, ultrasonic therapeutics
  - physics of ultrasonic actuation of matter (e.g. drug, drug vehicle, gas bubble, cell, tissue, organs)
- **In addition, the student is able to read scientific literature on biomedical ultrasonic applications in linear and non-linear domain.**

Wei et al. 2013: https://doi.org/10.1371/journal.pone.0058995

”Ideology” of the course

Physics → Applications → Exercises → Lab-work

Contents of the course

1. Linear acoustics

- Basic physics of acoustics
- Ultrasound imaging principles
- Quantitative ultrasonics

2. Non-linear acoustics

- Basic high-intensity ultrasound (HIU) physics
- Acoustic radiation force
- Ultrasound streaming
- Cavitation
- Shock waves
- Permeabilization, cutting & disintegration

3. Thermal acoustics

- Heating

Early ultrasonics

- Pyroelectric effect, early/mid 19th century
  - Electric potential (V) response to temperature change
- René Just Haüy and Antoine César Becquerel proposed in 19th century :
  - Mechanical stress → Electric charge
  - Unfortunately, the experiments were inconclusive
- Pierre and Jacques Curie 1880
  - Pressure applied to quartz crystals → voltage
- Paul Langevin's SONAR studies during WW I (20th century)
  - Quartz sandwich transducer for submarine detection (lethal to fish in US beam)

Lorentz, Einstein and Langevin in 1927

http://www.ob-ultrasound.net/langevin.html

→ Modern ultrasonics

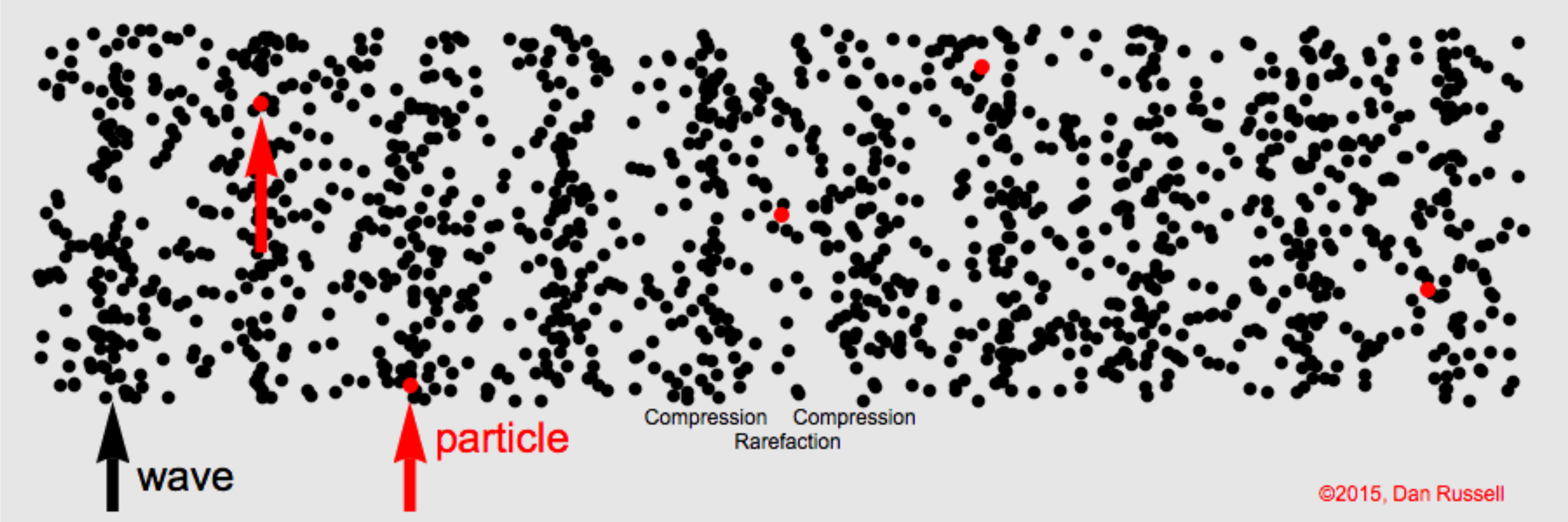
Why is ultrasound an attractive modality?

- Allows non-destructive non-invasive non-touching **evaluation and actuation** of materials (engineering materials, biological tissue)
- Approaches:
  - Imaging (*e.g.* in industry, medicine)
  - Quantitative characterization of material (research, engineering applications, medicine)
  - Ultrasound-assisted experimental setups
- Non-ionizing
- Cheap (vs. X-ray, CT, MRI, nuclear imaging)

1. LINEAR ACOUSTICS

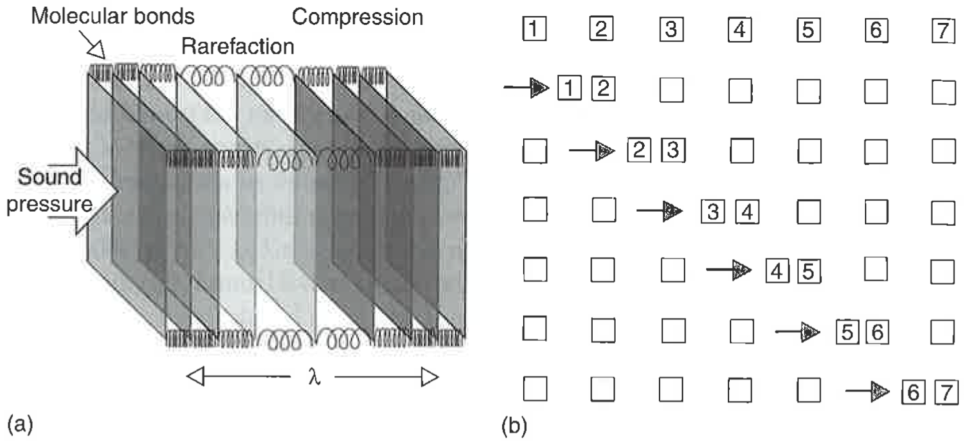
Basic physics of acoustics

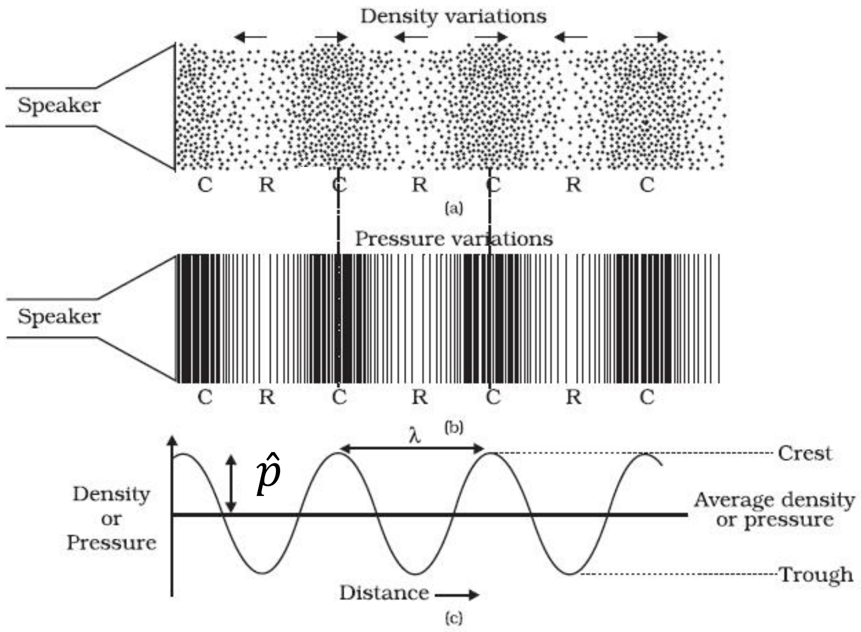
What is sound?



What is sound?

