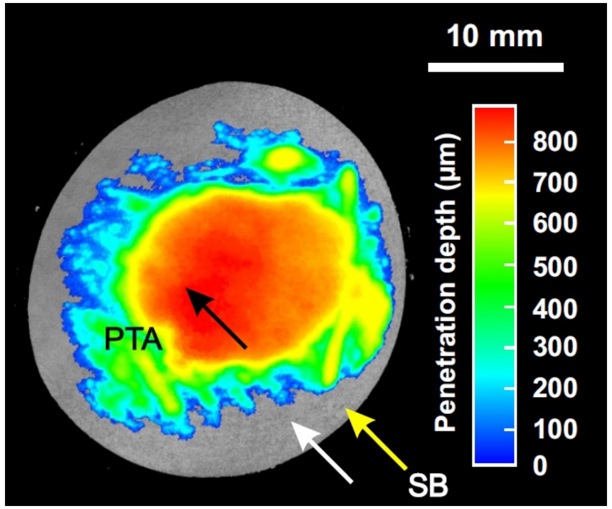
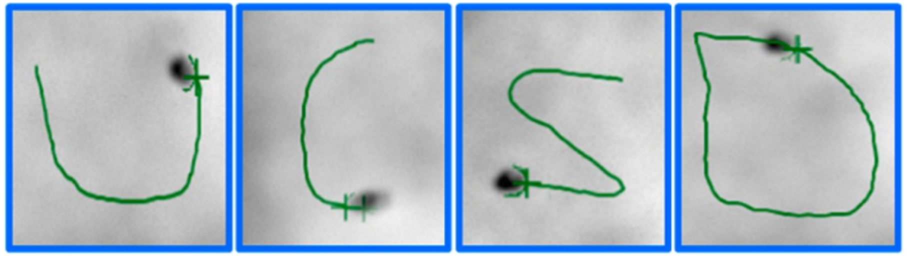
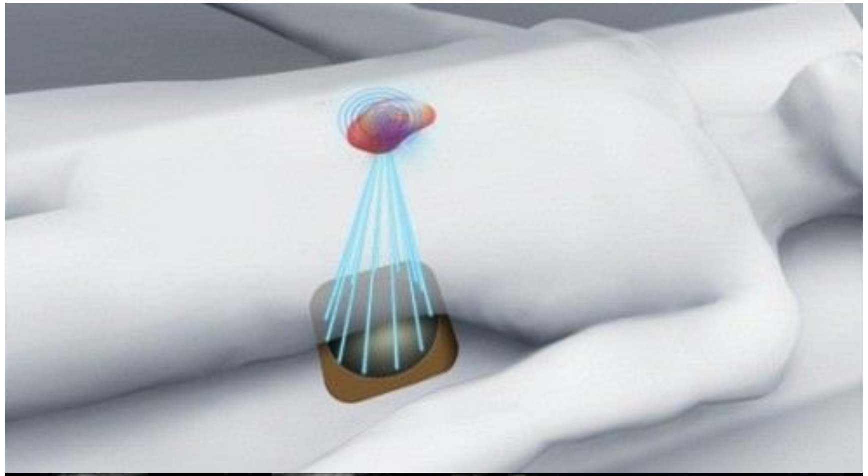
Biomedical Ultrasonics, 5 cr

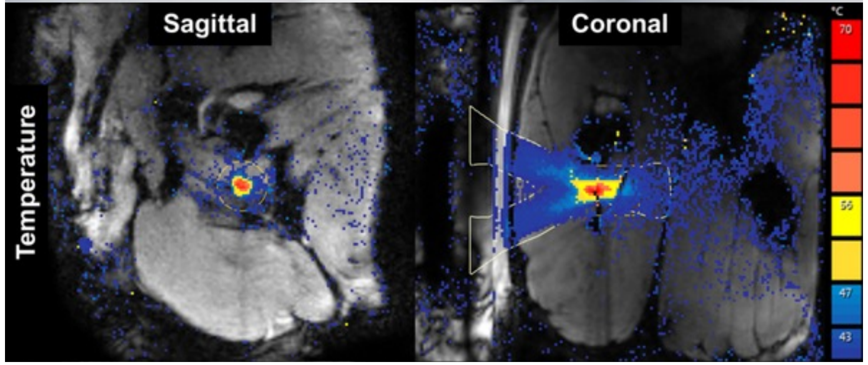
Heikki Nieminen

13.9.-7.12.2021









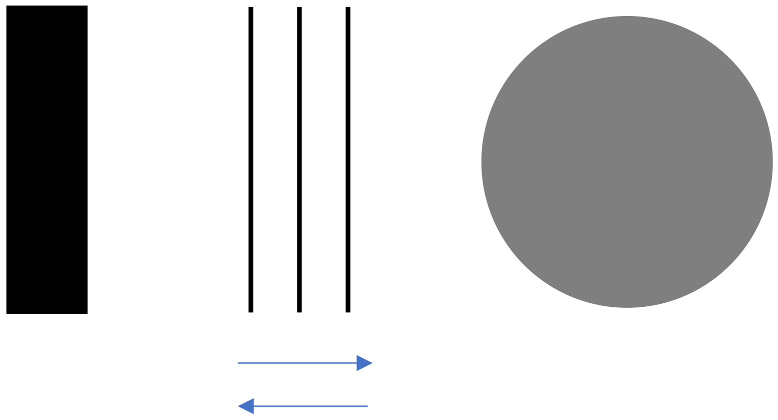
Quantitative ultrasonics

Basic principles

- Different experimental arrangements allow one to characterize tissue properties in a quantitative way
- Quantitative ultrasonics ➔ quantitative diagnostics
- Contrast mechanisms:
  - Reflection coefficient
  - Transmission coefficient
  - Attenuation
  - Speed of sound
- The contrast mechanisms is typically needed to reveal the pathological state
  - The idea is to relate the ultrasound physics to pathology

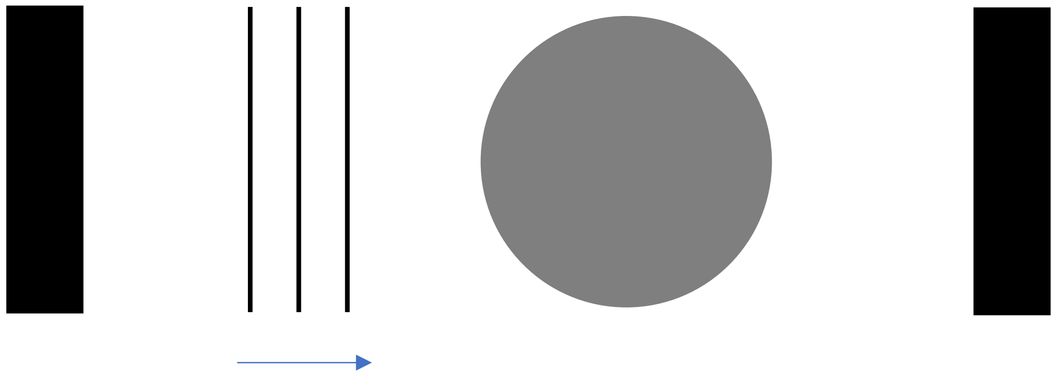
Common measurement geometries

Reflection mode (RX):



Ultrasound transducer (transmitter/ receiver) | Pulse | Object

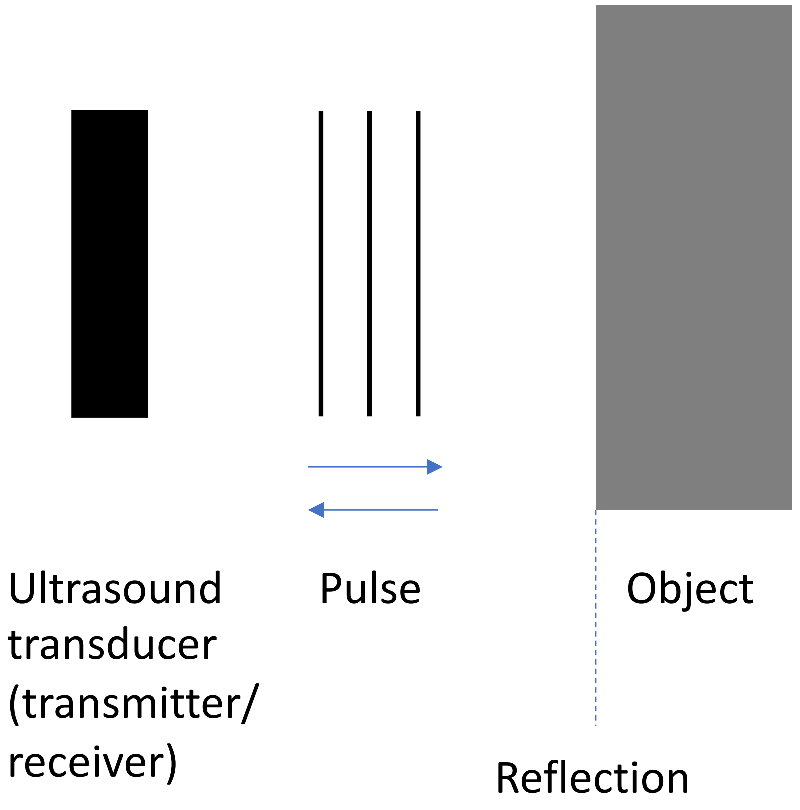
Transmission mode (TX):



Ultrasound transducer (transmitter) | Pulse | Object | Ultrasound transducer (receiver)

Reflection measurement

- Reflection coefficient



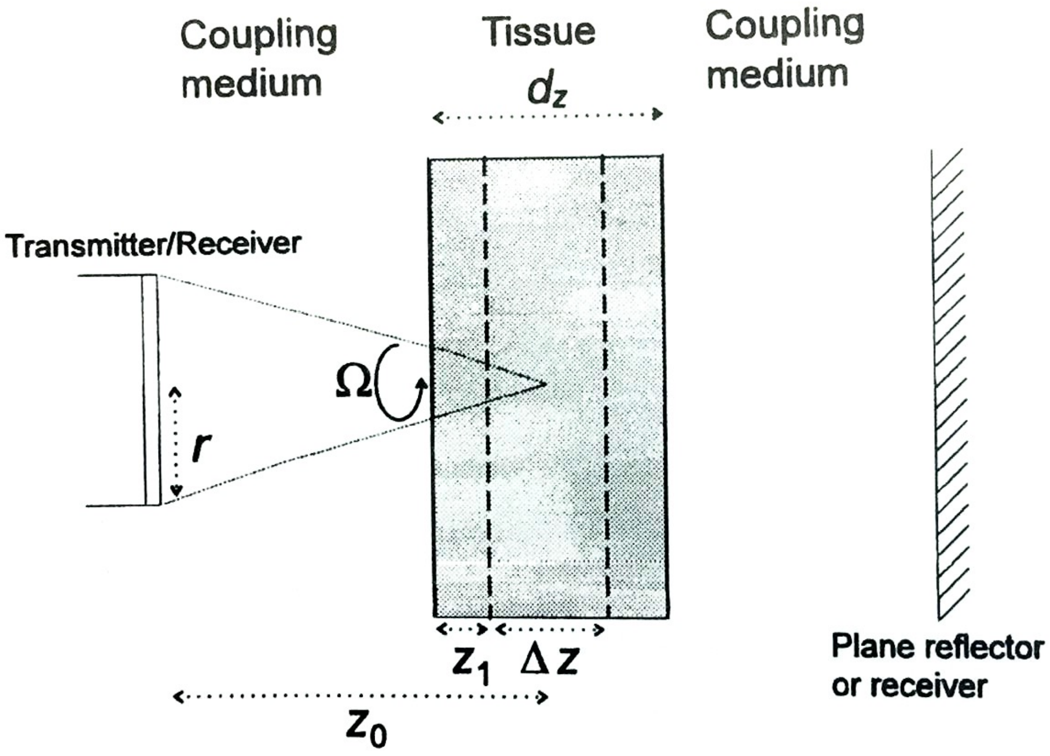
$$R = \frac{p_r}{p_i}$$

i = incident wave
r = reflected wave

Pressure of the incident wave can be measured by measuring the pressure of the reflected wave when having a pefrect reflector at the same location as the surface of the object. The replace the perfect reflector by object to measure the pressure of the reflected wave from the object.

