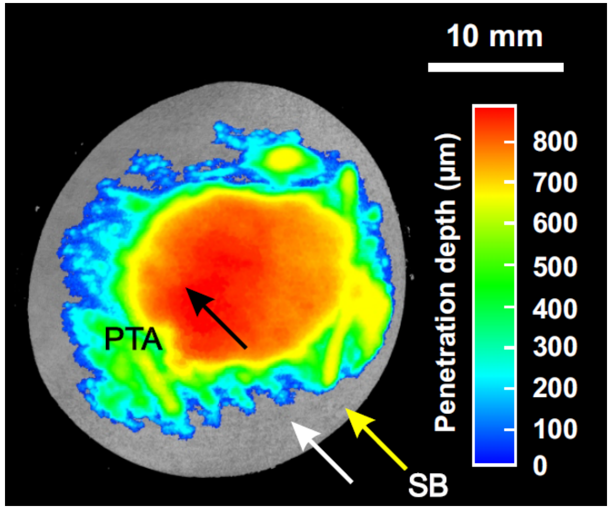
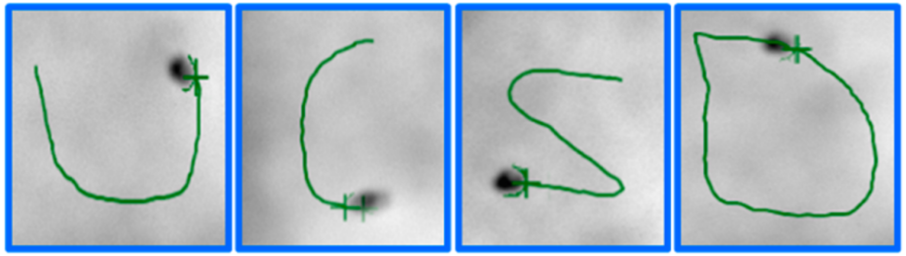
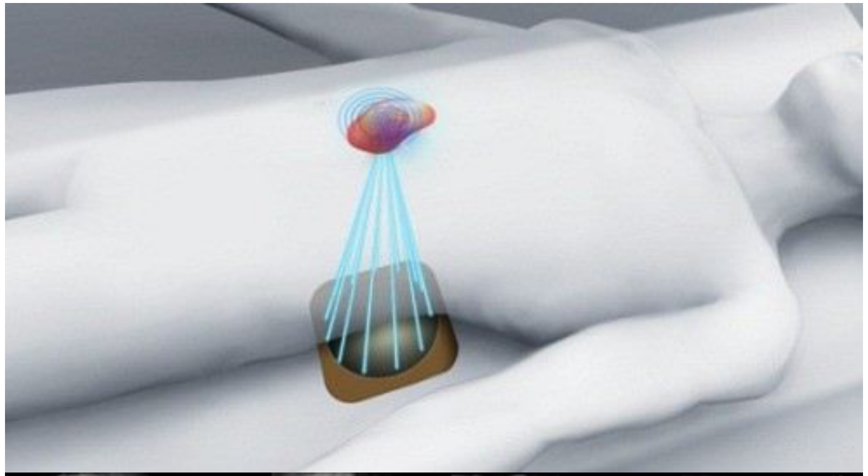
Biomedical Ultrasonics, 5 cr