- Sound is a travelling density/pressure disturbance

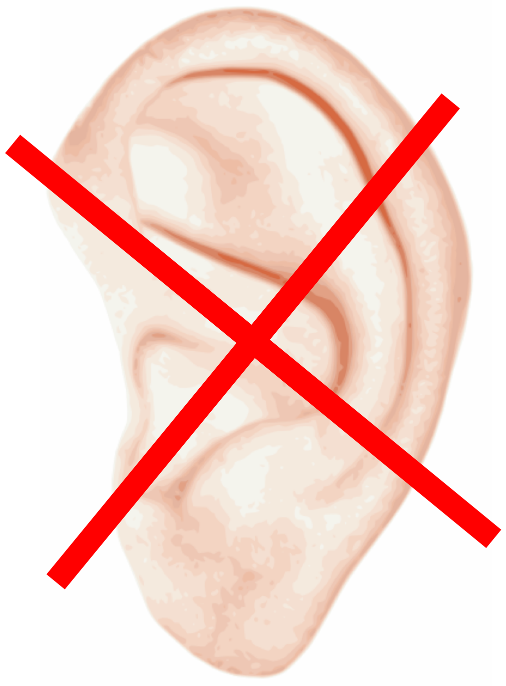




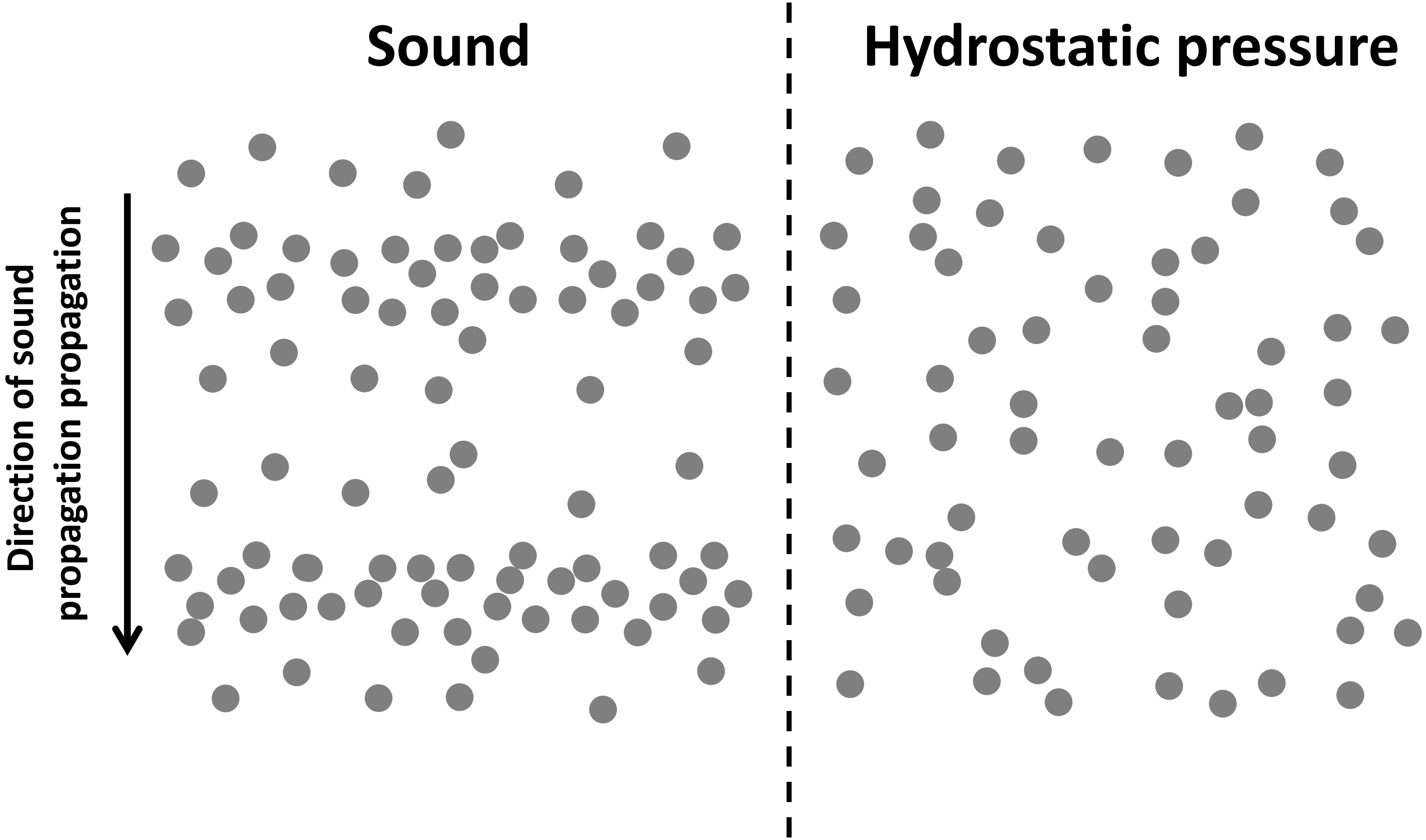
$\hat{p}$ = pressure amplitude
λ = wavelength

What is ultrasound?

Ultrasound is a travelling density/pressure disturbance oscillating at a frequency > 20 kHz



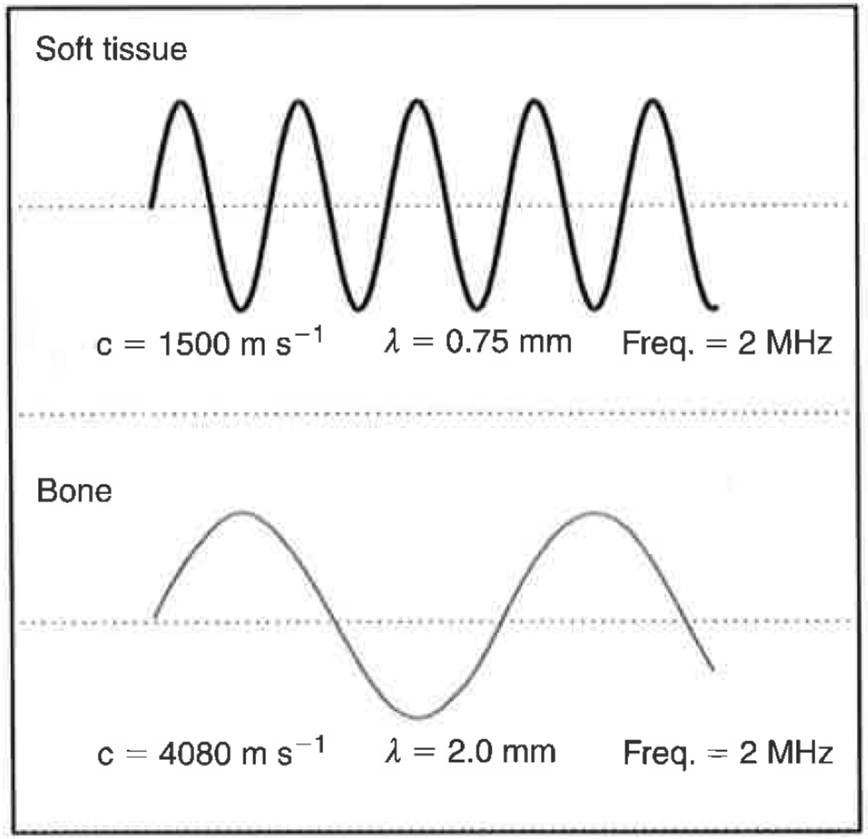
Pressure vs. hydrostatic pressure



Sound

Hydrostatic pressure

Wavelength

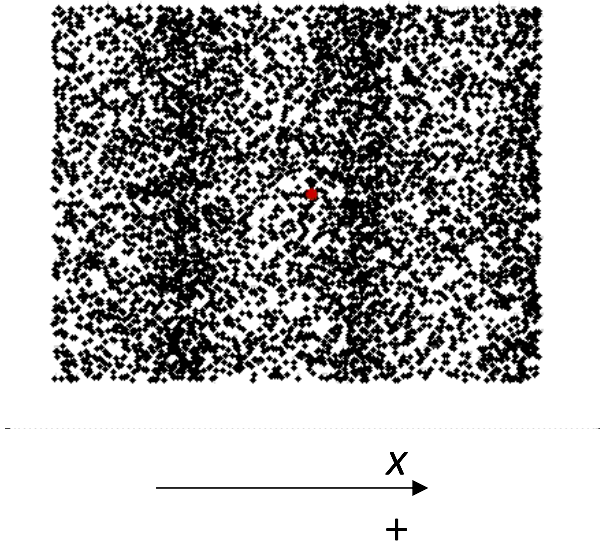


$$\lambda = \frac{c}{f}$$

λ = wavelength
c = speed of sound
f = frequency

Pressure of sound

Longitudinal wave



p = complex pressure
$\hat{p}$ = peak pressure amplitude
i = imaginary unit
t = time
x = position