Duck p. 68-69

Transmission measurement: speed of sound



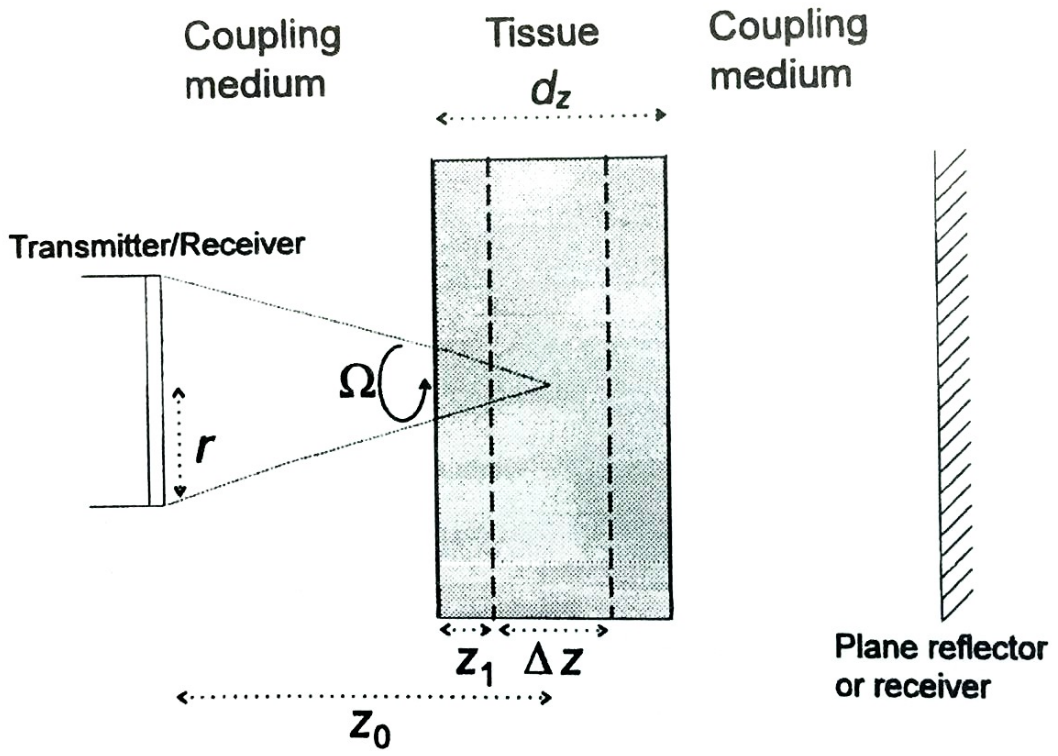
Measurement of speed-of-sound in reflection mode:

$$\frac{1}{c_t} = \frac{1}{c_w} - \frac{\Delta t}{2d_z}$$

t = tissue
w = water

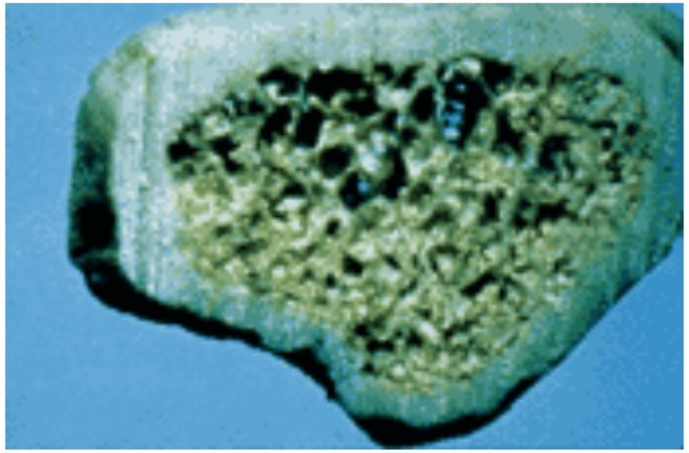
Transmission measurement: attenuation coefficient

- to be derived in the exercises



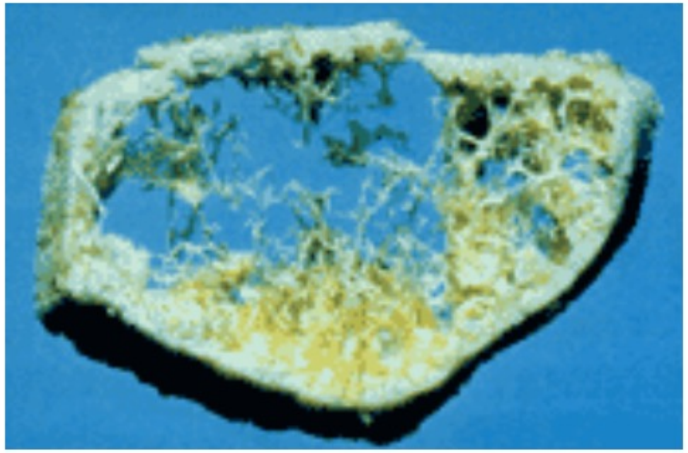
Osteoporosis

Normal



(a)

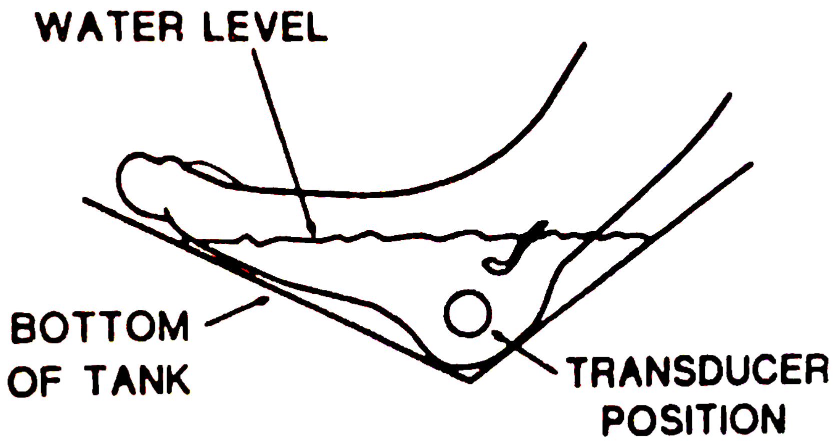
Osteoporosis

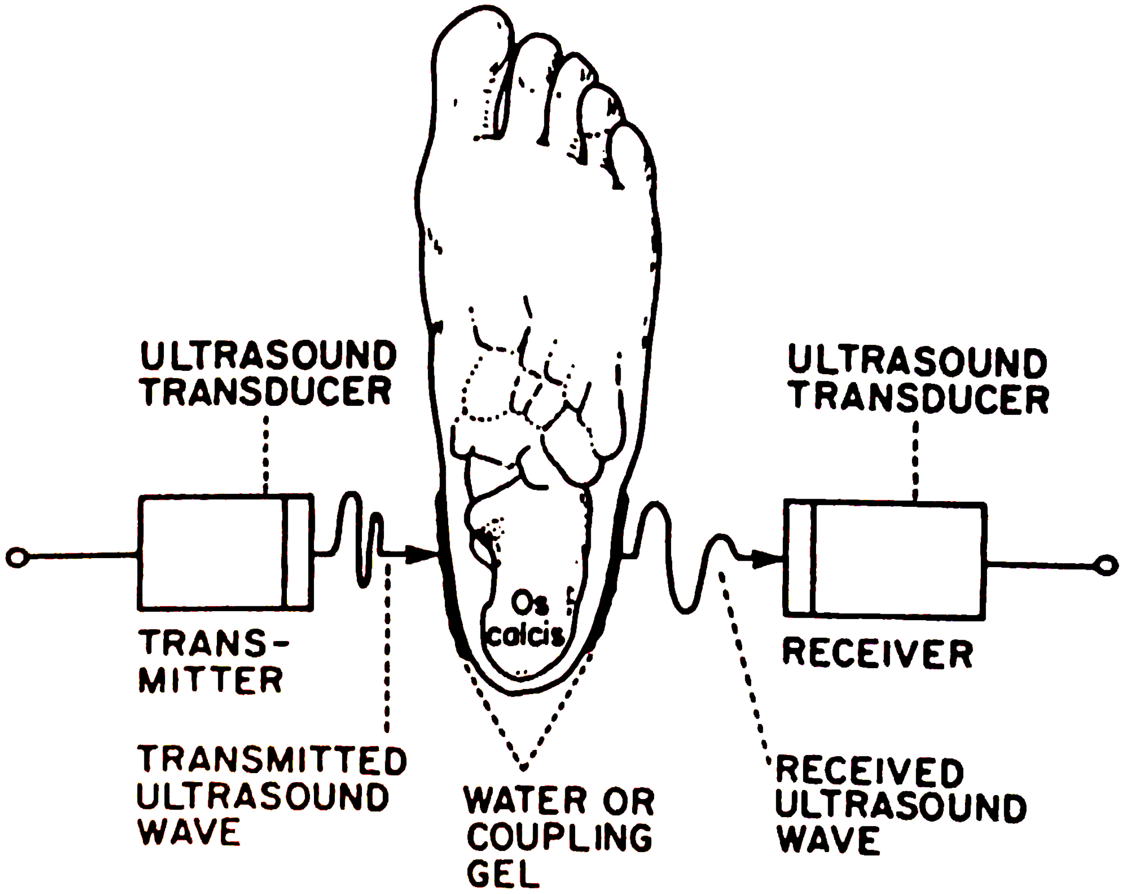


(b)

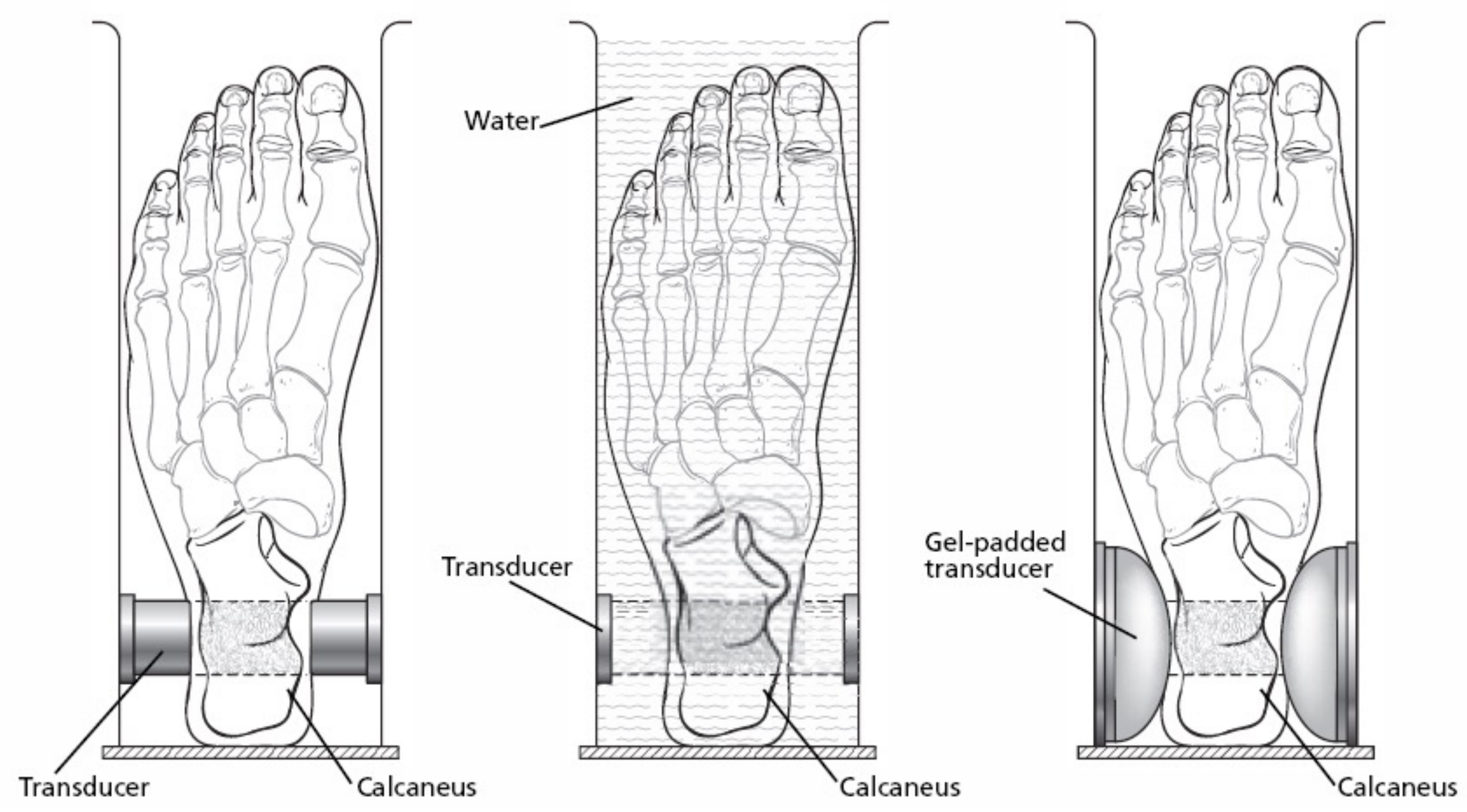
Duck p. 293

Quantitative ultrasound for assessment of bone mineral density



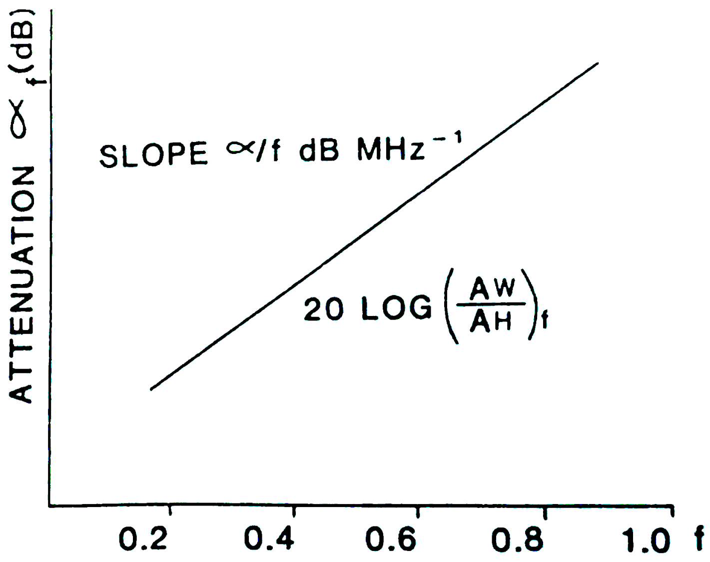


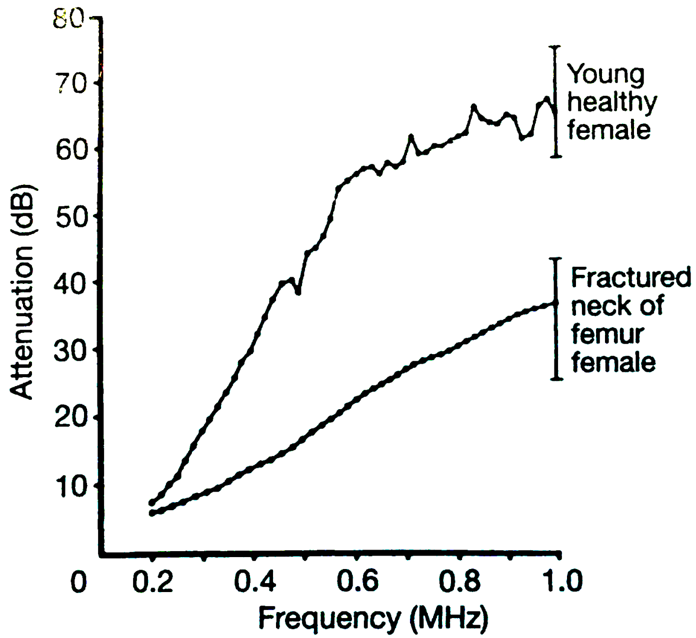
Quantitative ultrasound for assessment of bone mineral density, different configurations



Duck p. 293-295

Quantitative ultrasound for assessment of bone mineral density





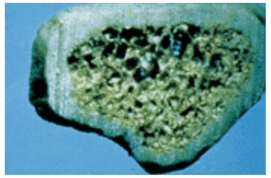
Broadband ultrasound attenuation (BUA):

$$\mathrm{BUA} = \frac{\mathrm{d}}{\mathrm{d}f}\left[20\log_{10}\left[\frac{A_W(f)}{A_H(f)}\right]\right]$$

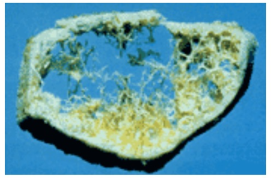
W = water, H = heel

Why is attenuation decreased by osteoporosis?