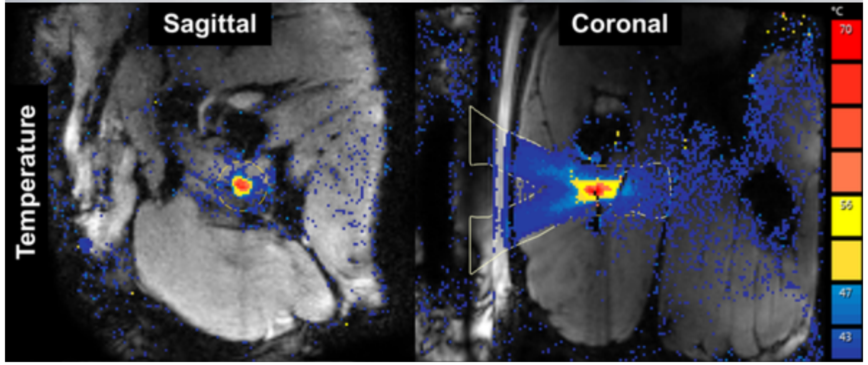
Heikki Nieminen

7.1.-31.5.2019

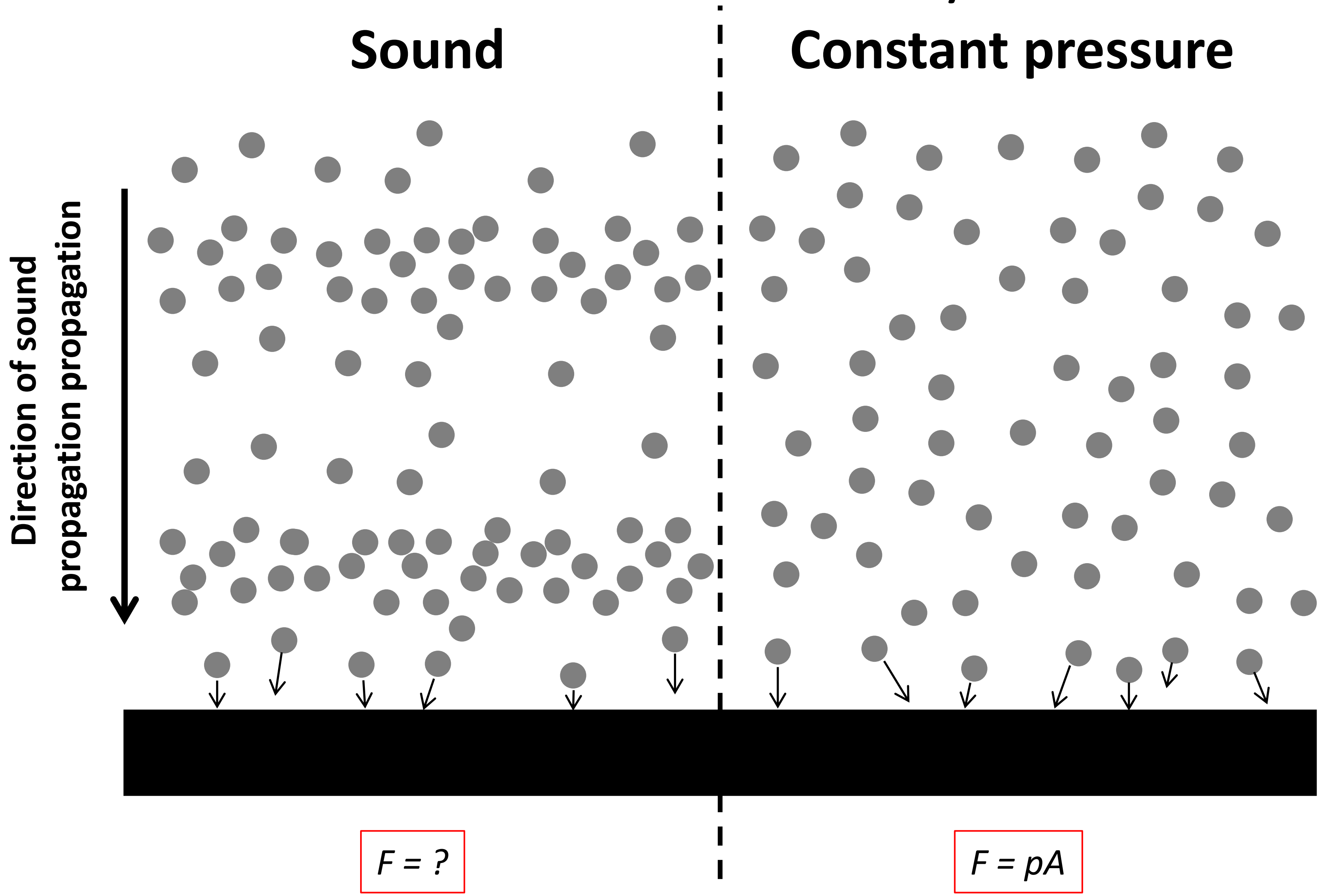








Particle motion at a boundary



General presentation of acoustic radiation force

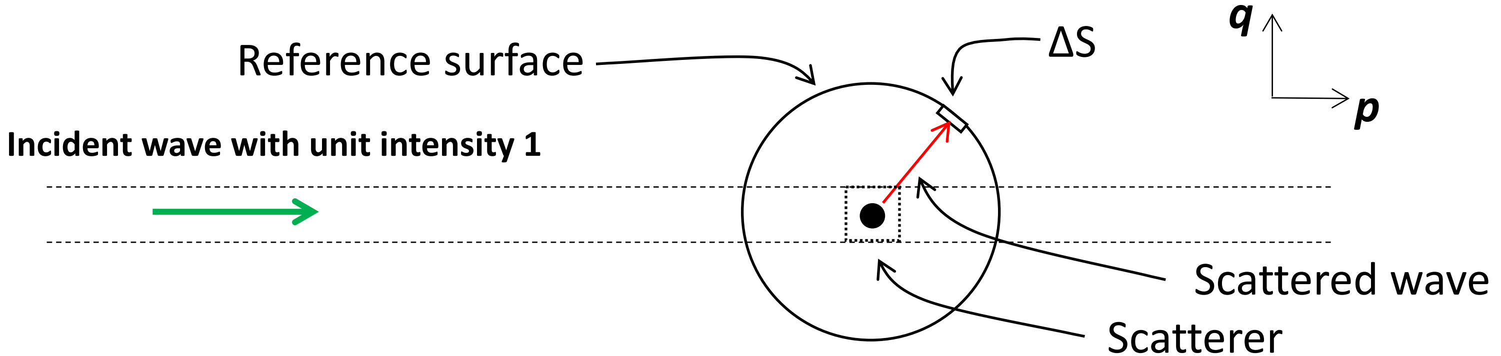
- Langevin radiation pressure, P_{Lan}, is defined as the energy density (time average over one cycle, sinusoidal wave)

$$P_{\mathrm{Lan}} = < E >_T = \hat{p}^2/2\rho_0 c^2$$

- The radiation force is a **vector quantity** and can be defined from the energy density as follows:

$$\boldsymbol{F} = \boldsymbol{d_r} < E >_T S$$

where $\boldsymbol{d}_{\mathrm{r}}$ is a *drag coefficient* vector containing two perpendicular unit vectors ***p*** and ***q*** in a 2D simplification.



Urban et al 2012. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3298414/

Drag coefficient

- In 2D the drag coefficient can be written as

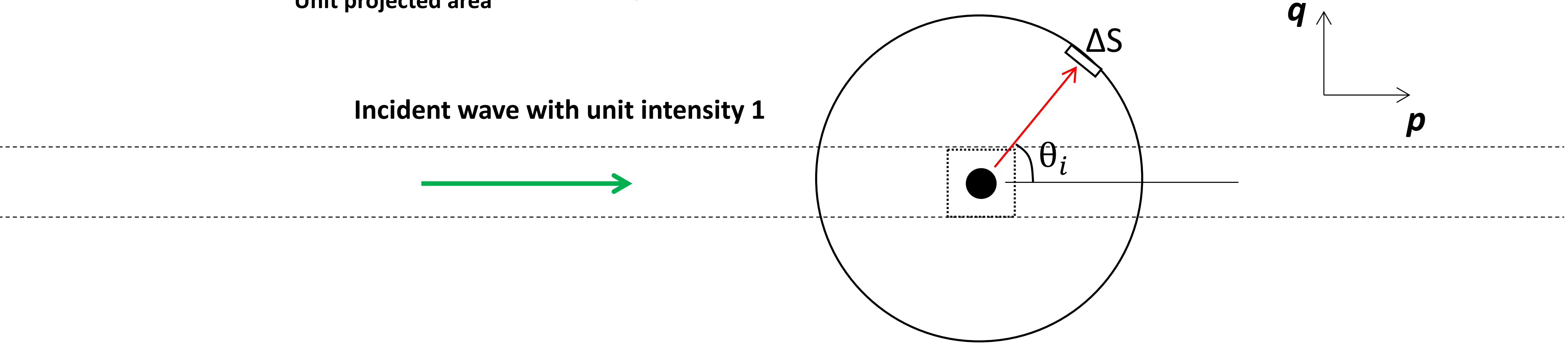
$$\boldsymbol{d_r} = \frac{\boldsymbol{p}}{S}\left(\Pi_a + \Pi_s - \Delta S \sum_i \gamma_i \cos\theta_i\right) - \frac{\boldsymbol{q}}{S}\left(\Delta S \sum_i \gamma_i \sin\theta_i\right)$$