Pressure (sinusoidal Continuous wave):

→ $$\boxed{\mathbf{p}_+ = \hat{p}e^{i(\omega t - kx)}}$$

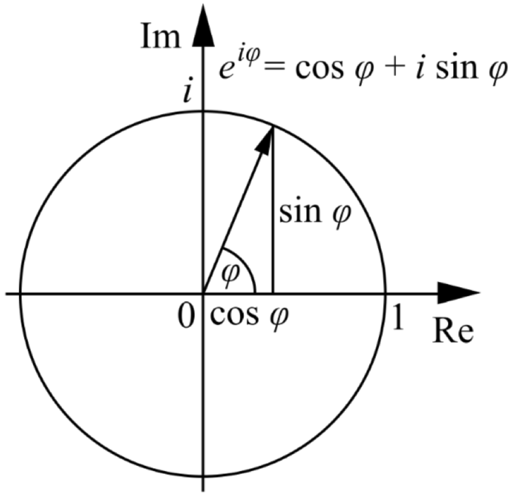
← $$\boxed{\mathbf{p}_- = \hat{p}e^{i(\omega t + kx)}}$$

Real pressure:

← $$\boxed{p = Re\{\mathbf{p}\}}$$

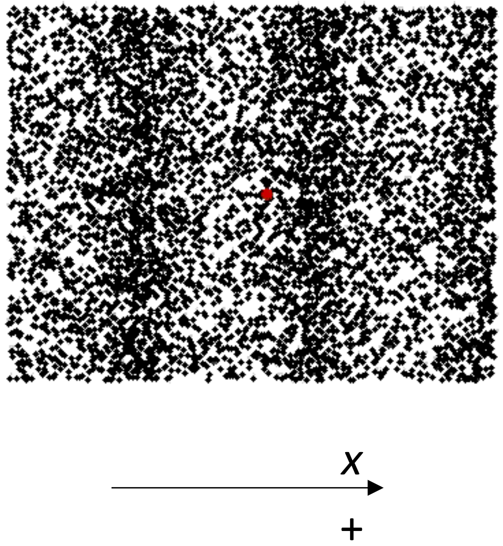
Wave number:

$$\boxed{k = \frac{2\pi}{\lambda}}$$



Particle discplacement

Longitudinal wave



p = complex pressure
$\hat{\boldsymbol{\xi}}$ = peak displacement amplitude
i = imaginary unit
t = time
x = position

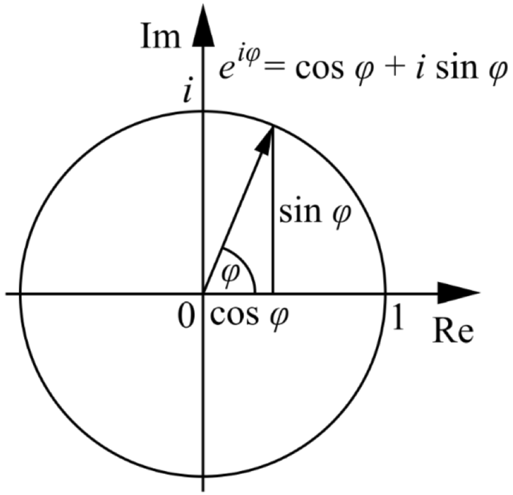
Particle displacement (sinusoidal continuous wave):

$$\longrightarrow \boxed{\boldsymbol{\xi}_+ = \hat{\xi} e^{i(\omega t - kx)}}$$

$$\boxed{\boldsymbol{\xi}_- = \hat{\xi} e^{i(\omega t + kx)}}$$

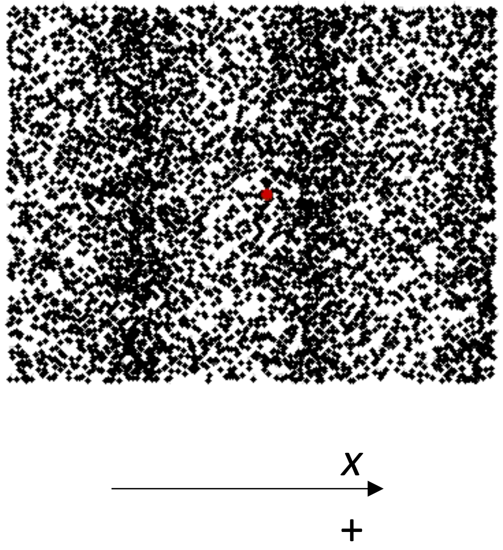
Real displacement:

$$\boxed{\xi = Re\{\boldsymbol{\xi}\}}$$



Particle velocity

Longitudinal wave



p = complex pressure
$\hat{u}$ = peak velocity
i = imaginary unit
t = time
x = position

Particle velocity (sinusoidal continuous wave):

→

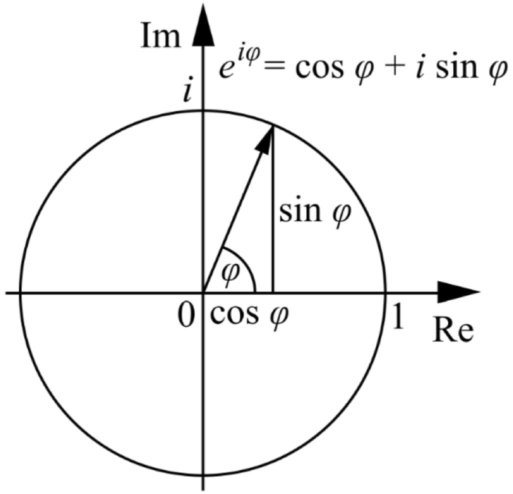
$$\boldsymbol{u}_+ = \frac{d\boldsymbol{\xi}_+}{dt} = i\omega\hat{\xi}e^{i(\omega t-kx)} = \hat{u}e^{i(\omega t-kx)}$$

←

$$\boldsymbol{u}_- = \hat{u}e^{i(\omega t+kx)}$$

Real particle velocity:

$$u = Re\{\boldsymbol{u}\}$$



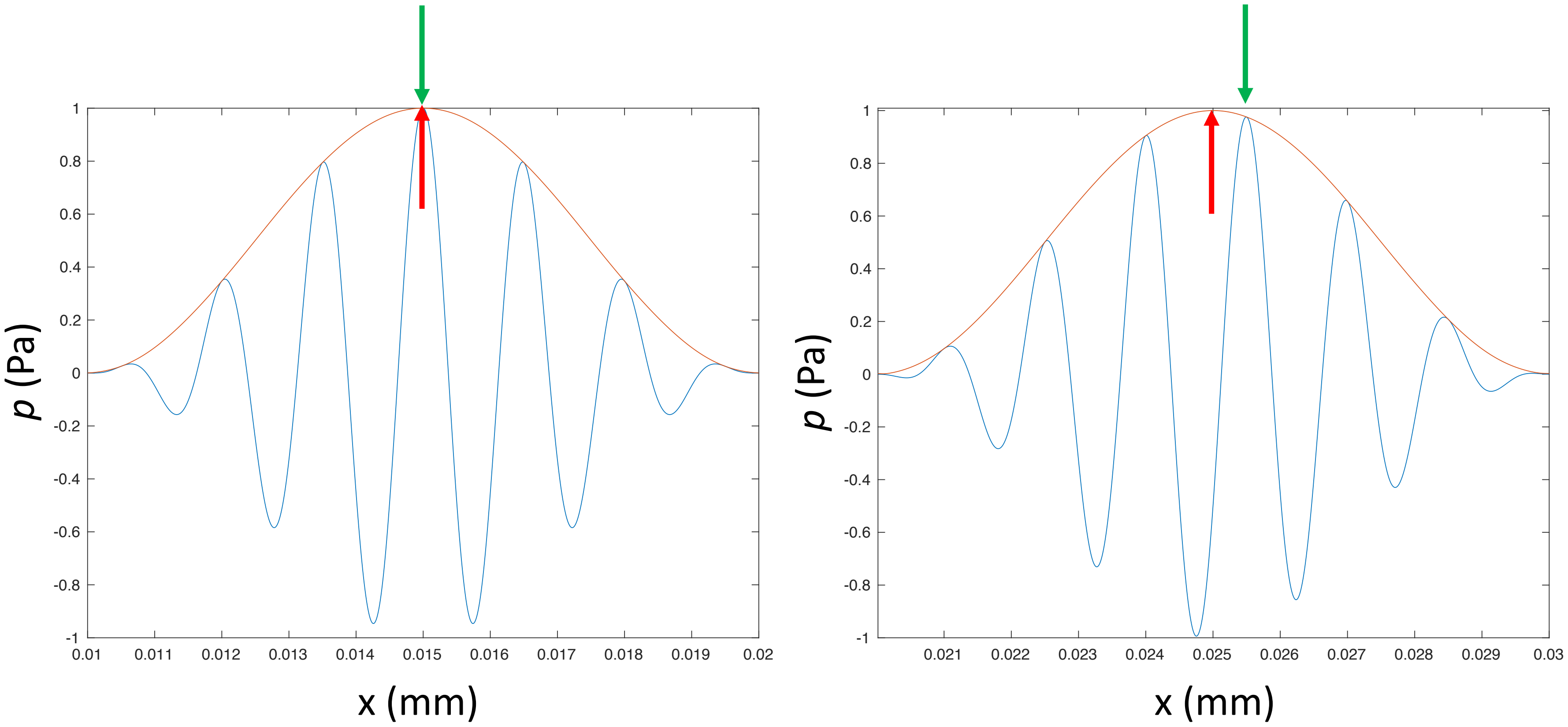
Intensity

- Intensity is describes the acoustic power of the ultrasound field per unit area
- Unit: W/m^2 or W/cm^2 (latter more commonly used in medical context)
- Instantaneous intensity:

$$I = \frac{p^2}{\rho c}$$

Speed of sound

- Phase velocity
- Group velocity



Acoustic impedance

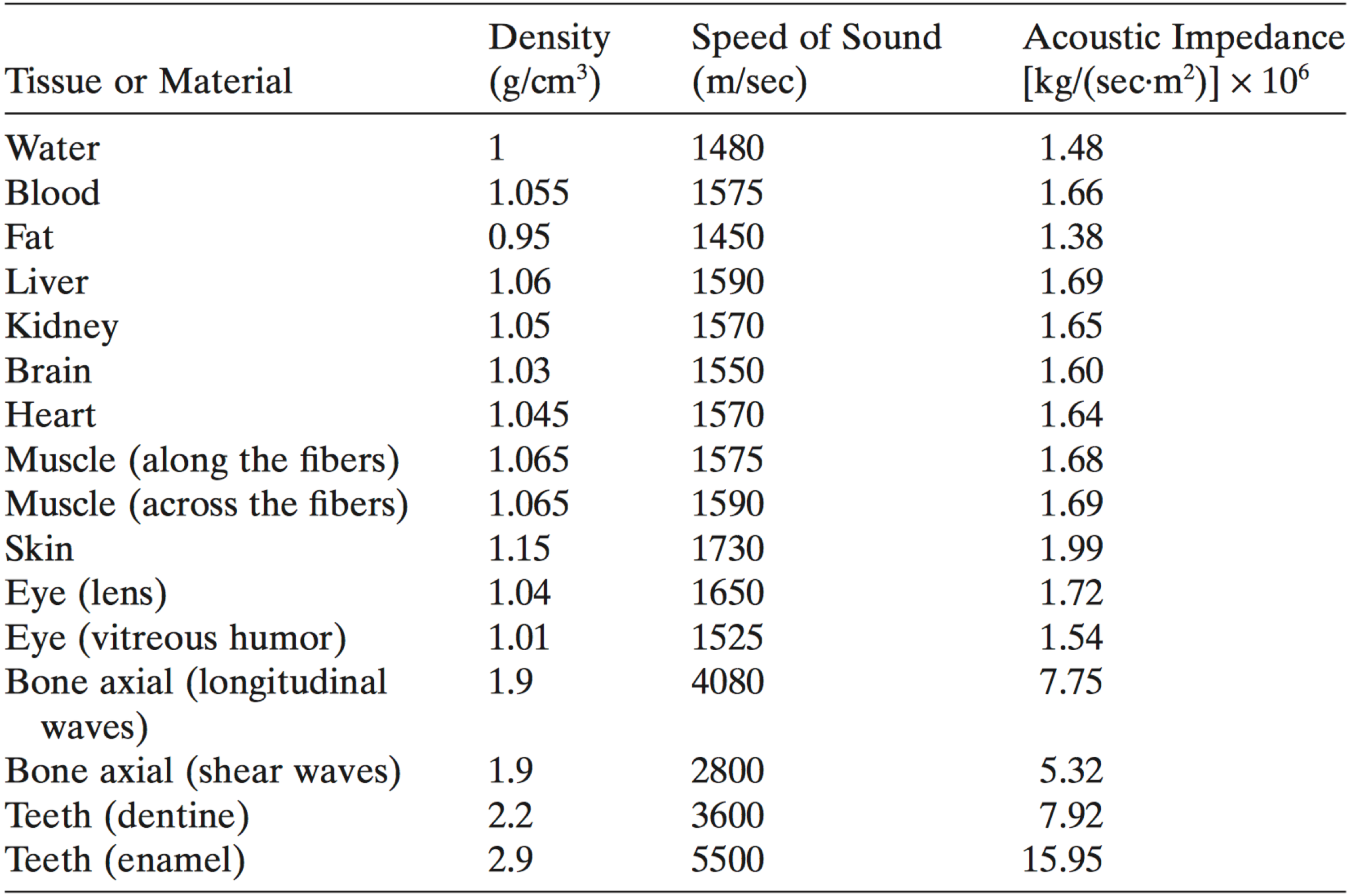
- A material property that describes how much *pressure* is generated in a medium from spatial displacement of its molecules at a given frequency. Sound is reflected at an interface between two materials with different acoustic impedances.

Acoustic impedance: $Z = \frac{p}{u} = \rho c$

Unit: kg / sm^2 or Rayl

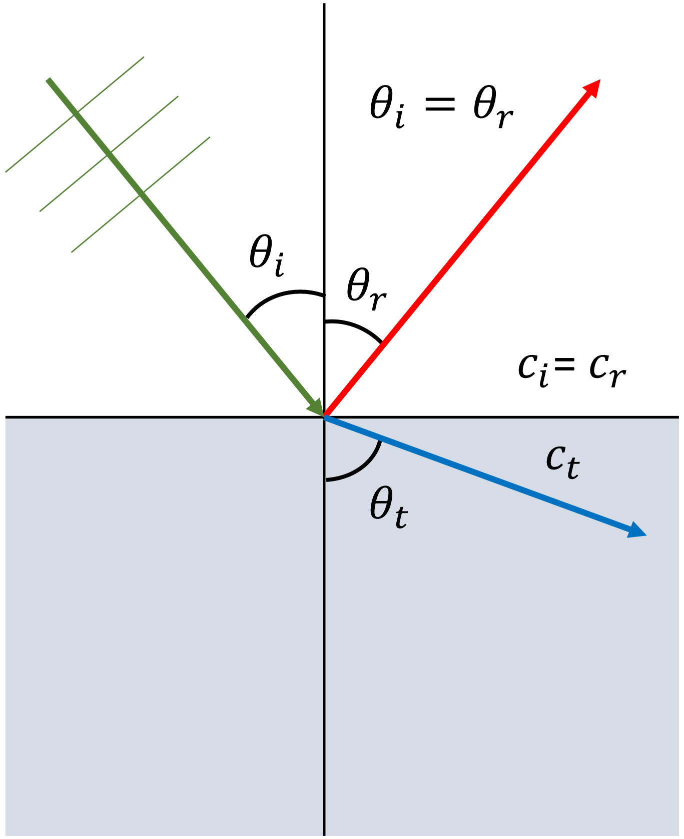
p = real pressure
u = particle velocity
c = speed of sound
ρ= density at rest