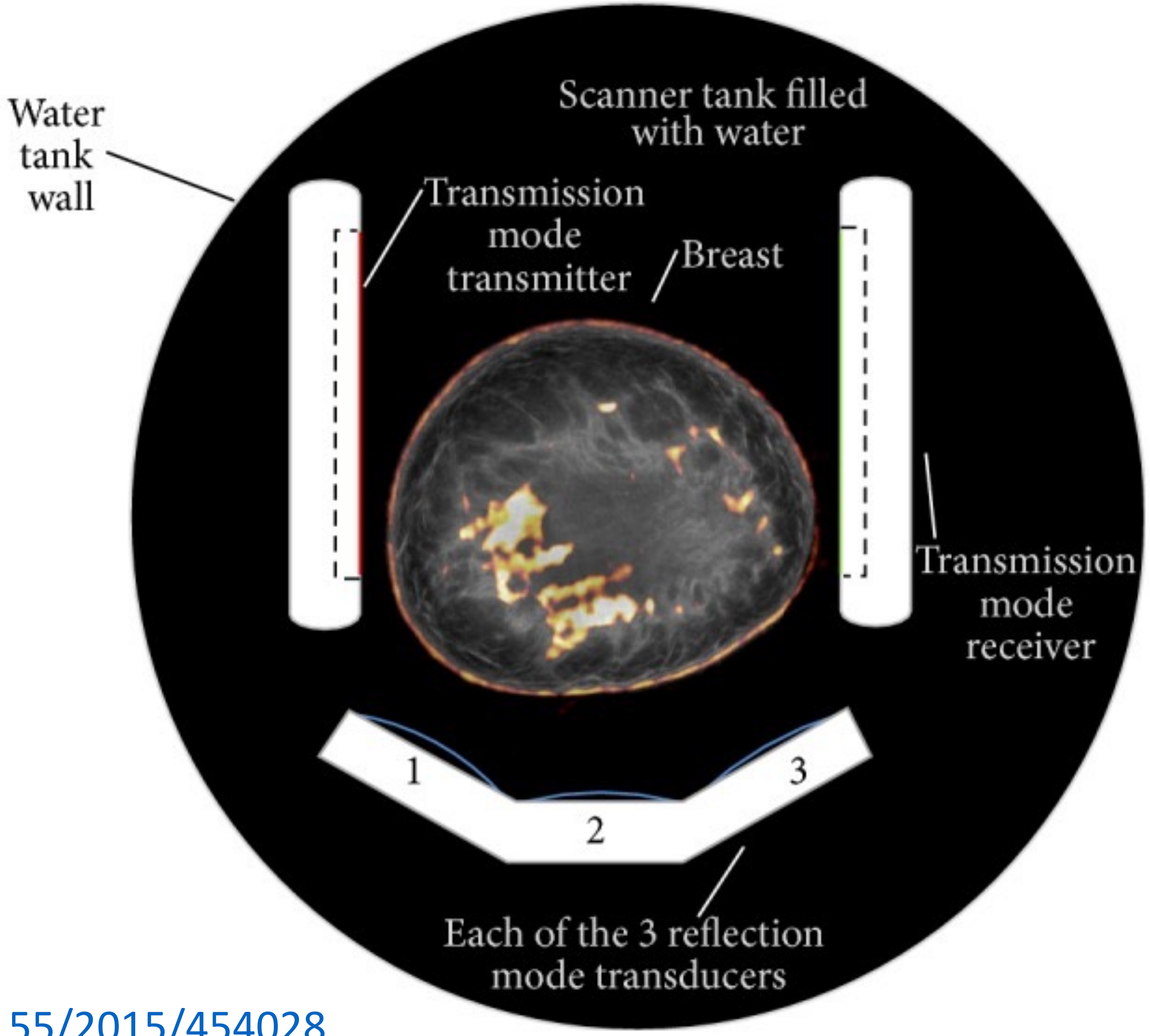
(a)



(b)

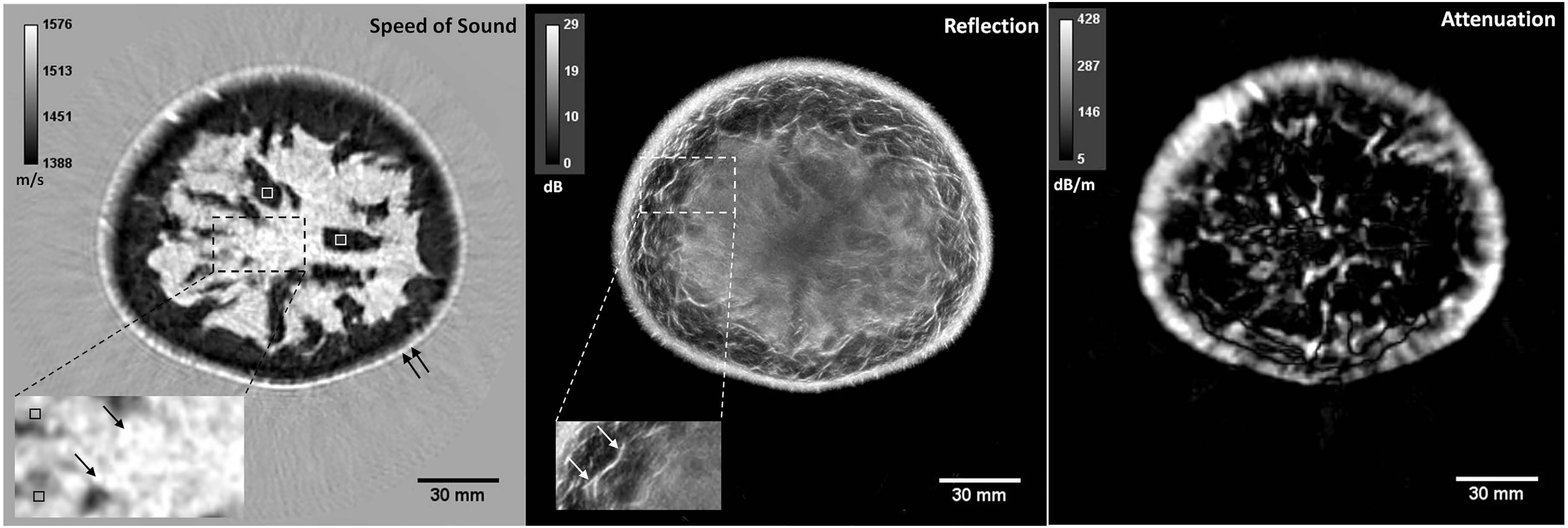


Quantitative ultrasound tomography (breast)



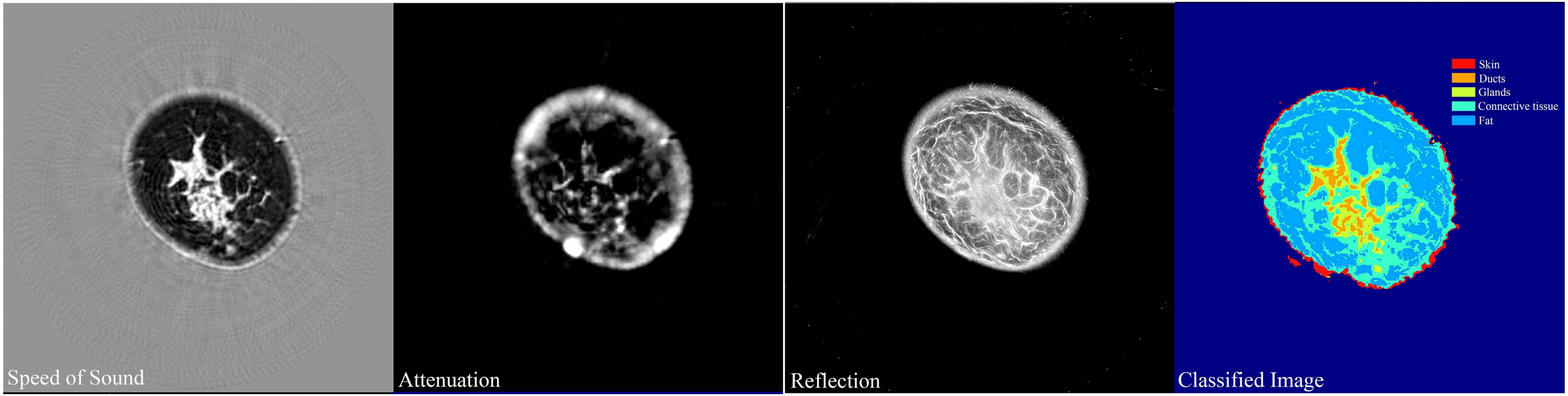
Lenox et al 2015: doi: 10.1155/2015/454028

Quantitative ultrasound tomography (breast)



Malik et al 2016: DOI: 10.1038/srep38857

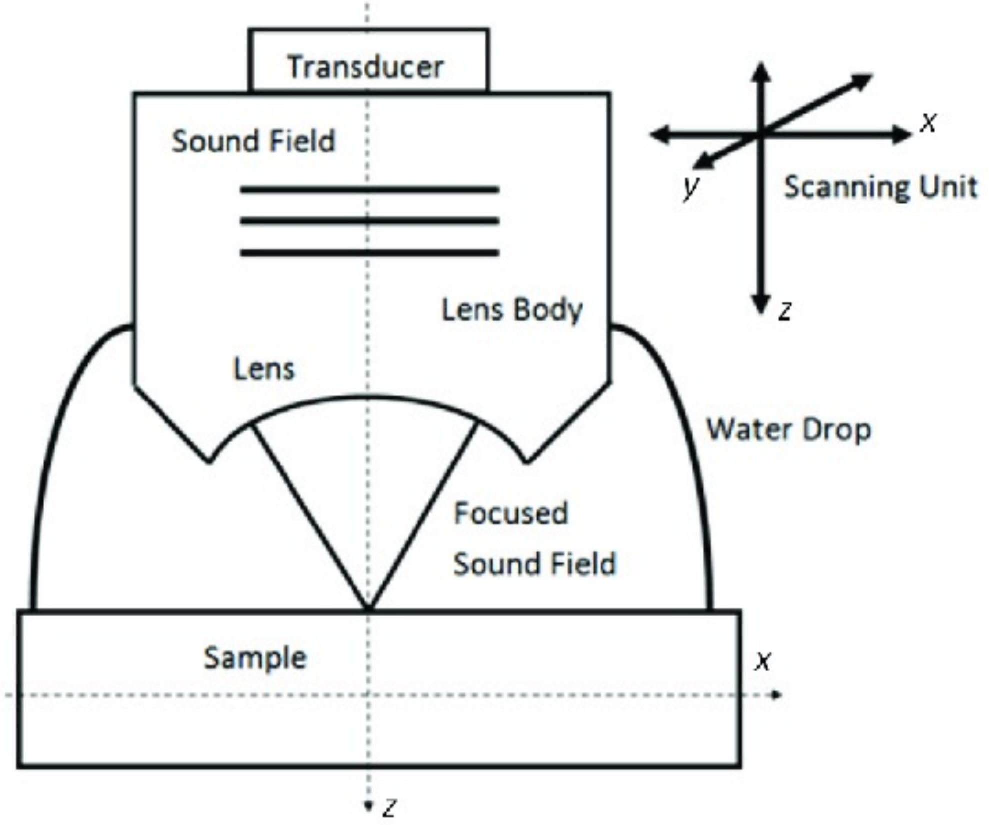
Quantitative ultrasound tomography (breast)



Malik et al 2016: DOI: 10.1038/srep38857

Scanning ultrasound microscopy (SAM)

- Microscopic imaging of acoustic properties of tissue



SAM: cortical bone

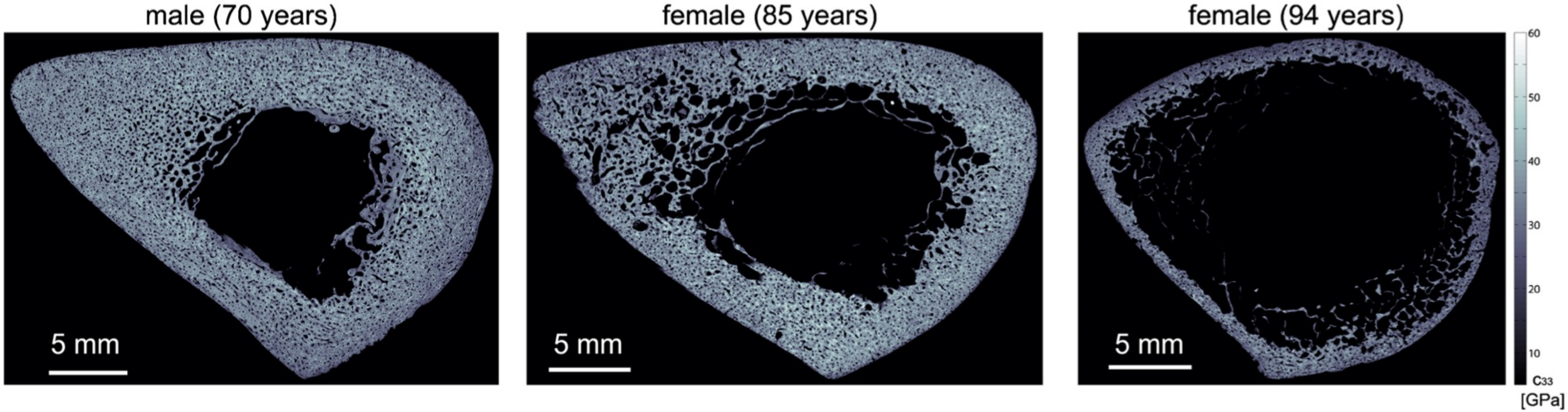


Fig. 1 Differences in the tibia mid-shaft micro- and ultrastructure in patients of increasing age depicted by 50-MHz scanning acoustic microscopy (SAM). The progression of bone deterioration (from left to right) results in an accumulation of large BMUs, cortical thinning and changes in the tissue stiffness. The medial (upper) region can be assessed in vivo by ultrasound