Unit projected area

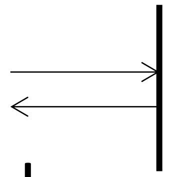
Absorbed power

Total scattered power

Scattered intensity at surface element ΔS



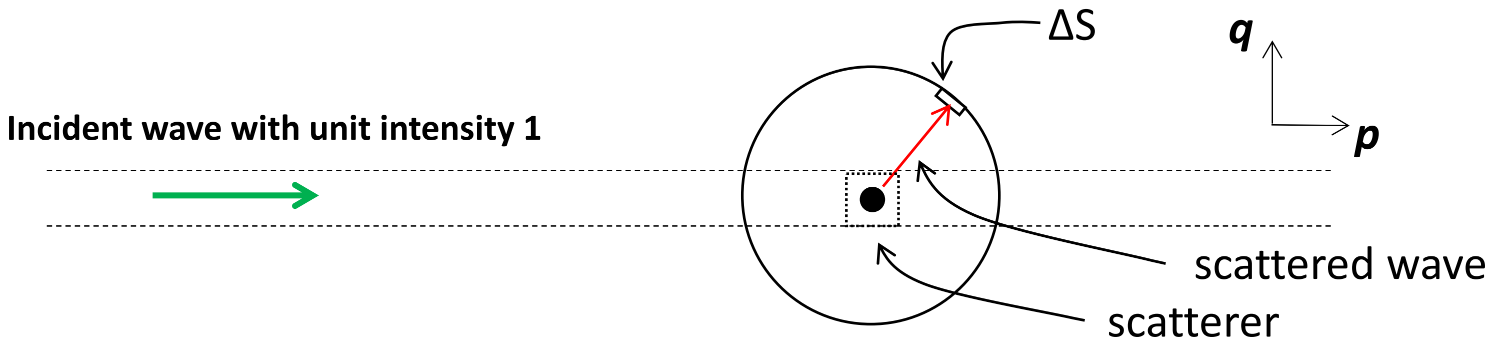
Perfect reflection, no absorption



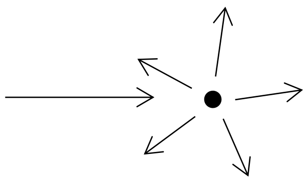
- E.g. wave meets a fluid-air interface at normal angle

$$\boldsymbol{d_r} = \frac{\boldsymbol{p}}{S}\underbrace{\left(\underbrace{\Pi_a}_{=0} + \Pi_s - \underbrace{\Delta S \sum_i \gamma_i \cos\theta_i}_{=-\Pi_s}\right)}_{=2\Pi_s} - \frac{\boldsymbol{q}}{S}\underbrace{\left(\Delta S \sum_i \gamma_i \sin\theta_i\right)}_{=0}$$

$$d_r = |\boldsymbol{d_r}| = 2\Pi_s = 2\ (\text{in p} - \text{direction}) \Rightarrow F = 2 < E >_T \mathrm{S}$$



Rayleigh scatterer



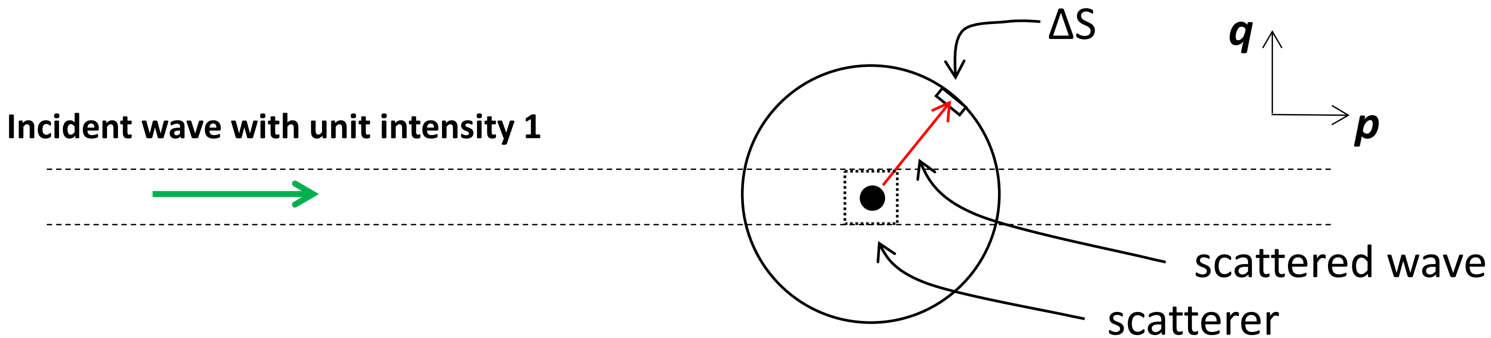
- Scatterer smaller than the wavelength:

$$\boldsymbol{d_r} = \frac{\boldsymbol{p}}{S}\left(\Pi_a + \Pi_s - \underbrace{\Delta S \sum_i \gamma_i \cos\theta_i}_{=0}\right) - \frac{\boldsymbol{q}}{S}\underbrace{\left(\Delta S \sum_i \gamma_i \sin\theta_i\right)}_{=0}$$

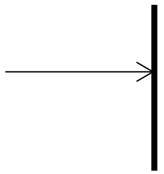
$$\boldsymbol{d_r} = \frac{\boldsymbol{p}}{S}(\Pi_a + \Pi_s) \Rightarrow$$

In tissue the scattering component is small and usually can be neglected

$$d_r = |\boldsymbol{d_r}| = \Pi_a + \Pi_s \approx \Pi_a \text{ (in p} - \text{direction)} \Rightarrow F \approx \langle E \rangle_T S$$