Acoustic impedance



Tissue or Material	Density (g/cm^3)	Speed of Sound (m/sec)	Acoustic Impedance [kg/(sec·m^2)] × 10^6
Water	1	1480	1.48
Blood	1.055	1575	1.66
Fat	0.95	1450	1.38
Liver	1.06	1590	1.69
Kidney	1.05	1570	1.65
Brain	1.03	1550	1.60
Heart	1.045	1570	1.64
Muscle (along the fibers)	1.065	1575	1.68
Muscle (across the fibers)	1.065	1590	1.69
Skin	1.15	1730	1.99
Eye (lens)	1.04	1650	1.72
Eye (vitreous humor)	1.01	1525	1.54
Bone axial (longitudinal waves)	1.9	4080	7.75
Bone axial (shear waves)	1.9	2800	5.32
Teeth (dentine)	2.2	3600	7.92
Teeth (enamel)	2.9	5500	15.95

Reflection and transmission of a propagating wave



Snell's law:

$$\frac{\sin\theta_i}{c_i} = \frac{\sin\theta_t}{c_t}$$

i = incident
r = reflected
t = transmitted

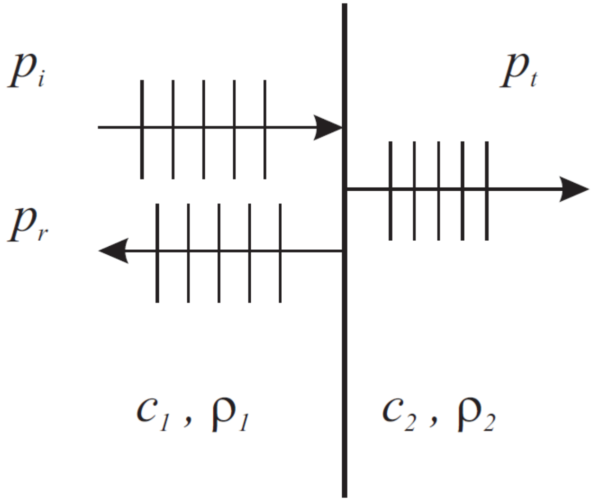
Reflection and transmission coefficients of pressure

Reflection coefficient

$$R = \frac{p_r}{p_i} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 - \rho_1 c_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \overbrace{\frac{K_2/c_2 - K_1/c_1}{K_2/c_2 + K_1/c_1}}^{\text{Applies to fluids}}$$

Transmission coefficient

$$T = \frac{p_t}{p_i}$$



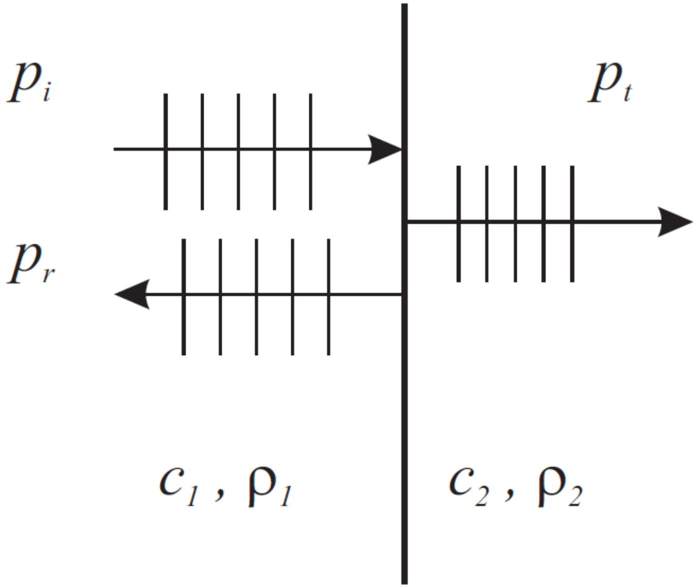
Reflection and transmission coefficient of intensity