Raum et al. 2014: DOI 10.1007/s11914-014-0205-4

SAM: myocardial infarction

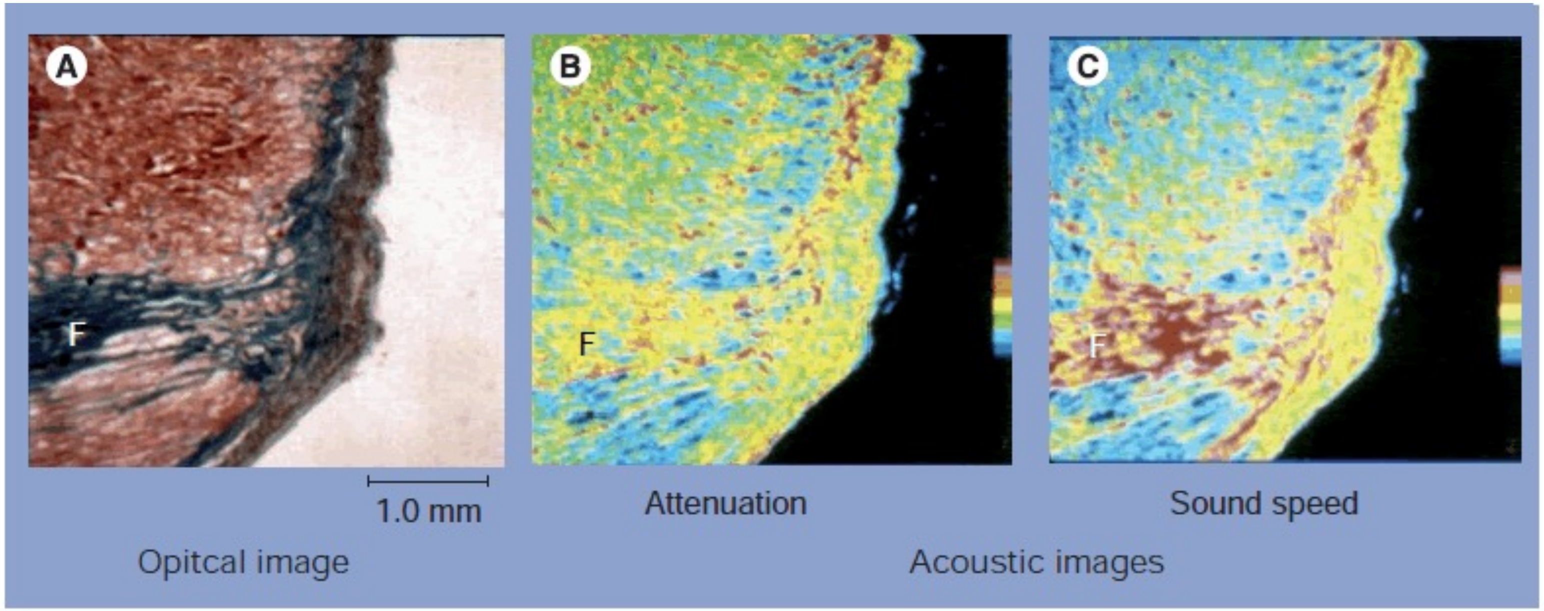


Figure 10. (A) Optical, (B) attenuation and (C) sound speed images of acute myocardial infarction.

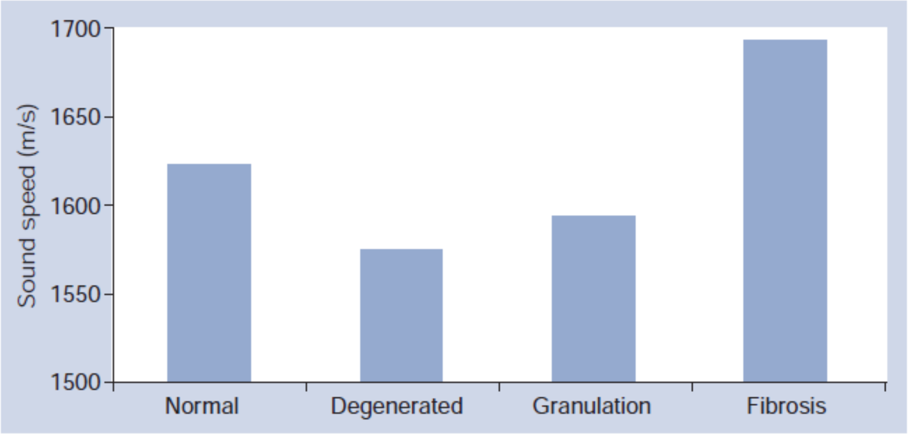


Figure 11. Sound speed in four kinds of tissue elements observed in acute myocardial infarction.

Ultrasound provides a label-free markers for tissue types and pathologies.

Saijo 2009: 10.2217/IIM.09.8

SAM: arterial wall

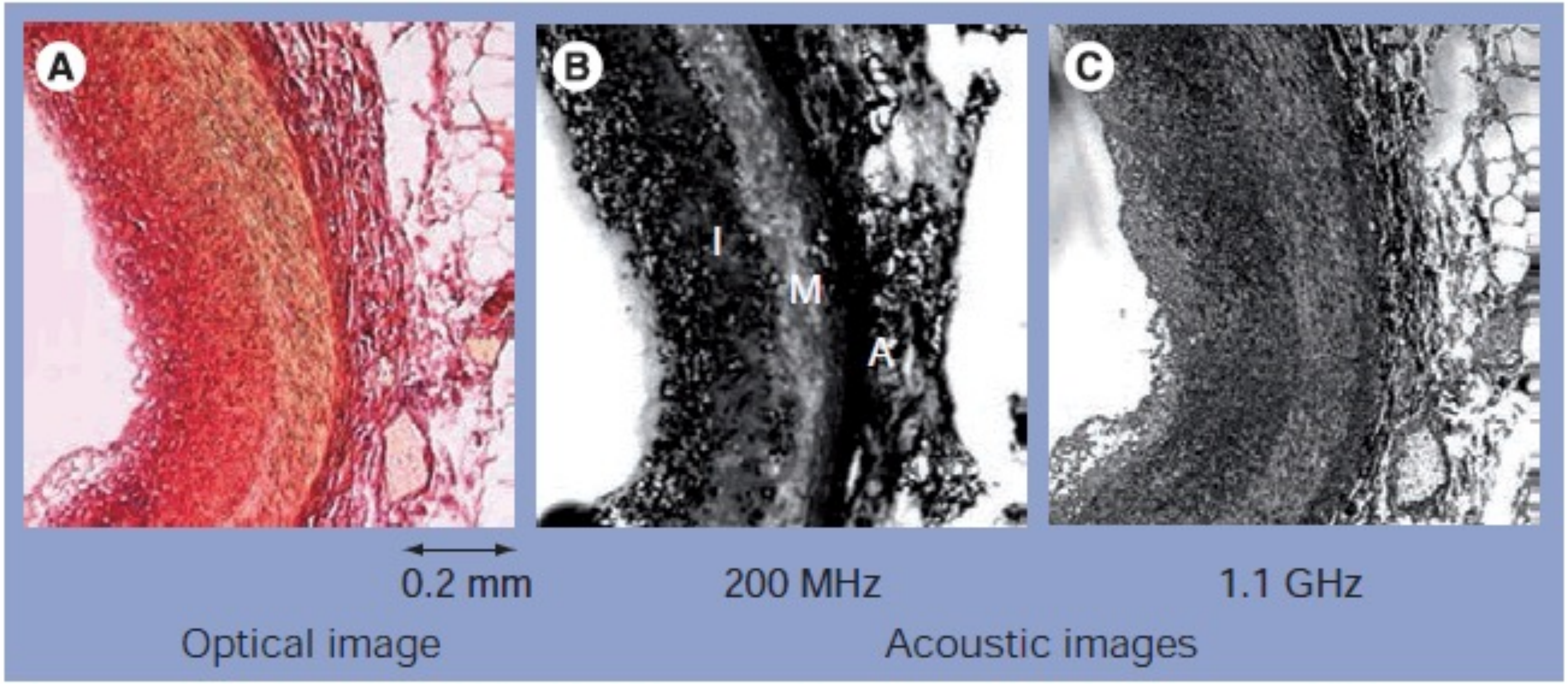


Figure 14. (A) Optical, (B) 200-MHz scanning acoustic microscope and (C) 1.1-GHz scanning acoustic microscope images of normal human coronary artery.
A: Adventitia; I: Intima; M: Media.

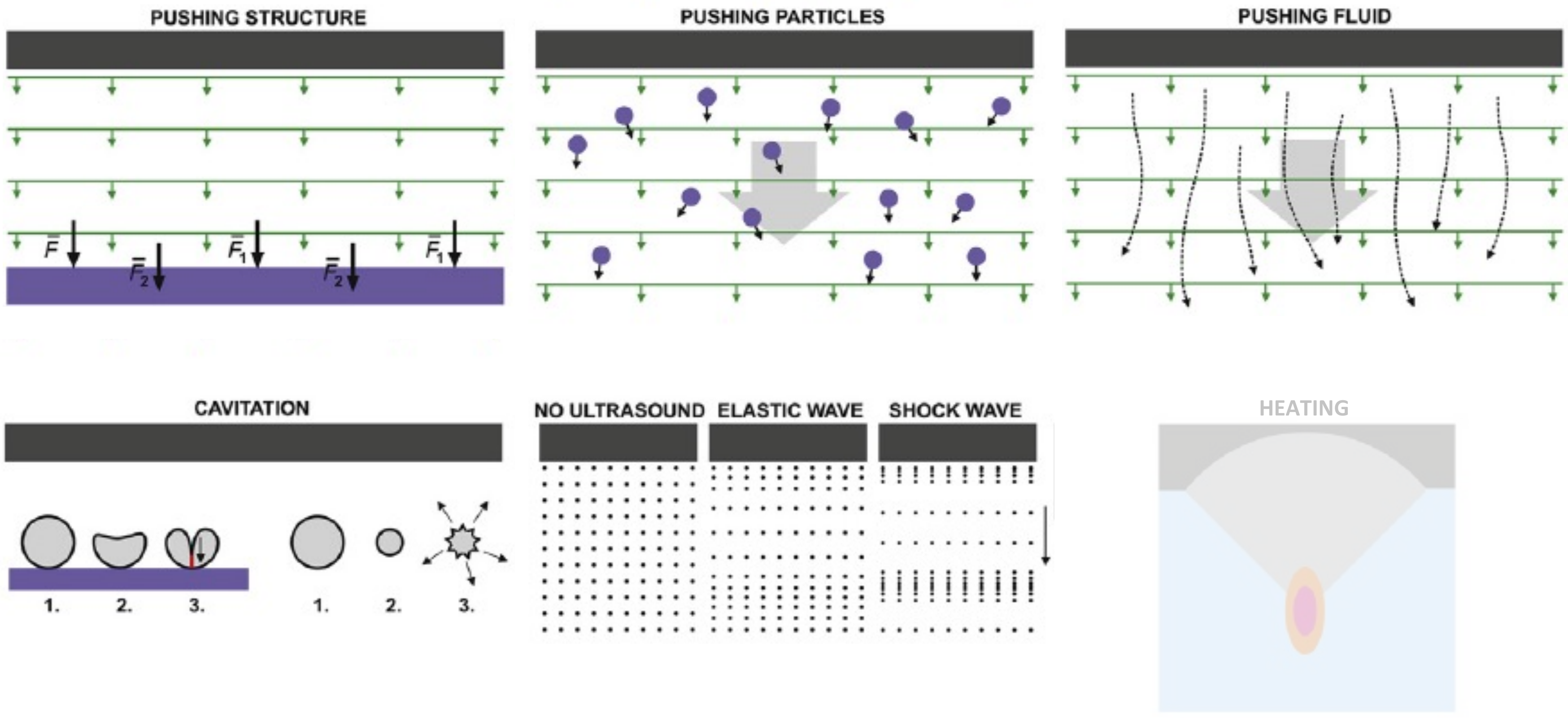
Saijo 2009: 10.2217/IIM.09.8

Non-linear ultrasonics

Non-linear ultrasonics

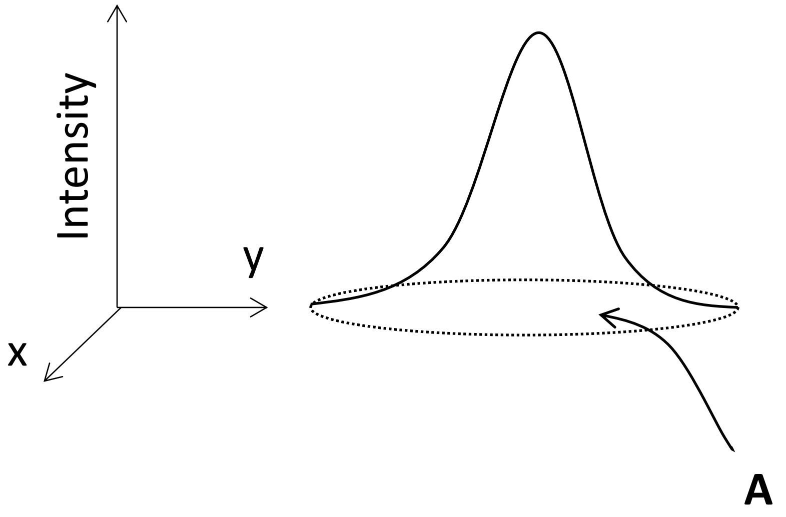
- The field of ultrasonics related to non-linear propagation of sound (relationships between particle displacement, particle velocity, velocity, pressure, density etc. are not linear)

Selected non-linear phenomena



Spatial average

- Spatial average-temporal average (SATA) (this is like I_{spta} supplemented by area integral)
- Spatial average-pulse average (SAPA) (Like I_{sppa} supplemented by area integral)



$$I_{\text{sata}} = \frac{\int_A \int_{t_1}^{t_2} p^2(t,x,y)\,dt\;\,dA}{A\,\rho c\,PRP}$$

t_1 = ? t_2 = ?

$$I_{\text{sapa}} = \frac{\int_A \int p^2(t,x,y)\,dt\;\,dA}{A\,\rho c\,PD}$$

Abbreviations and terms

Abbreviation or term	Definition
Absorption	Loss of acoustic energy converted into other forms of energy such as heat.
Acoustic discontinuity	Spatially abrupt change in *e.g. speed of sound* or *acoustic impedance* at an interface between two materials.
Acoustic impedance	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 radiation force	Force induced by sound impinging on sound-absorbing material (*e.g.* tissue) or acoustic interfaces (*e.g.* fluid-tissue or gas-fluid –interface).
ARFI, *i.e.* Acoustic Radiation Force Impulse imaging	An elasticity imaging technique in which acoustic radiation force produces spatial tissue displacement, which is recorded by *ultrasound* imaging device. The detected spatial displacement are converted into spatial elasticity images that can be used to diagnose *e.g.* hard tumors deep in the body that are difficult to palpate.