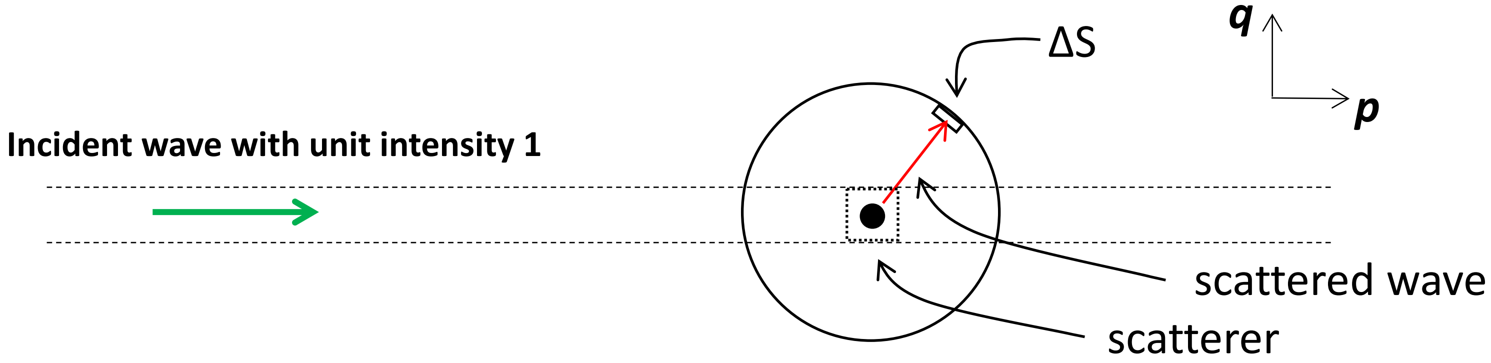
Perfect absorption, no reflection



- E.g. wave meets an oily target

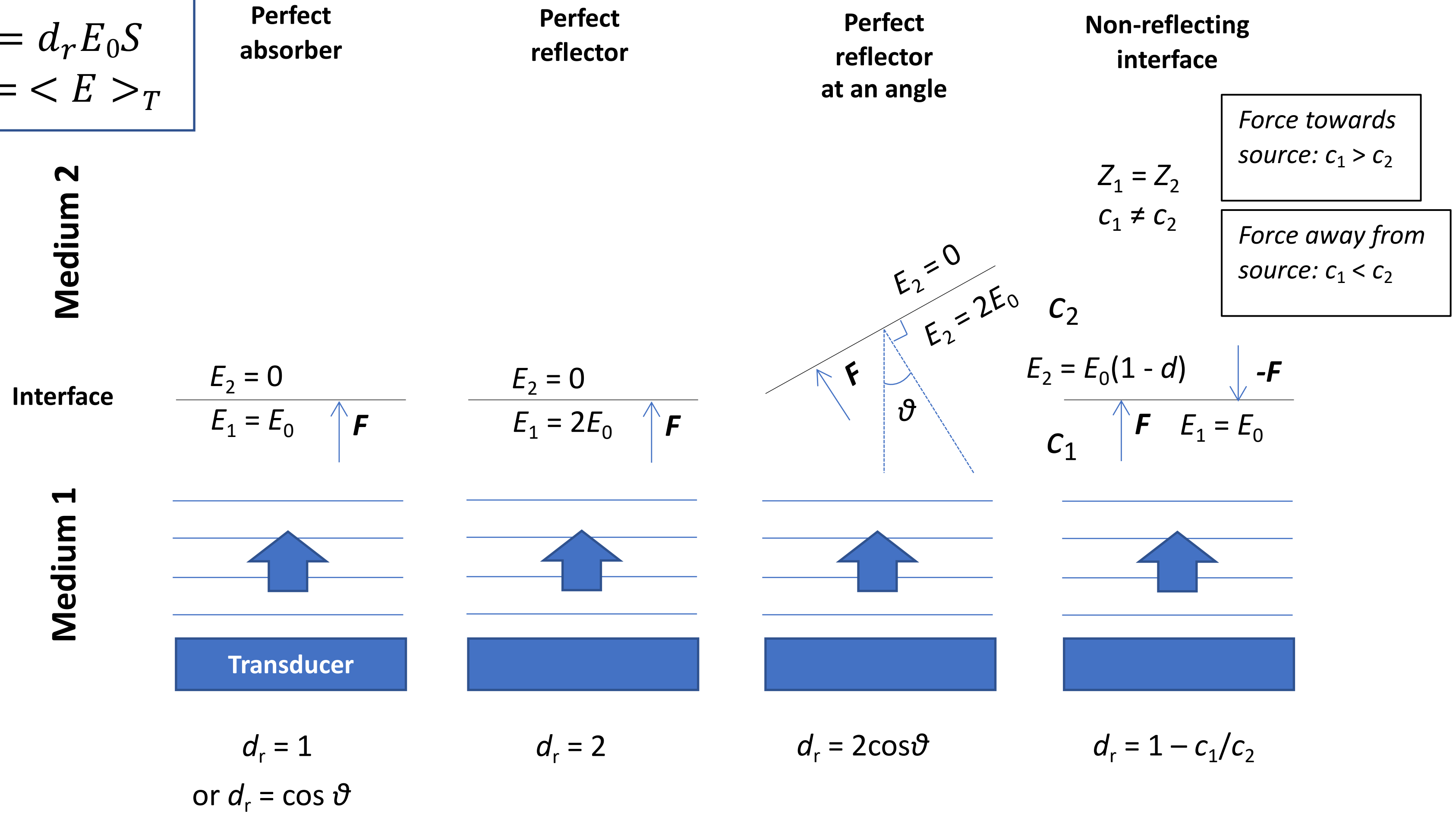
$$\boldsymbol{d_r} = \frac{\boldsymbol{p}}{S}\left(\underbrace{\Pi_a}_{=1} + \underbrace{\Pi_s}_{=0} - \underbrace{\Delta S \sum_i \overset{=0}{\gamma_i} \cos\theta_i}_{=0}\right) - \underbrace{\frac{\boldsymbol{q}}{S}\left(\Delta S \sum_i \overset{=0}{\gamma_i} \sin\theta_i\right)}_{=0}$$

$$d_r = |\boldsymbol{d_r}| = \Pi_a = 1\ (\text{in p} - \text{direction}) \Rightarrow F =< E >_T \mathrm{S}$$



Acoustic radiation force at a boundary: different cases

$$F = d_r E_0 S$$
$$E_0 = \langle E \rangle_T$$



Radiation force

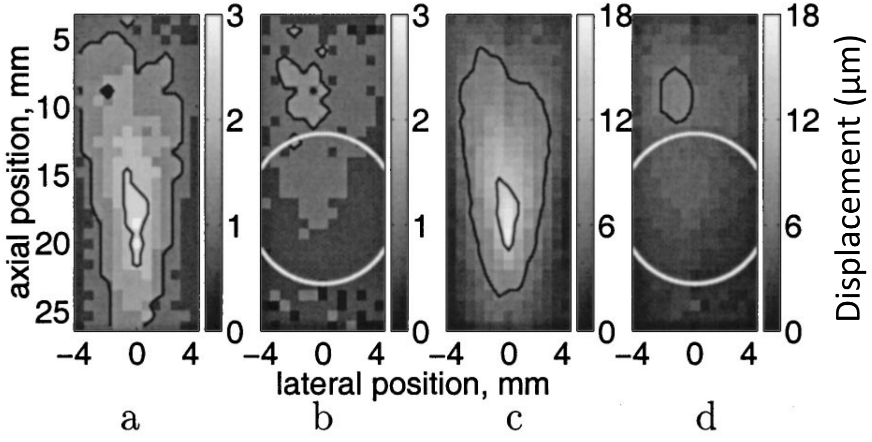
(travelling longitudinal wave)