Reflection coefficient

$$R_I = R^2 = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

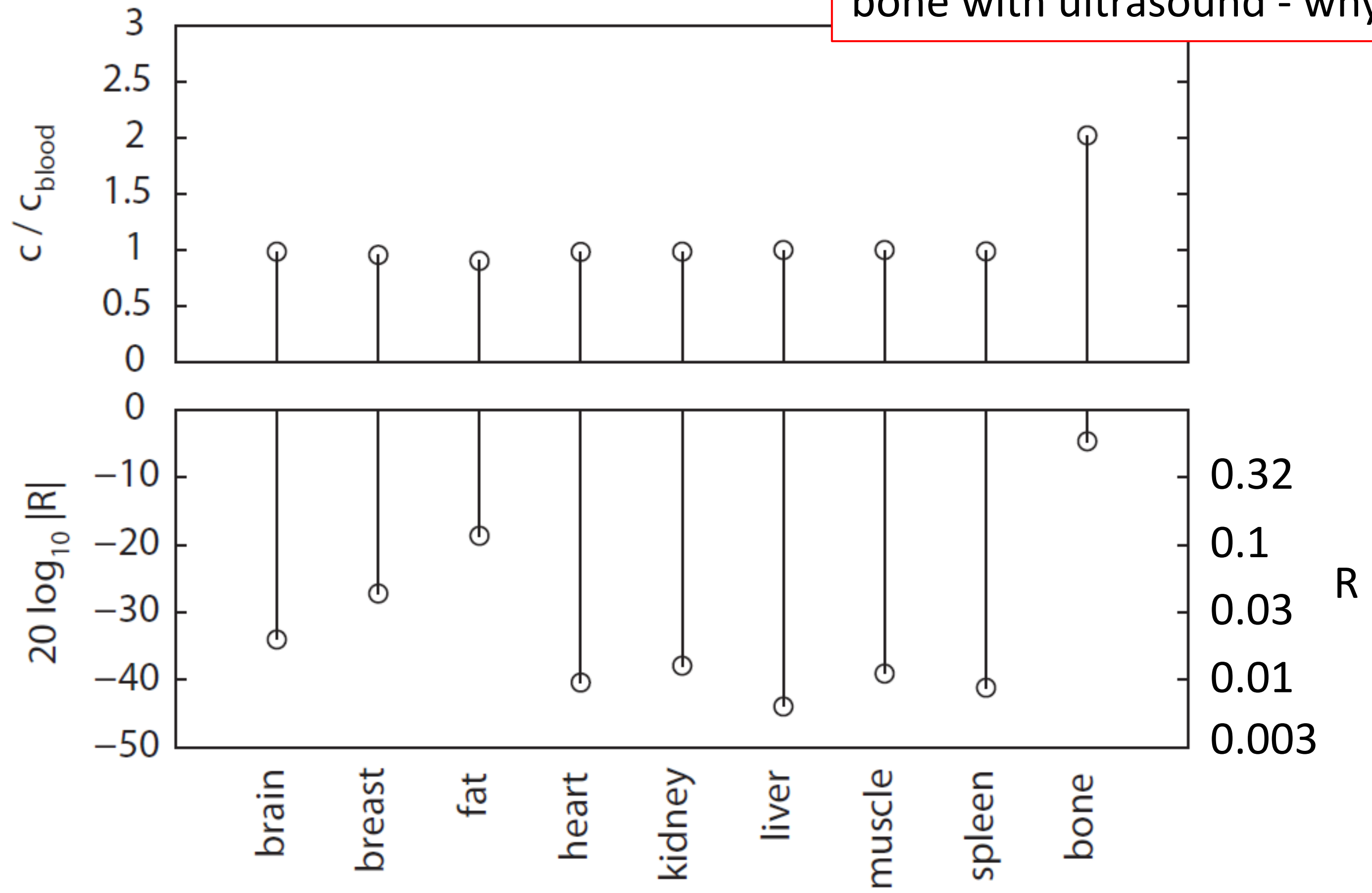
Transmission coefficient

$$T_I = 1 - R^2$$



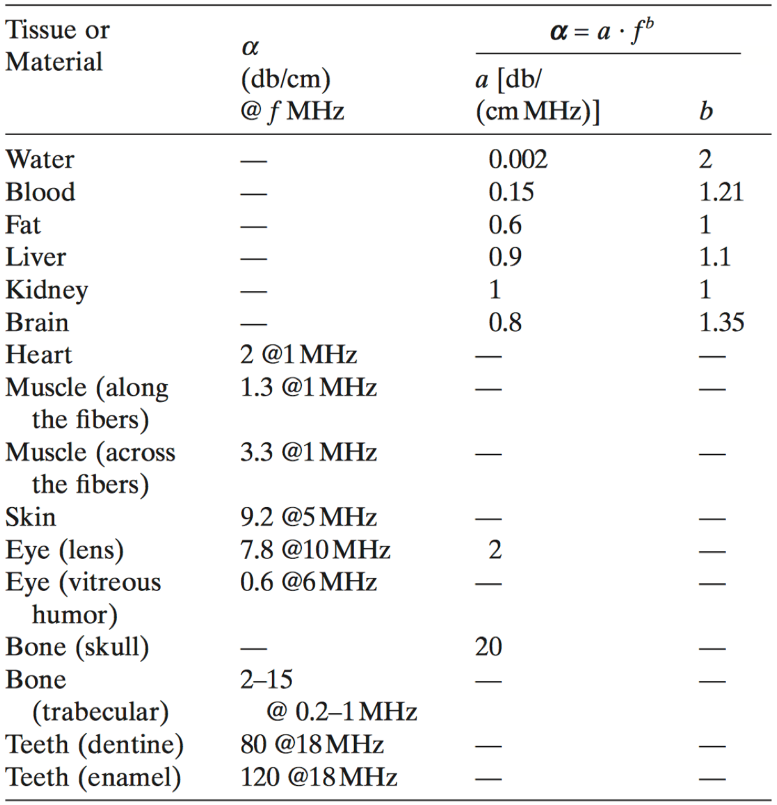
Ultrasound reflection coefficients in the body (ballpark)

Usually, you do not want to hit the bone with ultrasound - why?



Attenuation

- In tissue sound energy is attenuated due to scattering and absorption



Tissue or Material	α (db/cm) @ f MHz	$\alpha = a \cdot f^b$	
		a [db/(cm MHz)]	b
Water	—	0.002	2
Blood	—	0.15	1.21
Fat	—	0.6	1
Liver	—	0.9	1.1
Kidney	—	1	1
Brain	—	0.8	1.35
Heart	2 @1 MHz	—	—
Muscle (along the fibers)	1.3 @1 MHz	—	—
Muscle (across the fibers)	3.3 @1 MHz	—	—
Skin	9.2 @5 MHz	—	—
Eye (lens)	7.8 @10 MHz	2	—
Eye (vitreous humor)	0.6 @6 MHz	—	—
Bone (skull)	—	20	—
Bone (trabecular)	2–15 @ 0.2–1 MHz	—	—
Teeth (dentine)	80 @18 MHz	—	—
Teeth (enamel)	120 @18 MHz	—	—

Usually, you do not want to hit the bone or lung with ultrasound - why?

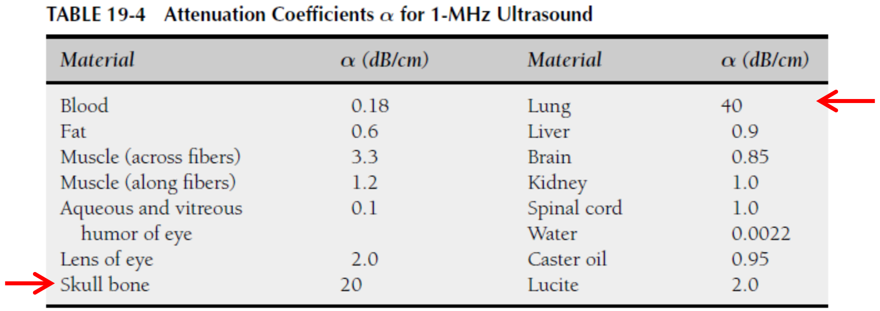
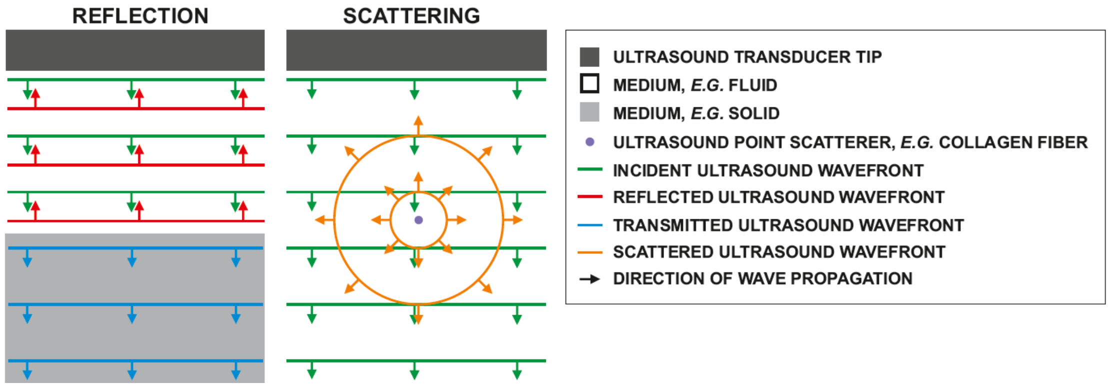


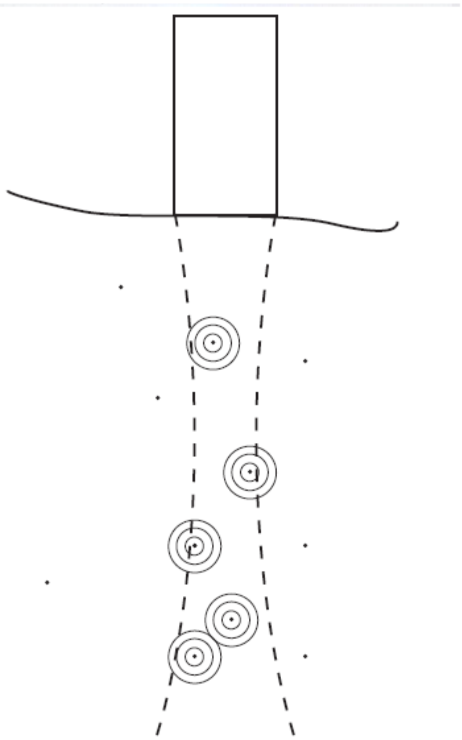
TABLE 19-4 Attenuation Coefficients α for 1-MHz Ultrasound

Material	*α (dB/cm)*	*Material*	*α (dB/cm)*
Blood	0.18	Lung	40
Fat	0.6	Liver	0.9
Muscle (across fibers)	3.3	Brain	0.85
Muscle (along fibers)	1.2	Kidney	1.0
Aqueous and vitreous humor of eye	0.1	Spinal cord	1.0
		Water	0.0022
Lens of eye	2.0	Caster oil	0.95
Skull bone	20	Lucite	2.0