Abbreviations and terms

Acoustic streaming	Streaming of fluids induced by *absorption* of sound into the medium.
Attenuation	Loss of acoustic energy due to *absorption*, sound scattering at *acoustic discontinuities* and spreading of the sound beam (geometric attenuation).
Cavitation (stable, inertial)	Interaction of acoustic *pressure* variation and gas *micro-bubbles* leading to radial bubble oscillation (stable cavitation). This can induce fluid streams around the bubble and shear forces on cells. Combining intense sound and micro-bubbles allows producing micro-implosions or fast and hot water-jets at the micro-scale that can micro-machine material (inertial cavitation). Cavitation is a threshold phenomenon that can be controlled by adjusting frequency, maximum negative sound pressure amplitude, and duration of the applied sound pulse.
Displacement	In *ultrasound* wave, molecules oscillate coherently around their rest position. The distance of molecules from their rest position is called a displacement. In longitudinal or shear waves the displacement of molecules occur along or perpendicular to the direction of ultrasound propagation, respectively.

Abbreviations and terms

HIU	High-intensity *ultrasound* or power *ultrasound* has ≳ 1W/cm² *intensity*.
HIFU, *i.e.* High-Intensity Focused Ultrasound	High-Intensity Focused Ultrasound is *HIU* that is produced by geometrically and/or electrically focusing ultrasound energy into a small volume. In medicine, HIFU is typically used to *thermally ablate* tumor tissue.
Intensity	Power of sound per unit area perpendicular to the direction of *ultrasound* propagation (SI unit: W/cm²). Ultrasound intensity is directly proportional to the square of ultrasound *pressure*.
Lithoptripsy	Method for breaking gallstones or other calculi by strong *shock waves*.
LIU	Low-intensity *ultrasound* or low power ultrasound has ≲ 1W/cm² *intensity*.
Longitudinal wave	See *displacement*.

Abbreviations and terms

Micro-bubble	A micron sized gas bubble. When a micro-bubble interacts with sound, a phenomenon called *cavitation* may occur. Micro-bubbles are used in medicine as *ultrasound* imaging contrast agents (enhanced scattering of sound) and in therapy applications (enhanced cavitation effects). Nano-bubbles have shown promise to act as ultrasound contrast agents.
PRF, *i.e.* pulse repetition frequency	The rate (Hz) at which *ultrasound* pulses or bursts are generated.
Pressure	Ultrasonic pressure appears as a travelling density disturbance of material oscillating at a frequency > 20 kHz.
Reflection	Reflection of sound occurs when sound meets an *acoustic impedance* mismatch (see *acoustic discontinuity*), which is greater in size than the wavelength (*e.g.* collagen bundle). When the discontinuity is of same size or smaller than the wavelength of the sound wave, *scattering* occurs instead of reflection. Collagen at superficial articular cartilage or inside cartilage is known to be a strong reflector or scatterer of ultrasound, respectively.

Abbreviations and terms

Scattering	See *reflection*.
Shear wave	See *displacement*.
Speed of sound	A property of a sound wave describing the travelling speed of a wave. In articular cartilage, the *ultrasound* speed is typically 1600-1700 m/s in MHz domain.
Shock wave	A travelling acoustic wave with steep temporal and spatial gradients in *pressure*. This is typically a short impulse-like acoustic wave with high pressure amplitude and broadband spectral content. Its propagation speed depends on *intensity*.
Thermal ablation	Removal of tissue by heat. This strategy is used *e.g.* in *HIFU* surgery, where tumor cells are killed by heating tissue with focused *ultrasound*.

Abbreviations and terms

Ultrasonic actuation	A process of using *ultrasound* to modify, machine or micro-machine material such as tissue. Common examples of ultrasound actuation are: - *cutting:* ultrasonic knife with vibrating blade to enhance surgical cutting of tissues. - *homogenization:* ultrasound can be used to homogenize tissue by typically combining low-frequency ultrasound with strong inertial *cavitation*. - *milling, abrading or polishing:* in these industrial actuation techniques high-intensity ultrasound is applied to milling, abrading or polishing tools to enhance the desired actuation effect. - *translation: acoustic radiation force* can move tissue or translate gas within a fluid. - *heating:* ultrasound can be used to selectively heat tissue for *thermal ablation* or hyperthermia. - *welding:* applying ultrasound to the bonding spot during a welding process, *e.g.* a stronger bond can be achieved. - *tearing:* stresses from *shock waves* can tear molecule bonds and consequently tear materials such as tissue. - *hardening* or *softening:* ultrasound can harden or soften some engineering materials.
Ultrasound	Coherent spatial oscillation of molecules exceeding the spectral range of human hearing (frequencies > 20 kHz) resulting in a travelling (or standing) waveform. Spatial oscillation of molecules results in density and *pressure* oscillation of the material.

Abbreviations and terms

Ultrasound speed	See *speed of sound*.
Wavelength	The length (m) of one sinusoidal oscillation of a wave. In articular cartilage, the wavelengths of 100 kHz, 1 MHz and 10 MHz *ultrasound* are about 16 mm, 1.6 mm an 160 µm.

Sound pressure level (SPL)

- Sound pressure level in Decibels (dB)

$$SPL_{\mathrm{dB}} = 10\log_{10}\left(\frac{p^2}{{p_{\mathrm{ref}}}^2}\right) = 10\log_{10}\left(\frac{I}{I_{\mathrm{ref}}}\right) = 20\log_{10}\left(\frac{p}{p_{\mathrm{ref}}}\right)$$

  - Reference pressure: $p_{\mathrm{ref}} = 2\cdot10^{-5}$ Pa
  - Reference intensity: $I_{\mathrm{ref}} = 10^{-12}$ W/m^2

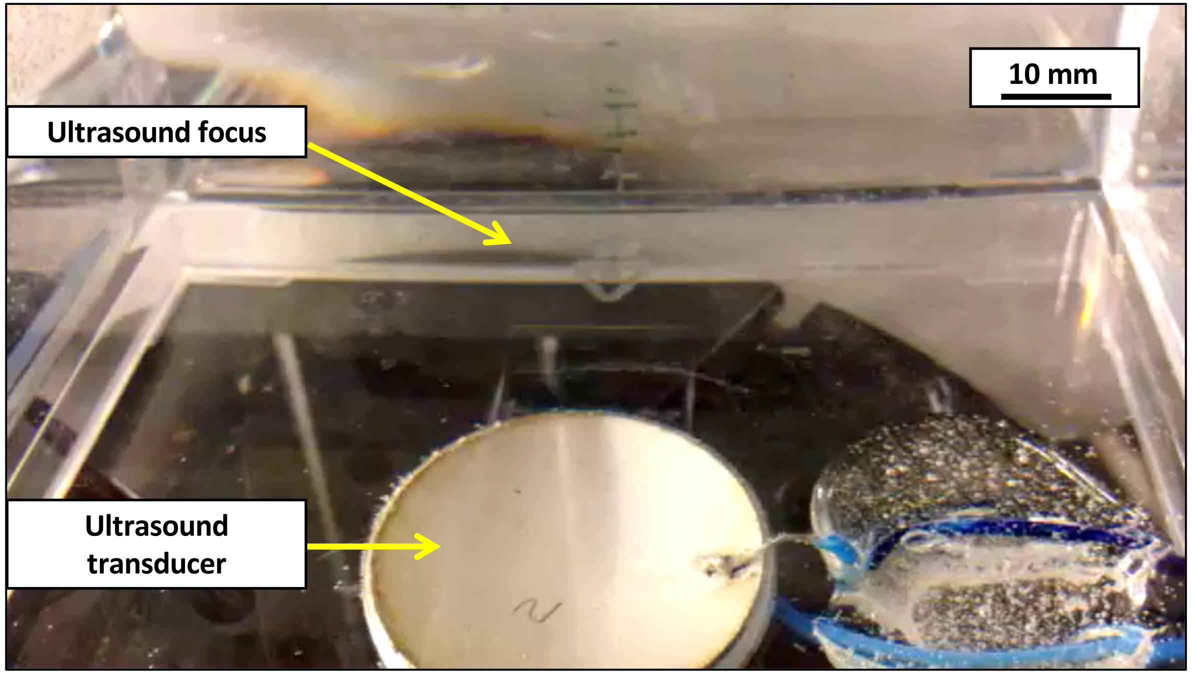
- Sound pressure level in Nepers (Np)

$$SPL_{\mathrm{Np}} = \log_e\left(\frac{p^2}{{p_{\mathrm{ref}}}^2}\right) = \log_e\left(\frac{I}{I_{\mathrm{ref}}}\right) = SPL_{\mathrm{dB}}/8.686$$

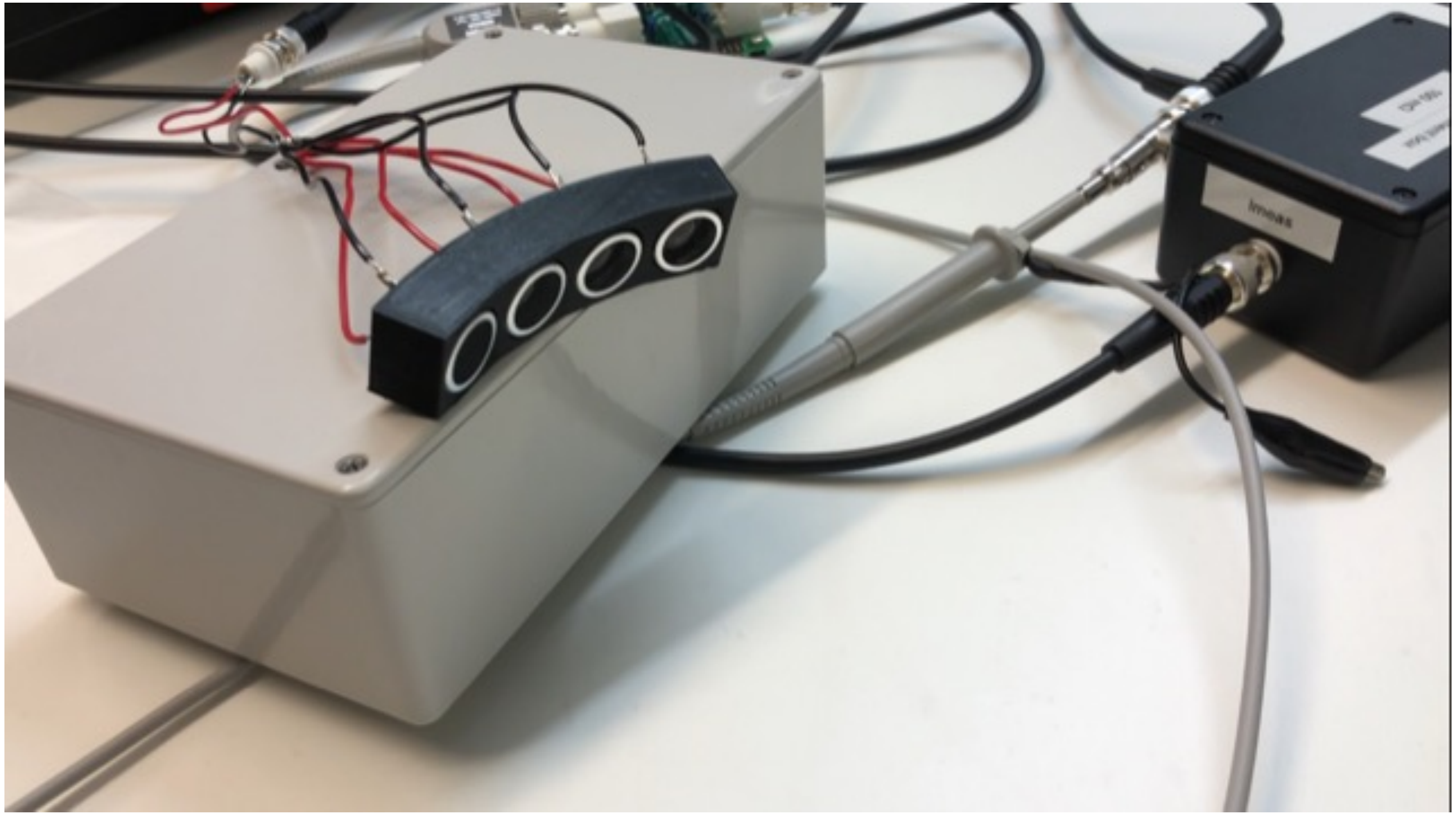
Acoustic radiation force

Acoustic radiation force

Ultrasound focused at water surface (VIDEO)