Real-life examples

Acoustic radiation force in attenuating medium: *remote palpation*

Phantom

No lesion | Lesion | No lesion | Lesion

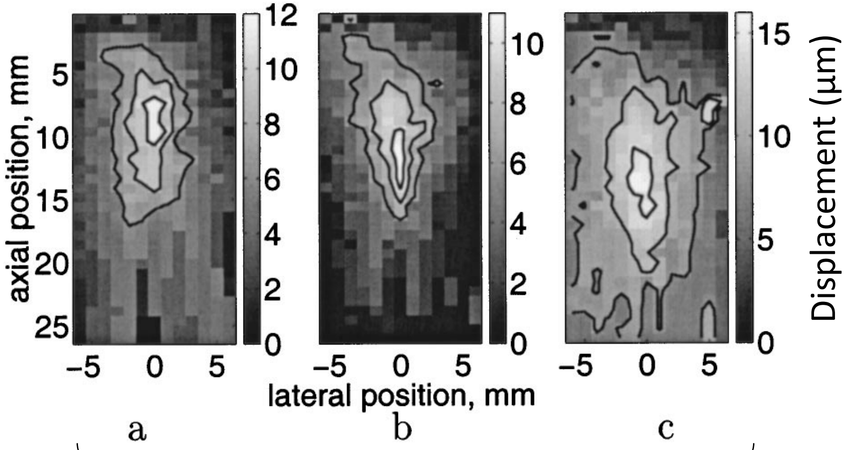


29 V across the transducer

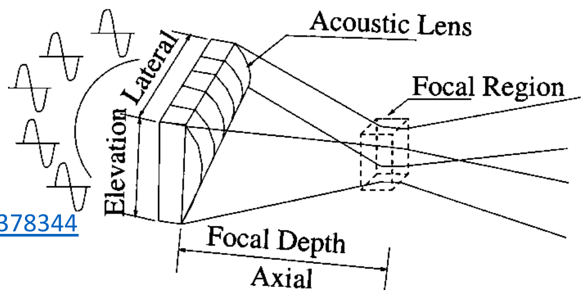
80 V across the transducer

Calf liver

10 mm | 15 mm | 20 mm



140 V across the transducer

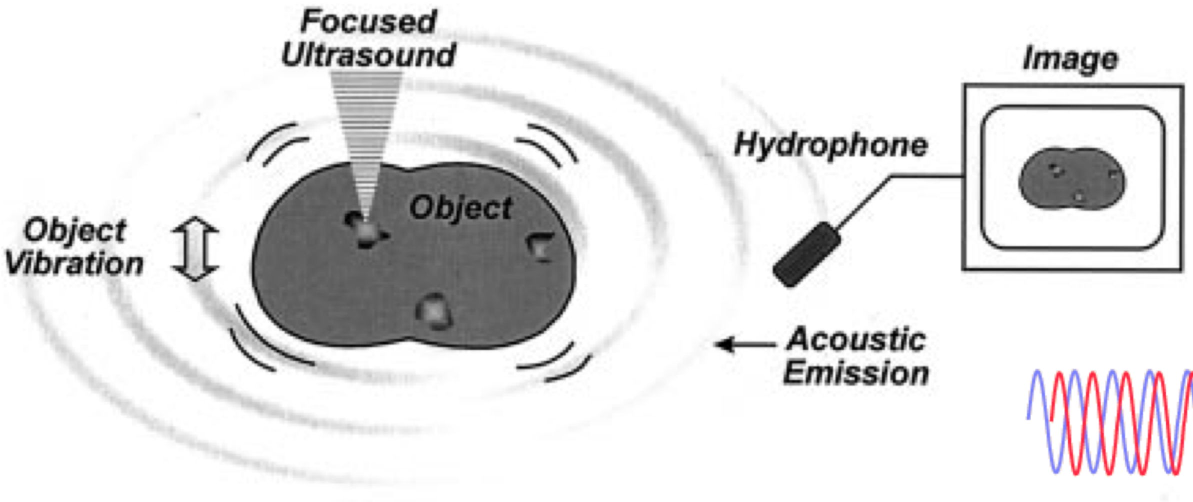


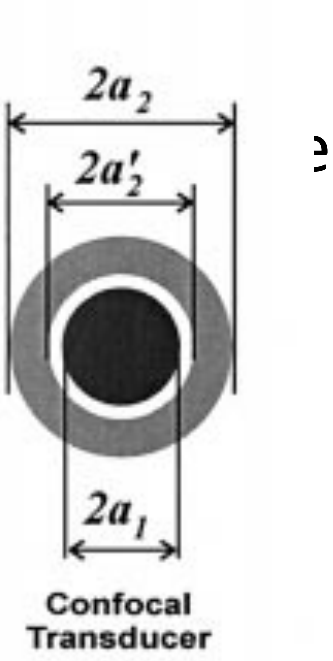
f = 7.2 MHz
I_{sptp} = 2.4 – 140 W/cm^2

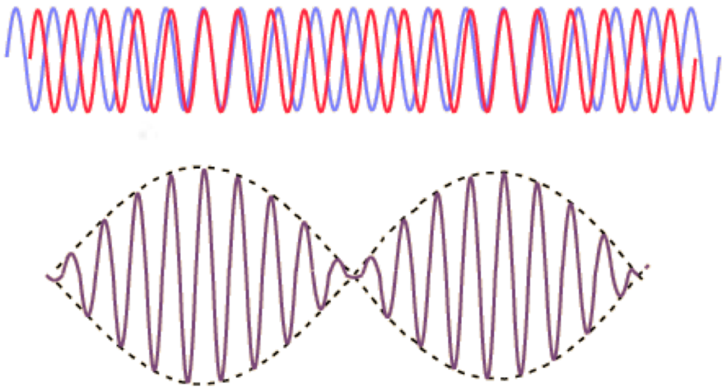
Nightingale et al 2001.
http://scitation.aip.org/content/asa/journal/jasa/110/1/10.1121/1.1378344

Ultrasound vibro-acoustography (USVA)