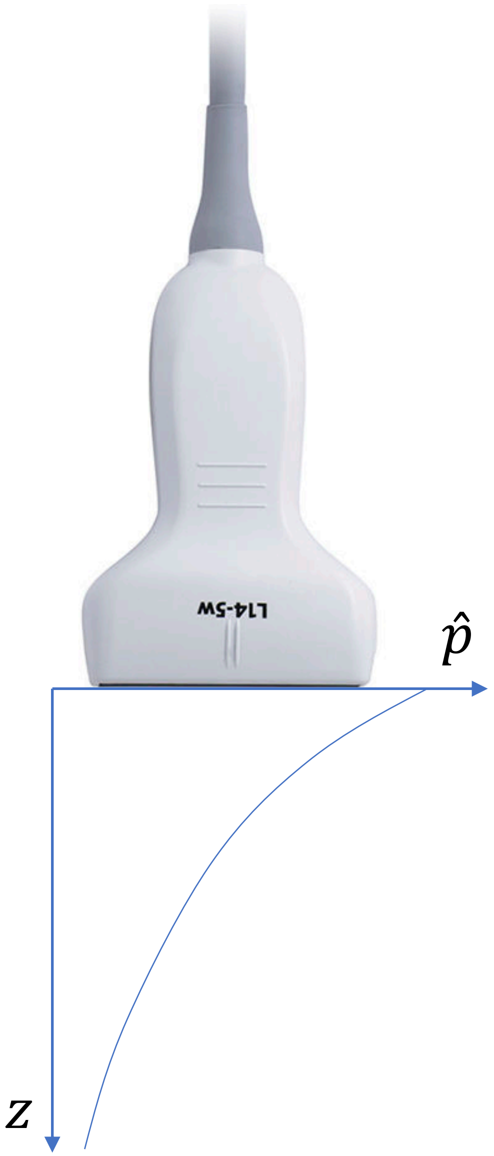
Absorption & scattering

- Sound energy is eventually absorbed as heat
- Scattering occurs when the reflector size is close to that of wavelength





Attenuation = absorption + scattering (planar wave)



$$\alpha = \alpha_{\mathrm{abs}} + \alpha_{\mathrm{scat}}$$

$$p = p_0 10^{-\frac{\alpha_{\mathrm{dB}} z}{20}}$$

$$p = p_0 e^{-\alpha_{\mathrm{Np}} z}$$

α_{abs} = absorption coefficient
α_{scat} = scattering coefficient
α_{dB} = attenuation coefficient in dB/cm
α_{Np} = attenuation coefficient in Neper/cm
p_0 = pressure at z = 0
p = peak pressure amplitude
z = distance

Geometric attenuation

- Planar source: $p_2 = p_1 e^{-\alpha x}$

$$I_2 = I_1 e^{-2\alpha x}$$

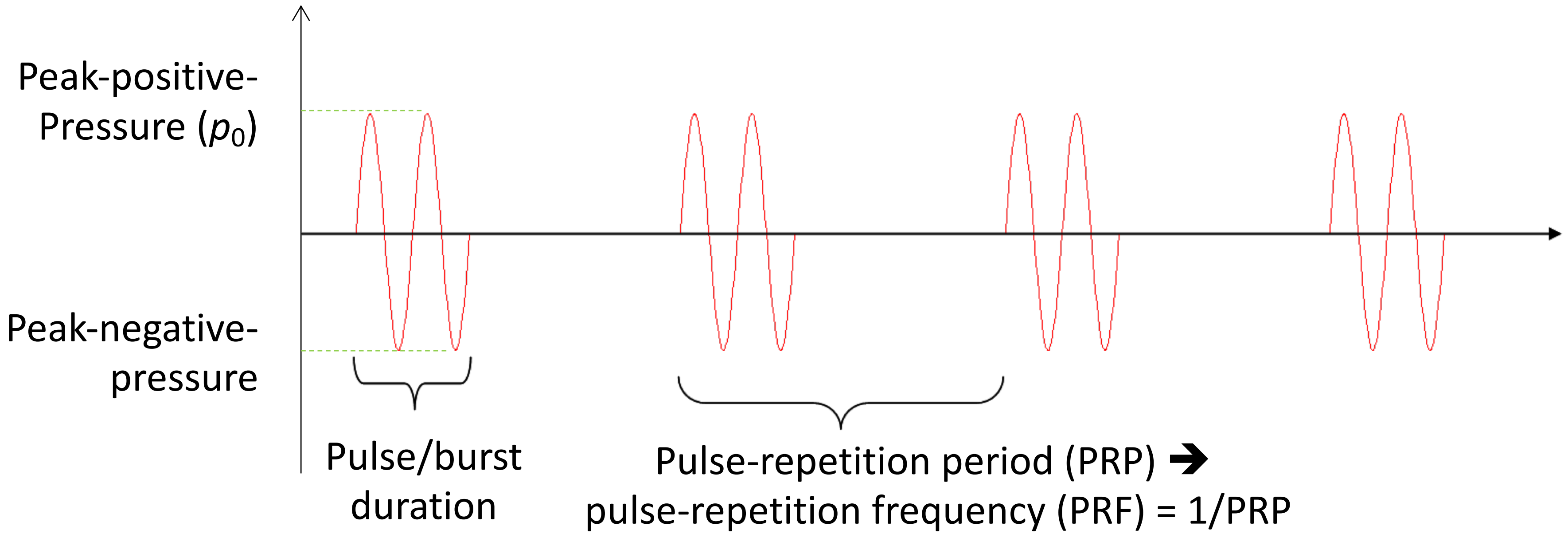
$$\alpha = -\frac{1}{2x}\ln\frac{I_2}{I_1} = \frac{1}{2x}\ln\frac{I_1}{I_2}$$

Unit: Np/cm

- Line source: $I_2 = ?\,I_1\, e^{-2\alpha r}$ $\quad p_2 = ?\ p_1\, e^{-\alpha r}$
- Point source: $I_2 = ?\,I_1\, e^{-2\alpha r}$ $\quad p_2 = ?\ p_1\, e^{-\alpha r}$

$\}$ Exercises

Pulse/burst concepts



Peak-positive-Pressure (p_0)

Peak-negative-pressure

Pulse/burst duration

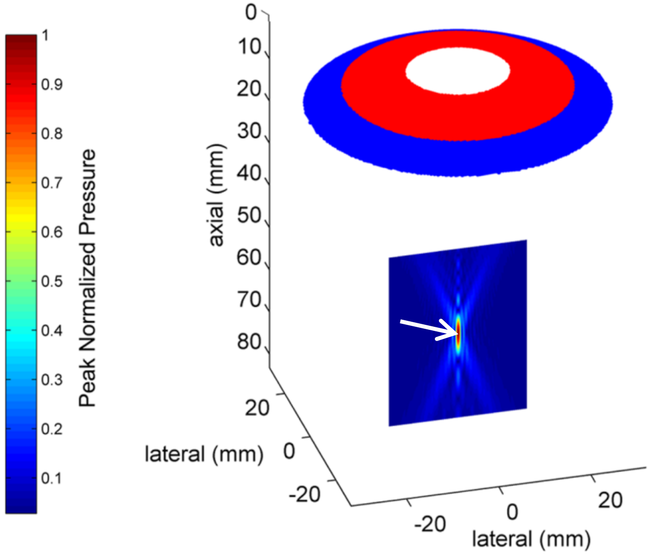
Pulse-repetition period (PRP) ➔ pulse-repetition frequency (PRF) = 1/PRP

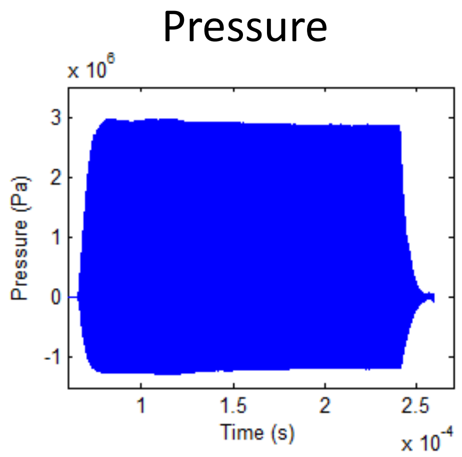
Duty cycle = the % of time when ultrasound is **ON** (in this example duty cycle is about 40%)

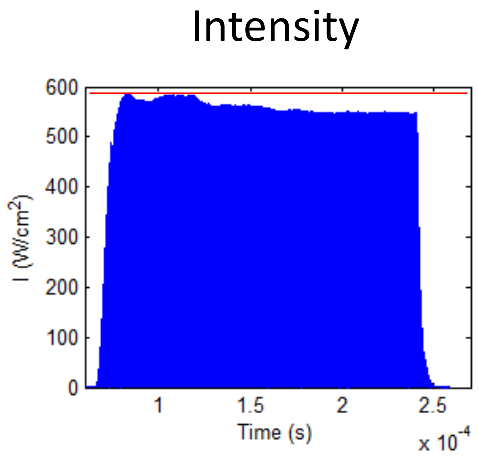
I_{sptp}

- **Spatial peak temporal peak intensity**
  - Intensity of the spatially & temporally the hottest ”spot” in the field