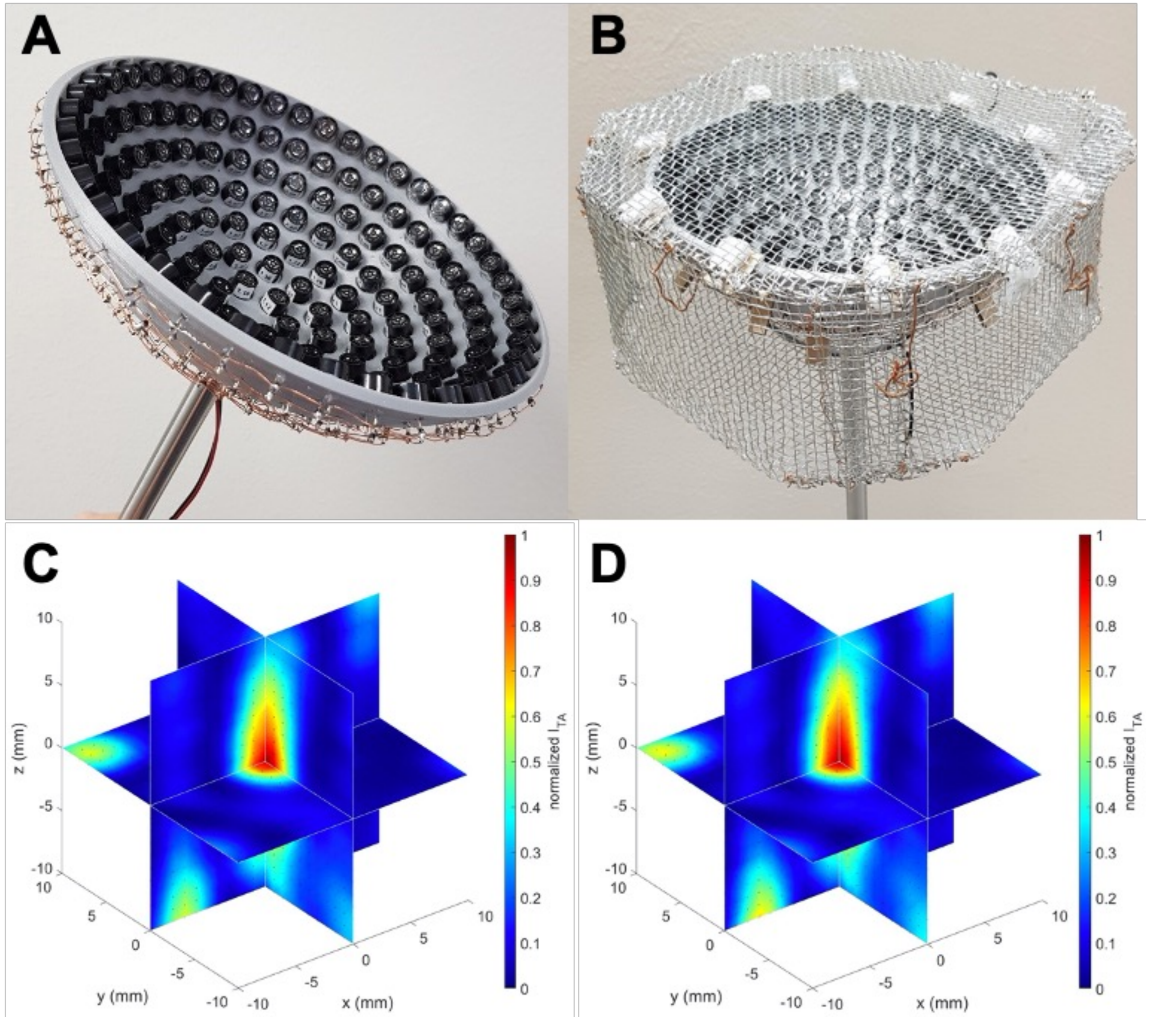


Acoustic radiation force



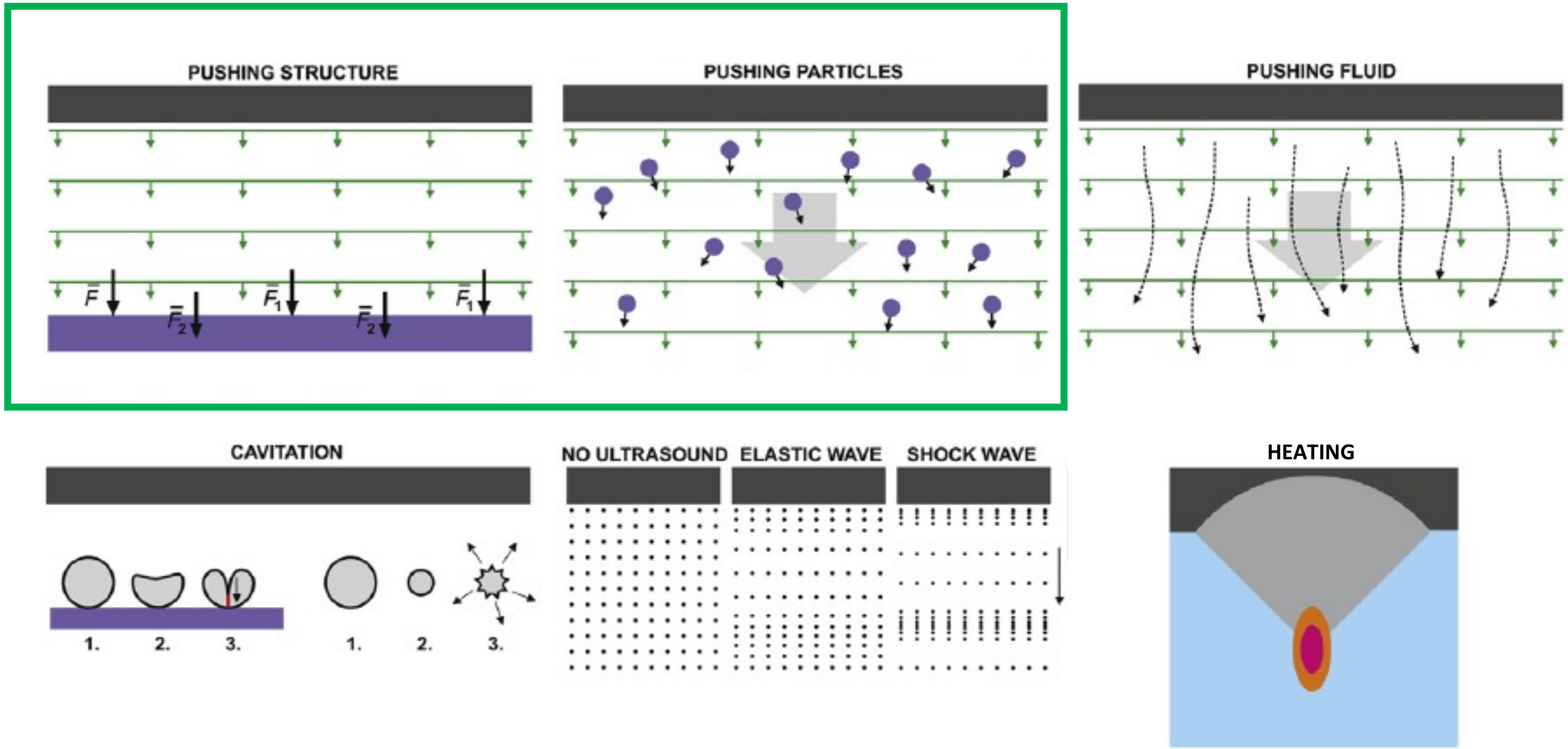
Acoustic radiation force

Generating touch sensations with ultrasound



Hayward et al. 2020:
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9251554

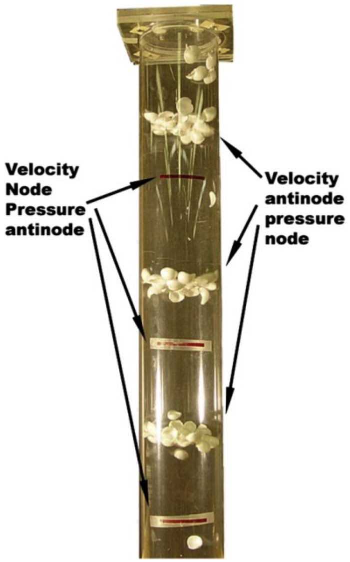
Acoustic radiation force physics



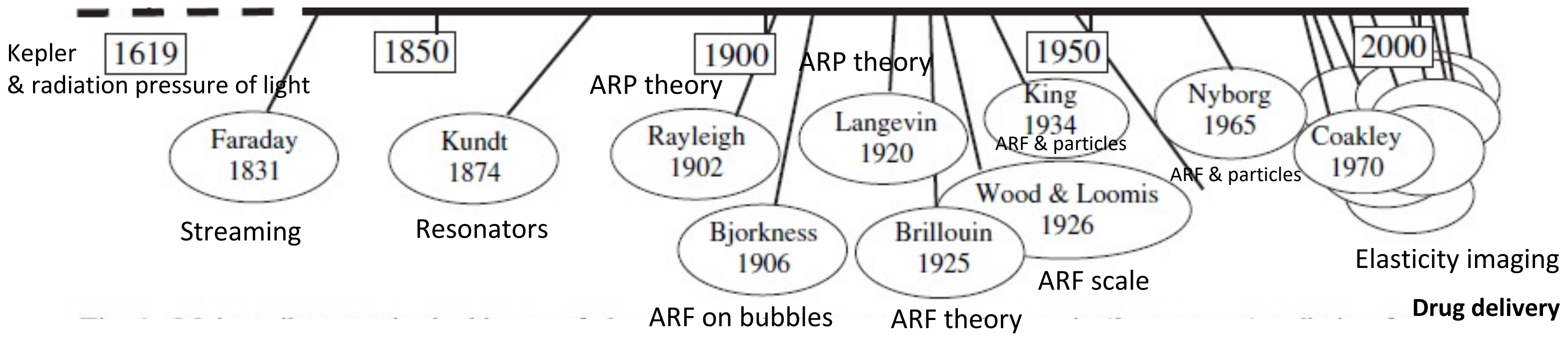
History of acoustic radiation force

- Streaming induced by sound waves was first observed by Faraday in 1830 (light powder moves with sound in air)
- Kundt & Lehman were able to trap powder in an acoustic resonator
- Lord Rayleigh published the first theory on acoustic radiation force in 1902, which was later beefed up by Langevin

Styrofoam chips levitating in a vertical Kundt's tube



Major milestones of acoustic radiation force



Lord Rayleigh 1842-1919

Reading:

Sarvazyan et al. 2010: http://www.sciencedirect.com/science/article/pii/S0301562910002450

Radiation force

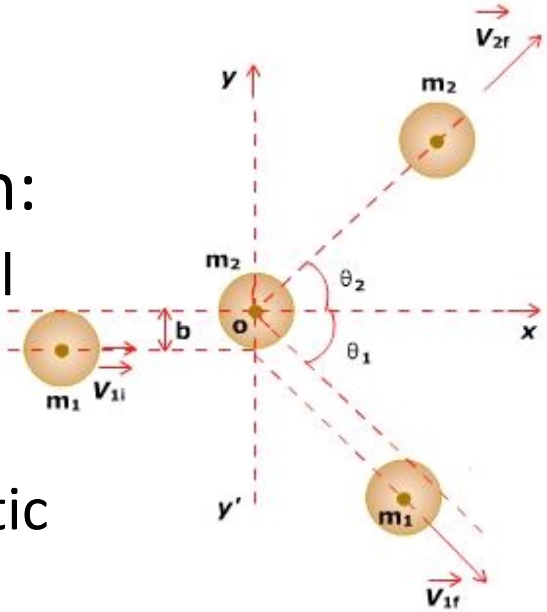
- ***Acoustic radiation force is a time-averaged force that an ultrasound can exert on material***
- During the following lectures we deal with the radiation force in the following cases:
  - Travelling waves
    - Longitudinal waves
      - Interfaces
      - Attenuating (absorption & scattering) medium
    - Surface acoustic waves (SAWs)
  - Standing waves
    - Longitudinal waves
    - SAWs

It is all about particles…

http://www.fotosearch.com/print/CSP424/k4247911/

Radiation force

- Acoustic radiation force occurs when:
  - Sound energy is absorbed into material
  - Travelling wave meets an acoustic discontuinity
  - Standing wave interacts with an acoustic discontinuity