- Objects are made to vibrate at a low frequency by rac e

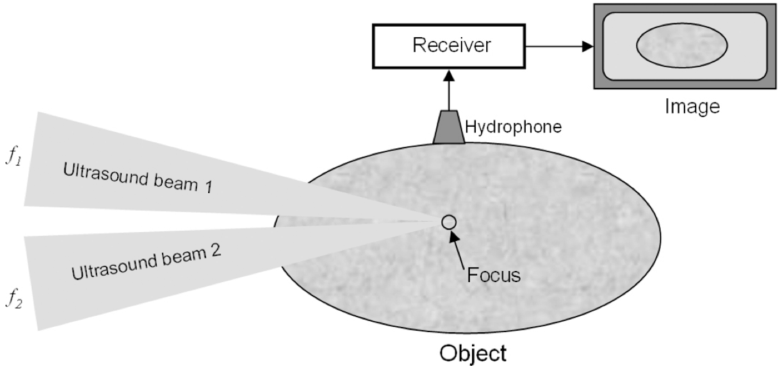






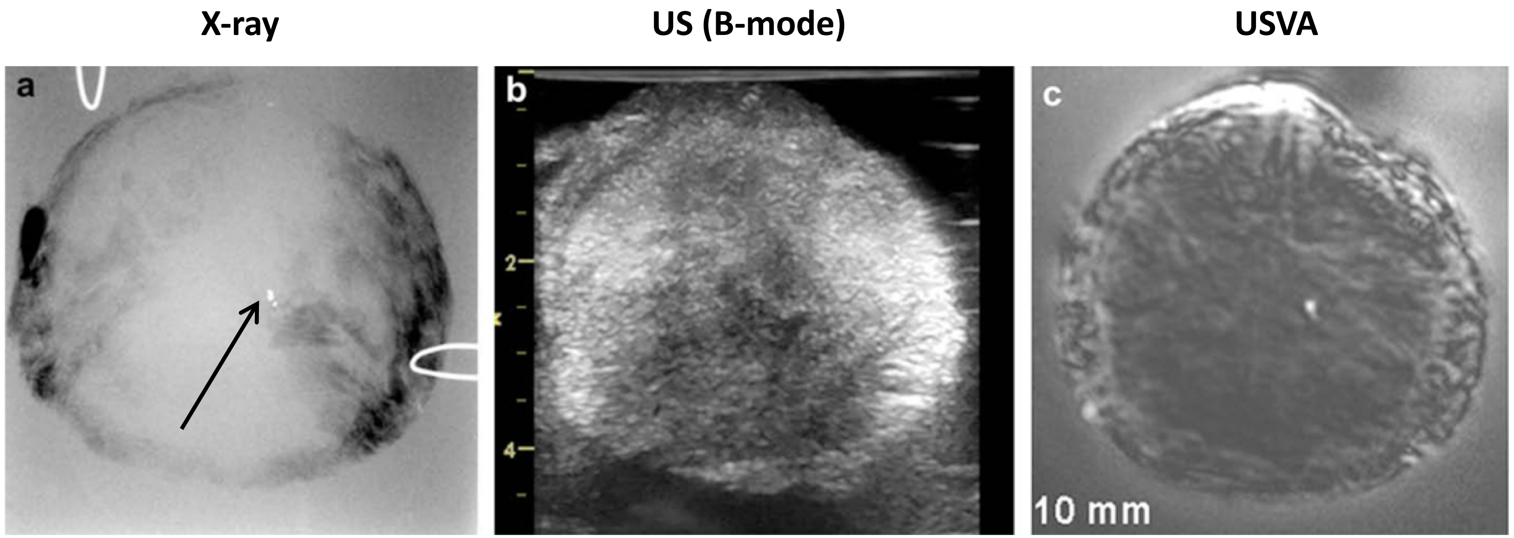
Fatemi et al. 1999: http://www.pnas.org/content/96/12/6603.full.pdf
http://hyperphysics.phy-astr.gsu.edu/hbase/sound/beat.html

Ultrasound vibro-acoustography (USVA)



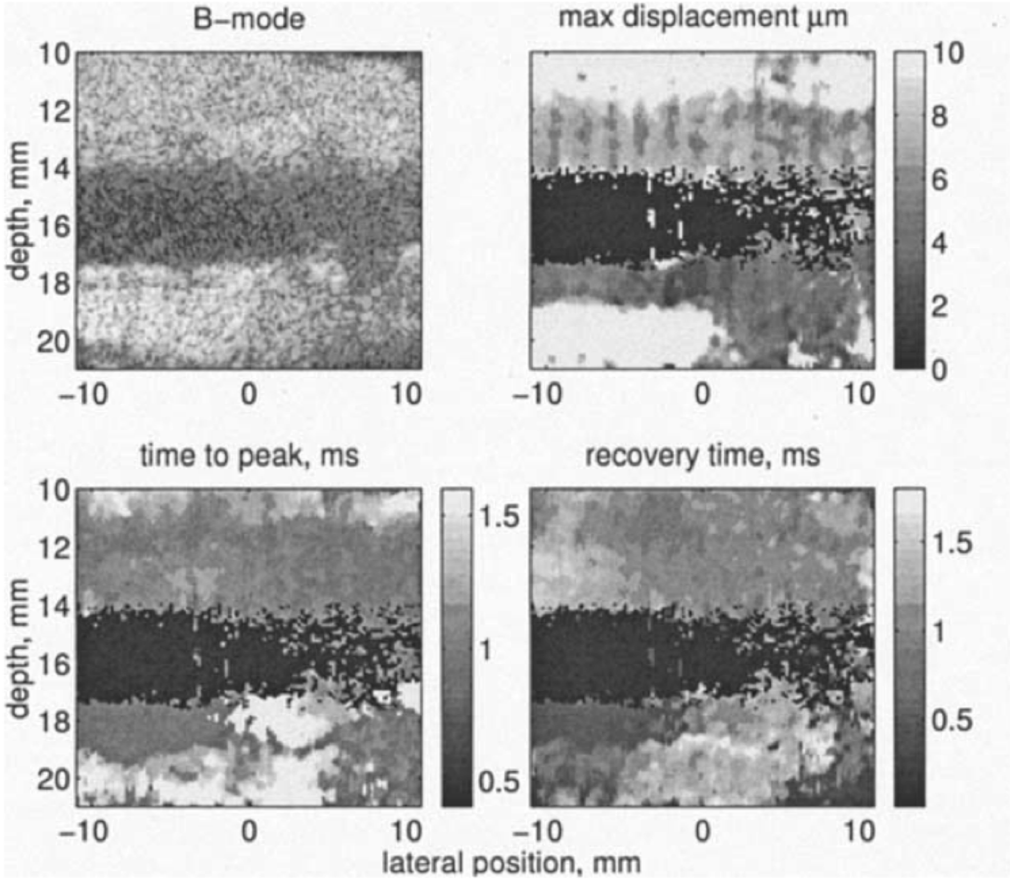
Two frequencies in MHz range
produces a beat frequency at kHz range

Human prostate with a localized miniature calcification



Urban et al. http://www.ncbi.nlm.nih.gov/pubmed/22423235

ARFI imaging (stiffening in vessel)