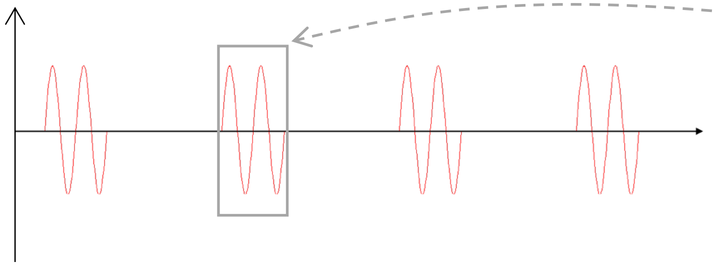
$$I_{\text{sptp}} = \{I(t,x,y,z)\}_{\max} = \left\{\frac{p^2(t,x,y,z)}{\rho c}\right\}_{\max}$$

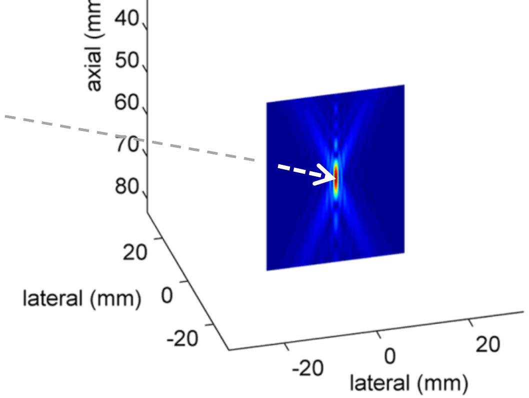



Pressure


Intensity

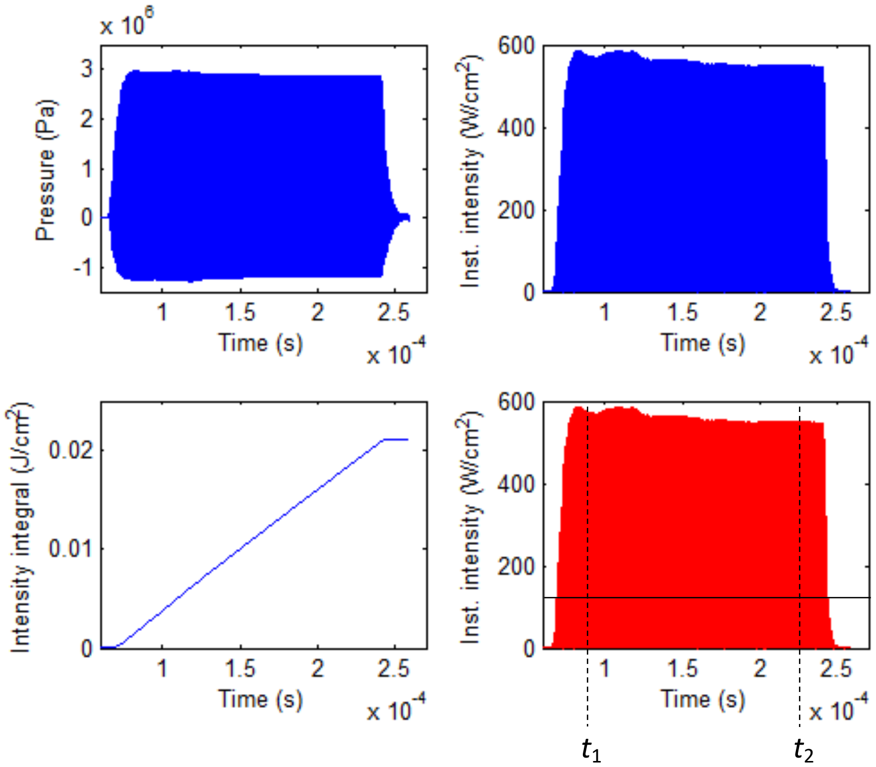
I_{sppa}





- **Spatial peak pulse average intensity**
  - Describes power of at the focus per unit area during a single pulse/burst at the hottest spot

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



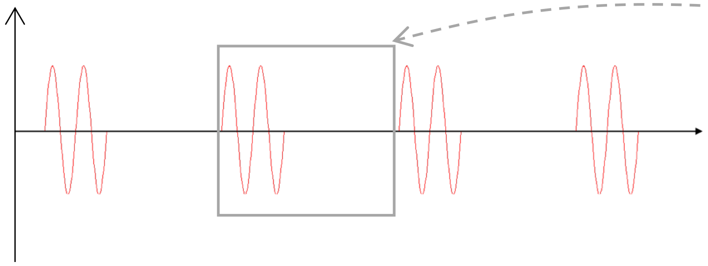
PD is defined as the 1.25 x the interval between time points, where intensity integral reaches 10% (t_1) and 90% (t_2) of the maximum.

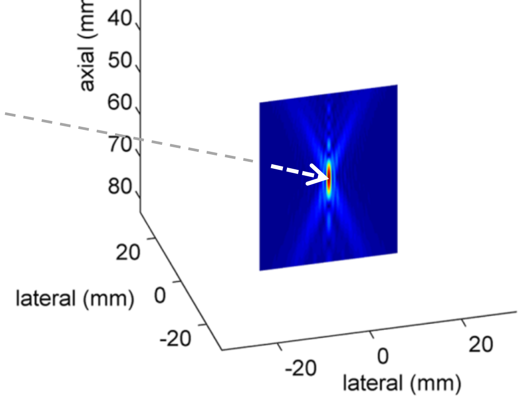
Integration is conducted over the entire pulse/burst.

PD = 138 µs

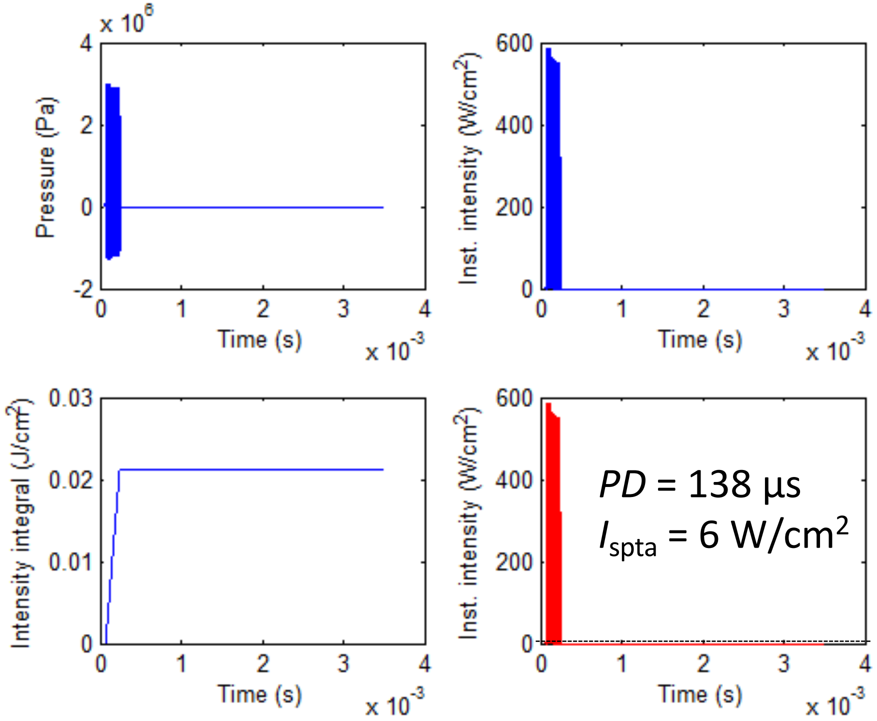
I_{sppa} = 123 W/cm^2

I_{spta}





- **Spatial peak time average intensity**
  - Describes the average power at focus across unit area during one PRP at the hottest spot



$$\boxed{I_{\text{sppa}} = \frac{\int_{t_1}^{t_2} p^2(t)\,dt}{\rho c\ PRP}}$$

PRP = pulse repetition period $= t_2$-t_1 = time from the beginning of a pulse/burst to the beginning of the next pulse