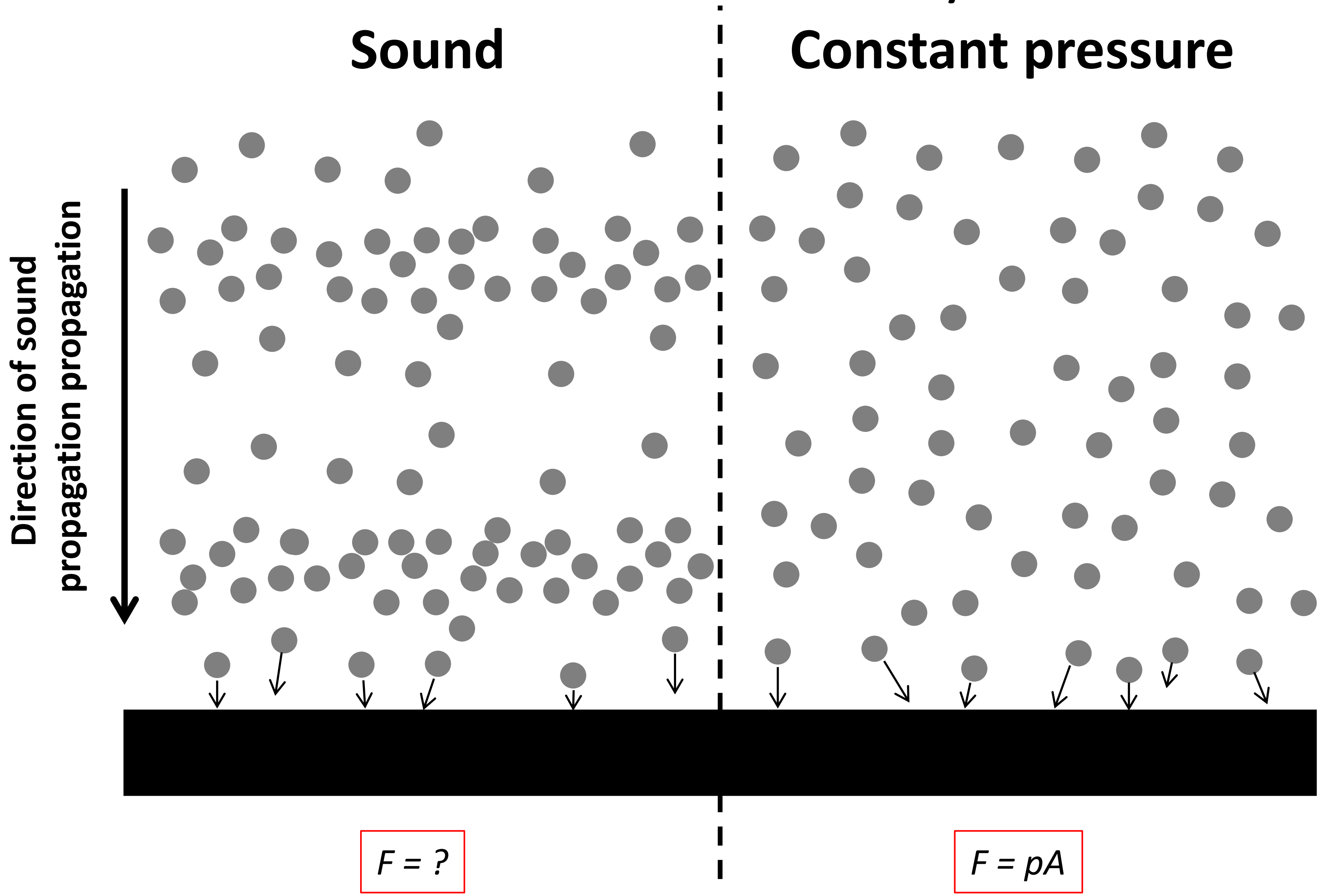
$F = dp/dt$

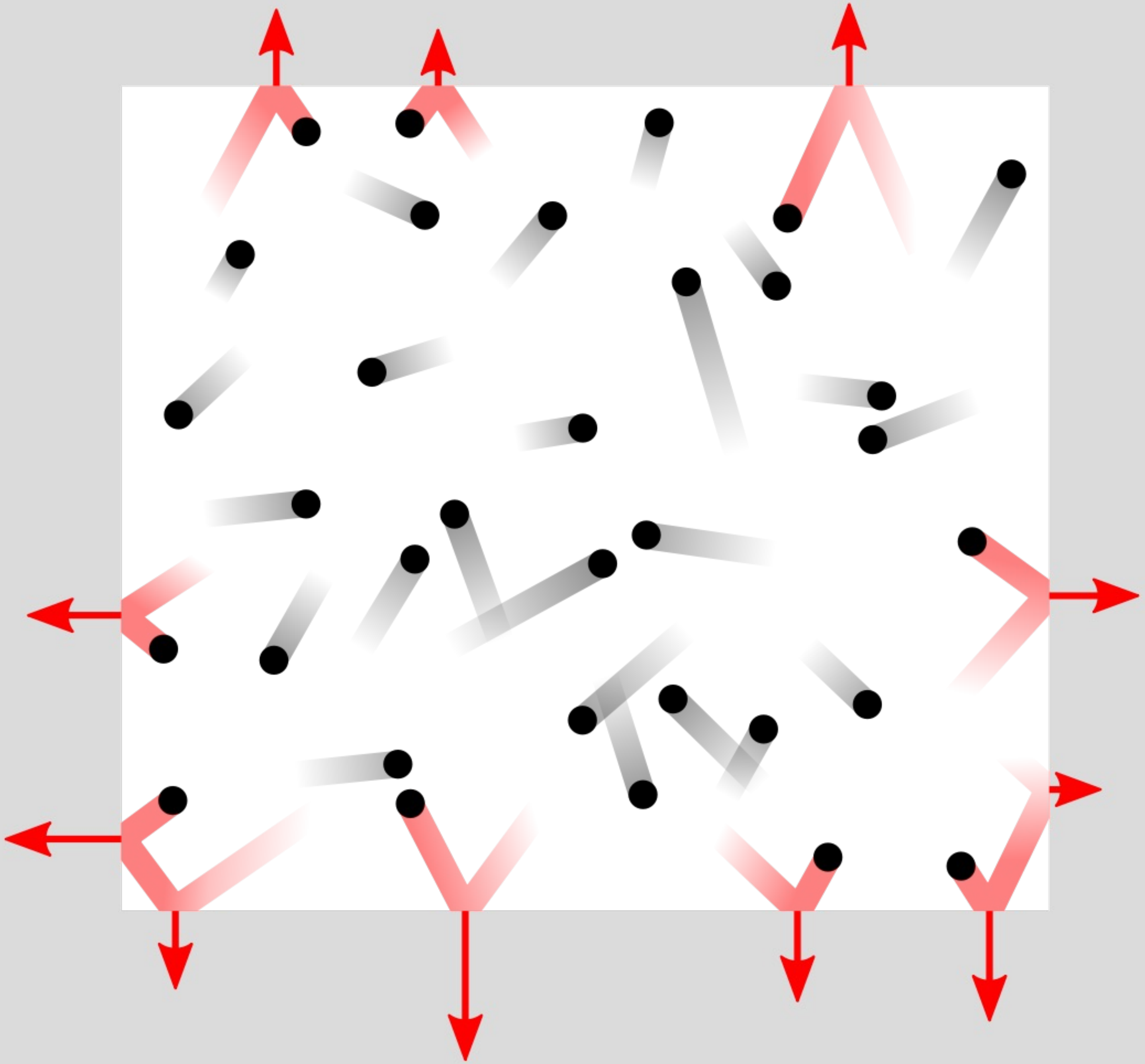
$m_1v_1 + m_2v_2 = m'_1v'_1 + m'_2v'_2$

Energy = constant

Radiation force
(travelling longitudinal wave)

Particle motion at a boundary





Pressure

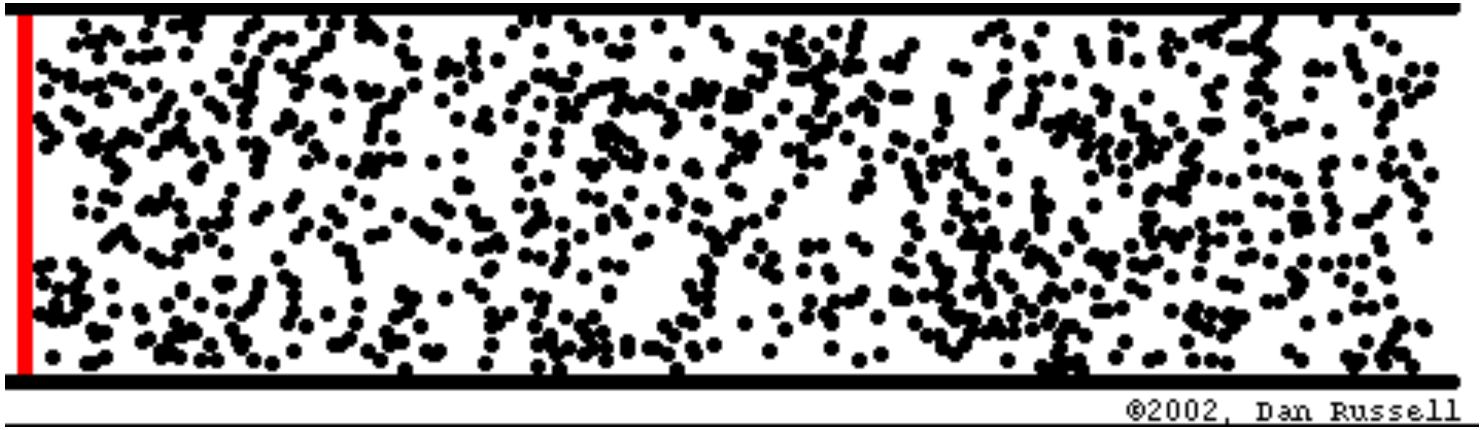
SI unit: Pascal = Pa = N/m^2 = J/m^3

Pressure can be considered as force per unit area or as energy per volume (energy density)

Acoustic radiation force

- We now deal with radiation forces induced by travelling waves (no standing wave stuff)
- Acoustic radiation force occurs always when sound is **reflected, scattered** or **absorbed**
- This is a phenomenon that occurs in both linear and non-linear acoustics

Travelling wave



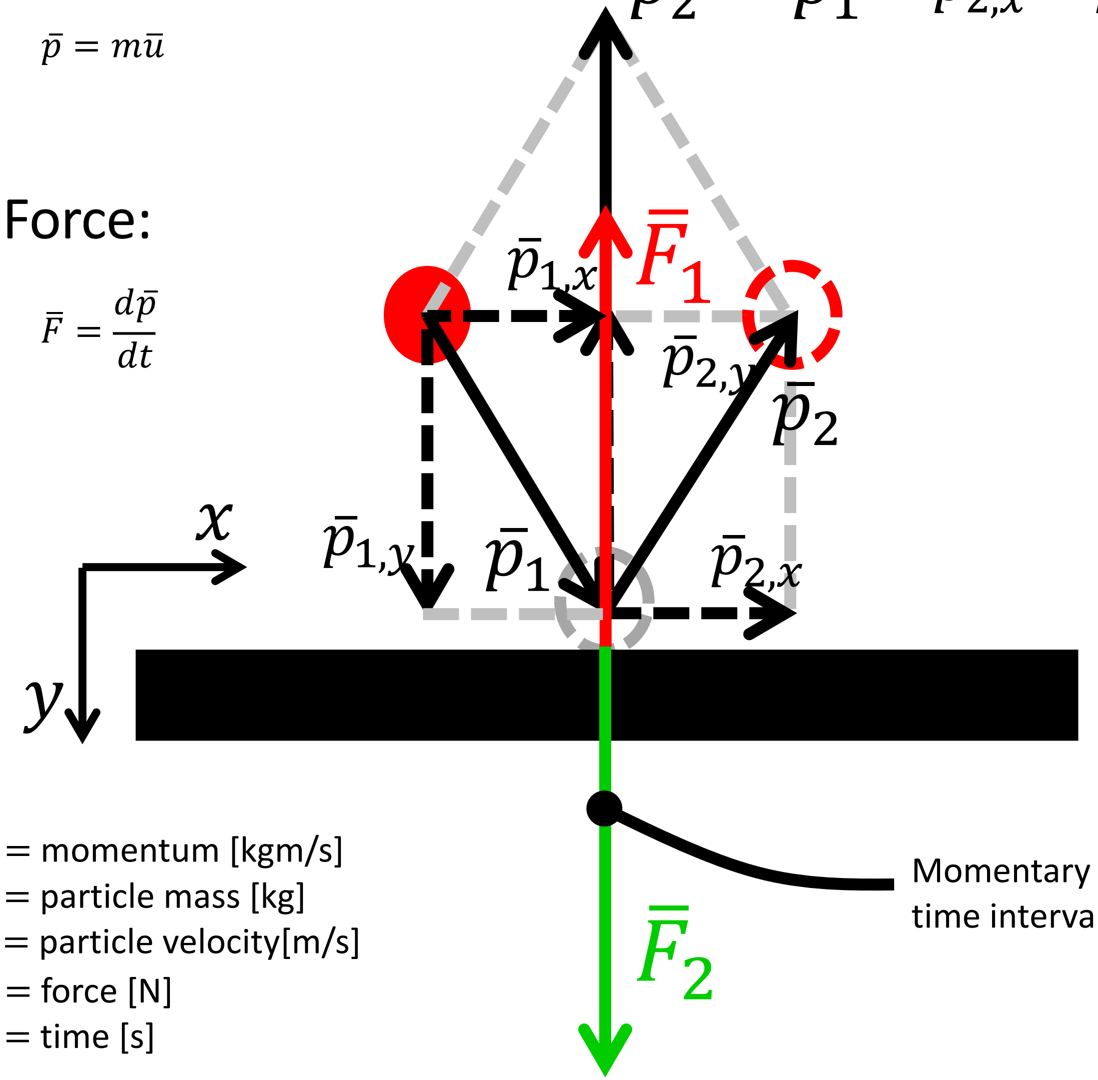
Change in momentum at elastic collision

Momentum:

$$\bar{p} = m\bar{u}$$

Force:

$$\bar{F} = \frac{d\bar{p}}{dt}$$



$$\bar{p}_2 - \bar{p}_1 = \underbrace{\bar{p}_{2,x} - \bar{p}_{1,x}}_{= \bar{p}_{1,x} - \bar{p}_{1,x} = 0} + \underbrace{\bar{p}_{2,y} - \bar{p}_{1,y}}_{= -\bar{p}_{1,y} - \bar{p}_{1,y} = -2\bar{p}_{1,y}} = -\mathbf{2}\,\bar{\boldsymbol{p}}_{\mathbf{1},\boldsymbol{y}}$$