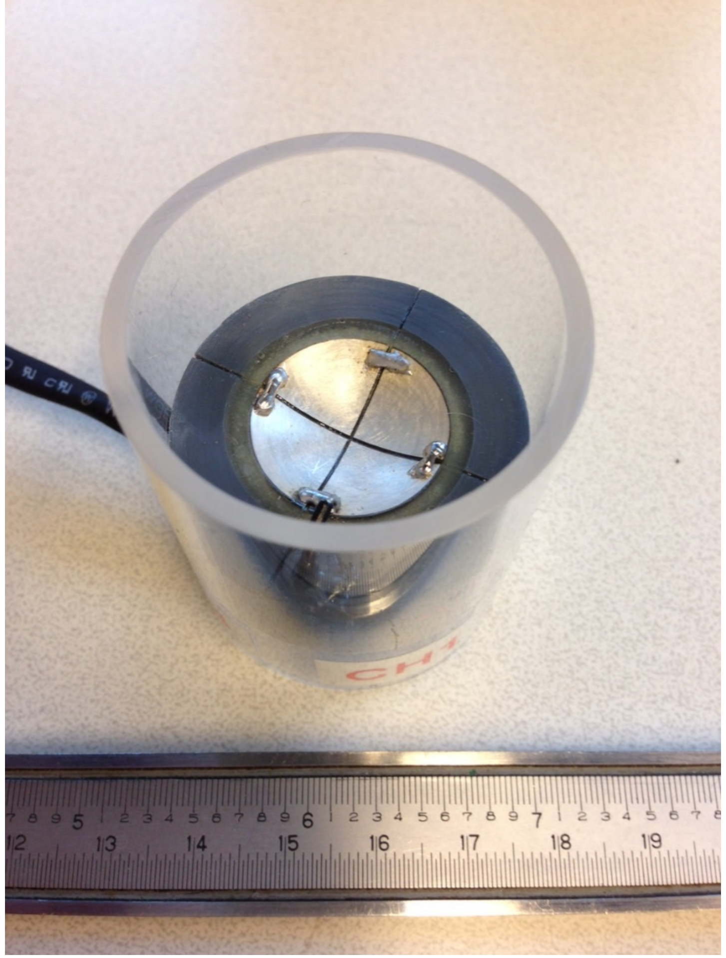


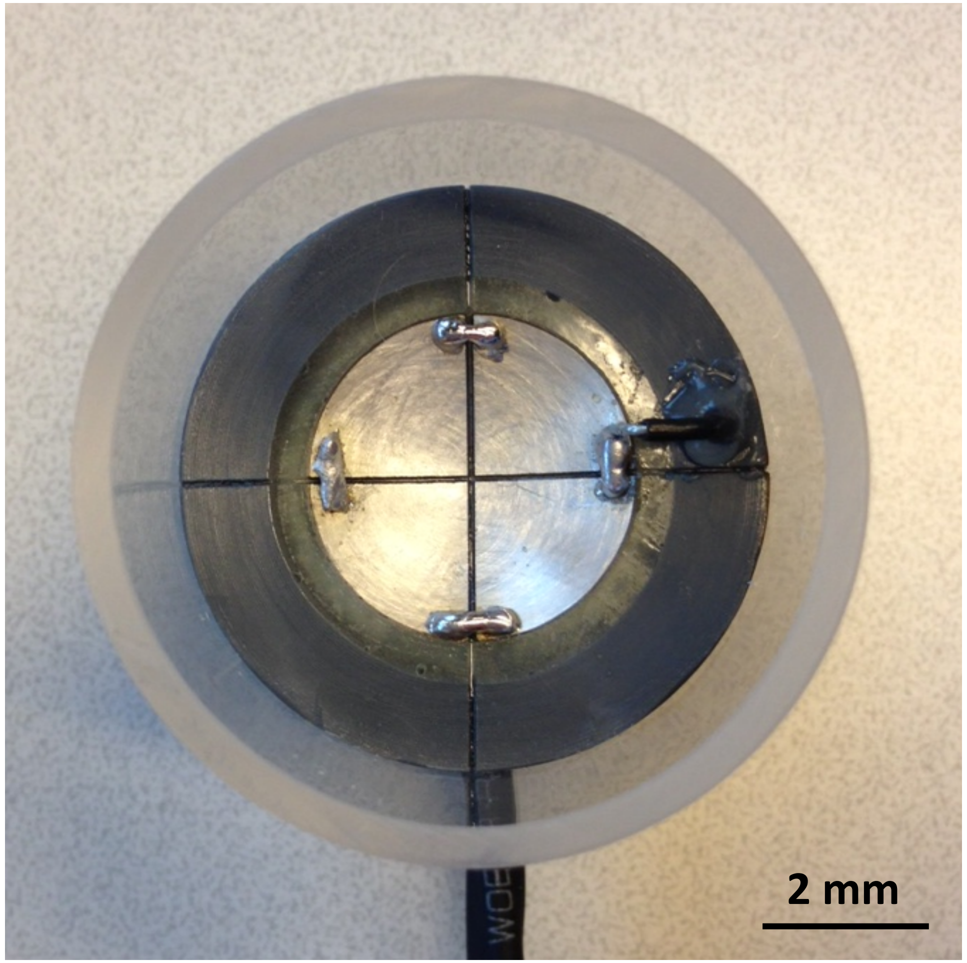
Human *ex vivo* vessel

What do you see in the images?

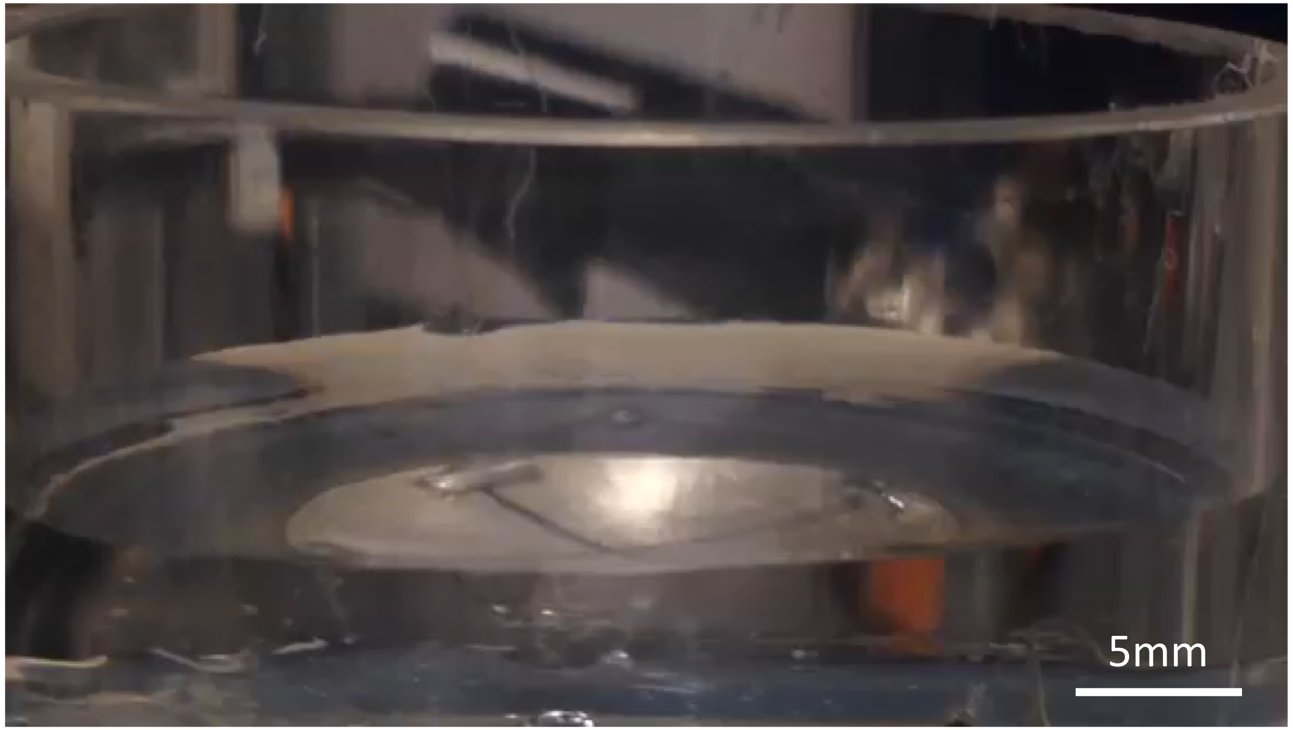
Tahey et al. http://www.sciencedirect.com/science/article/pii/S0301562904001905