$$F_1 = \frac{dp_y}{dt} = \frac{-2p_{1,y}}{\Delta t}$$

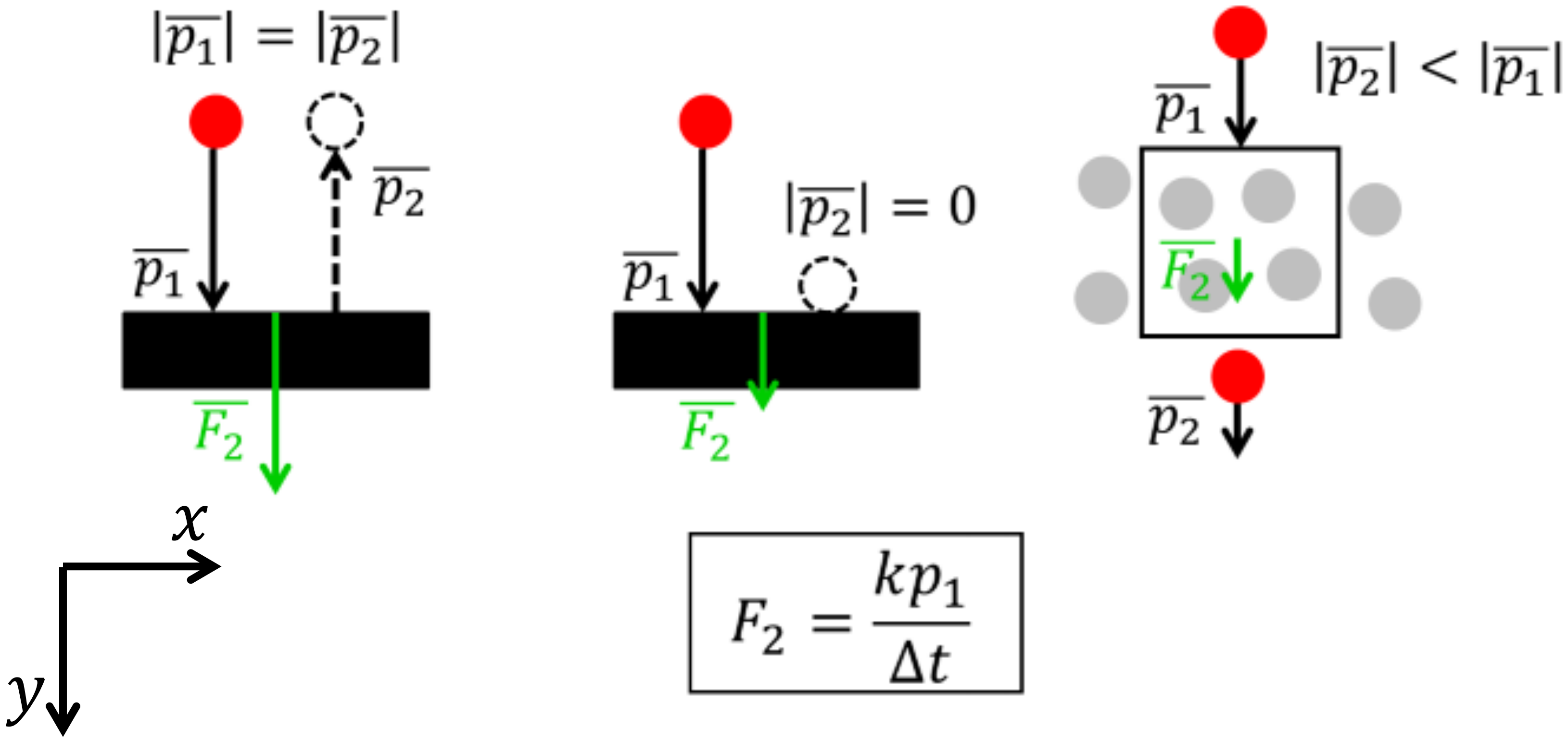
k
$=$

$$F_2 = -F_1 = \frac{2p_{1,y}}{\Delta t}$$

Momentary force exerted on the surface at time interval Δt

$\bar{p}$ = momentum [kgm/s]
m = particle mass [kg]
$\bar{u}$ = particle velocity[m/s]
$\bar{F}$ = force [N]
t = time [s]

Change in momentum at particle collision



$$F_2 = \frac{kp_1}{\Delta t}$$

What is the constant *k* in the different cases?

Acoustic radiation force at an absorbing boundary

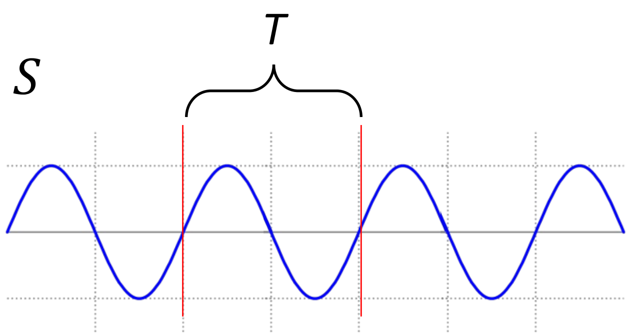
- In general terms, Langevin radiation pressure, P_{Lan}, is defined as the energy density averaged over one cycle (sinusoidal wave). For a harmonic plane wave the radiation pressure can be expressed as:

$$P_{\text{Lan}} = \langle E \rangle_T = \frac{\hat{p}^2}{2\rho_0 c^2} = \frac{I}{c} \qquad [\text{J / m}^3]$$

- By assuming P = F/A, the radiation force at a boundary can be expressed as

$$F = d_r \langle E \rangle_T \, S$$

d_r = drag coefficient



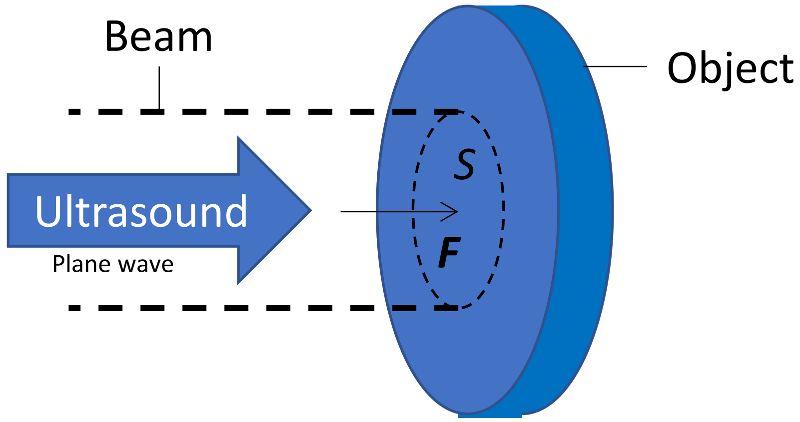
- However, one must consider whether the sound is reflecting from the interface or is absorbed.

Acoustic radiation force at an absorbing boundary (plane wave)

- Where the target is greater than the beam, the radiation force *F* for an absorbing target can be expressed as $F = \int \left(\frac{I}{c}\right) \mathrm{d}S = \frac{I}{c} S = \frac{W}{cS} S = \frac{W}{c}$, where *W* is the total acoustic power of the beam.
- All the sound energy is converted to a time-averaged force

In more general terms:

$F = d_r < E >_T S = d_r \frac{W}{c}$, where $d_r = 1$

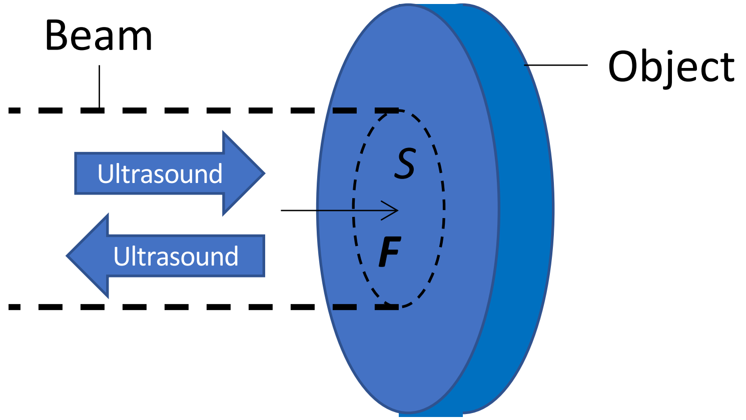


Acoustic radiation force at a reflecting boundary

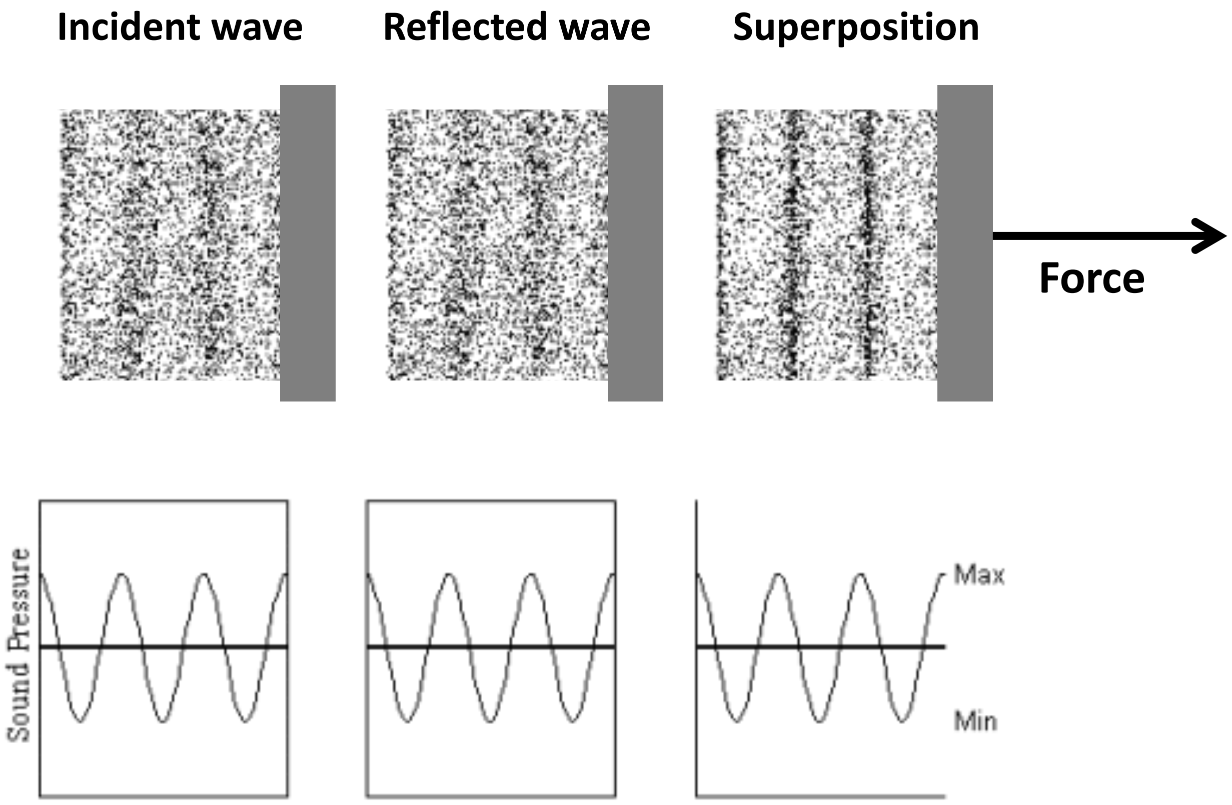
- If the interface is reflecting, one must take into account the contribution by reflection to Langevin pressure (*e.g.* at steel plate surface or water-air interface)
- By assuming P = F/A, the radiation force then can be expressed as $F = 2 < E >_T S$

In more general terms:

$$F = d_r < E >_T S = d_r \frac{W}{c}, \text{where } d_r = 2$$



Reflecting target



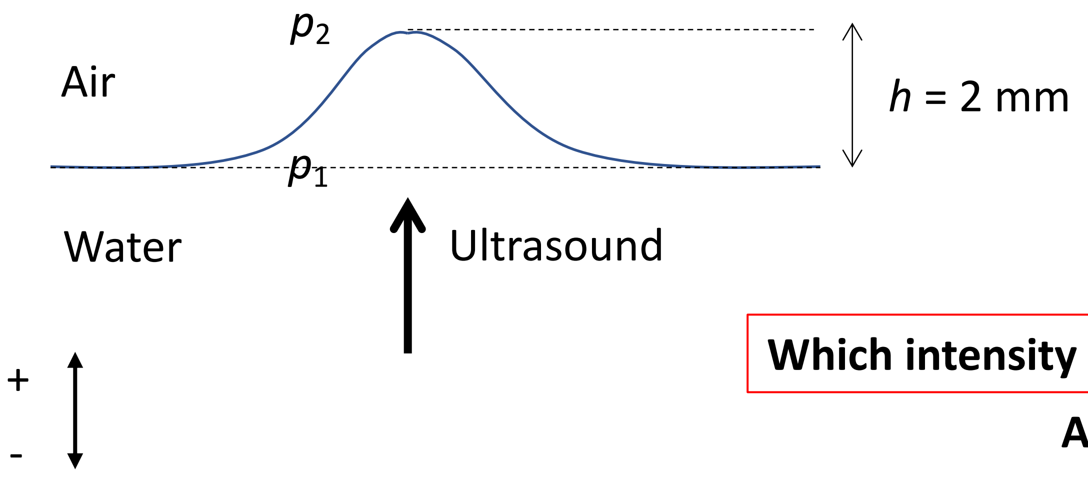
Excercise: Radiation force –generated fountain at fluid-air interface

- How would you estimate the intensity of the field with a ”acoustic fountain” height at water-air interface?

(Don’t mix this with streaming!)

Radiation force and ”suck-in force” from hydrostatic pressure balance out

$$F_{\text{radiation}} + F_{\text{hydrostat}} = 0$$



$$P_{\text{Lan}} A = \underbrace{\Delta p}_{= p_2 - p_1} A$$

$$\Rightarrow \quad 2I / c_0 = \rho_0 g h$$

$$\Rightarrow \quad I = \rho_0 g h c_0 / 2$$

Which intensity value did you just calculate?

Answer: I_{spta}

Acoustic radiation force

Ultrasound focused at water surface (VIDEO)