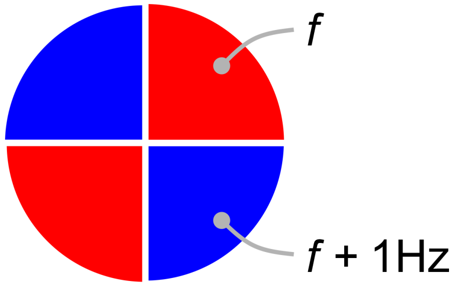
Sonic screwdriver / confocal transducer



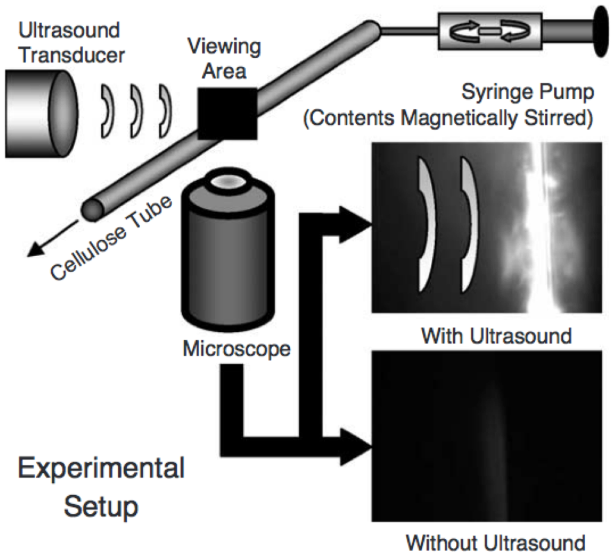


Confocal transducer in action

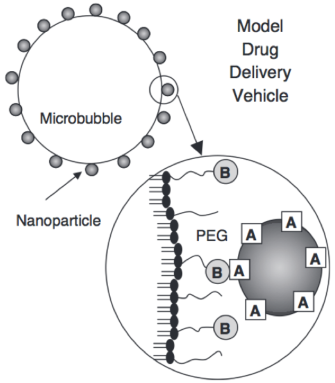




Radiation force –based drug release of nanoparticles from lipid micro-bubbles



Fluorescent Nanoparticles (20 or 400 nm) loaded on a lipid-shelle micro-bubble



Step 1: 1.3-s radiation force pulse at 3 MHz, 150 kPa PNP
Step 2: 5-cycle fragmentation pulse at 1.5 MHz and 1.1 MPa PNP

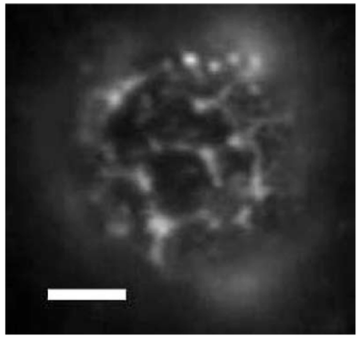
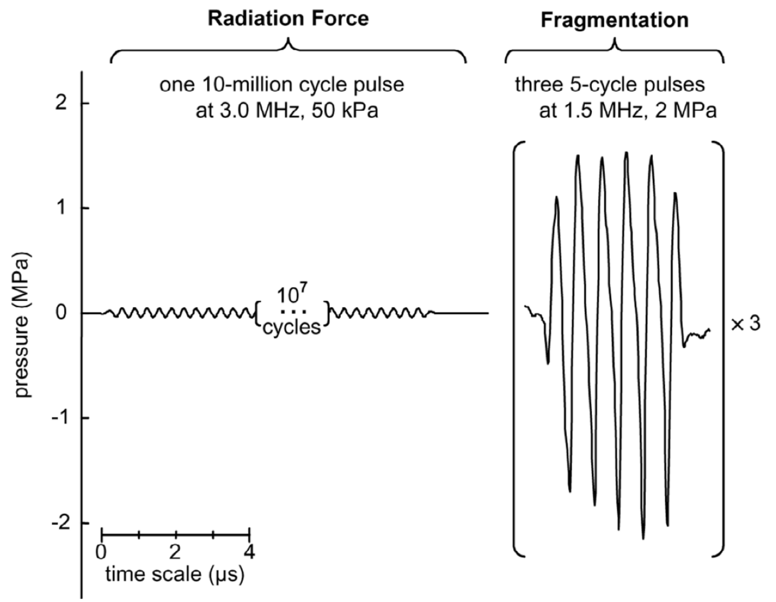
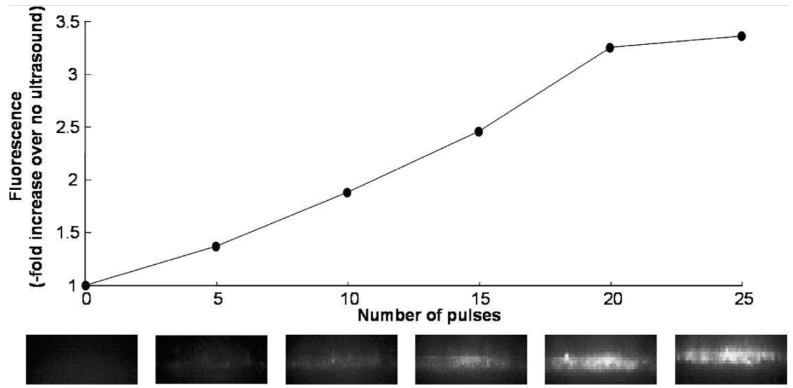


Fig. 3. Nanobead distribution on the surface of the vehicles. Vehicles were created as described in Materials and methods. A sample of the vehicle solution was observed on a 100× water immersion objective. The fluorescence within the image is yellow-green fluorescence emitted by the nanobeads bound to the microbubble surface. The scale bar corresponds to 5 μm in length.

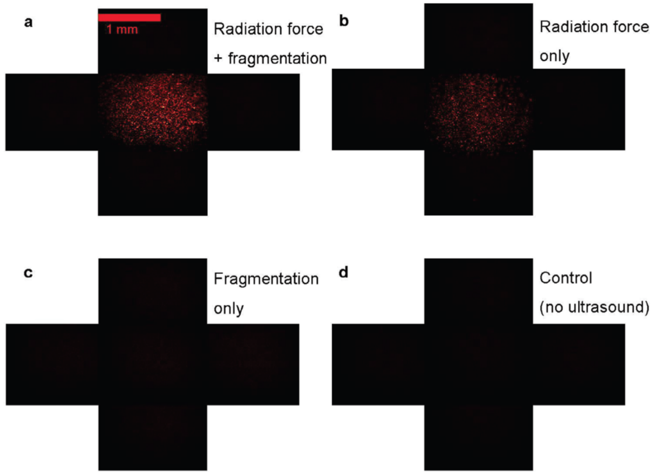
Lum et al. http://www.sciencedirect.com/science/article/pii/S0168365905006486

Radiation force –based drug release of agent from lipid micro-bubbles

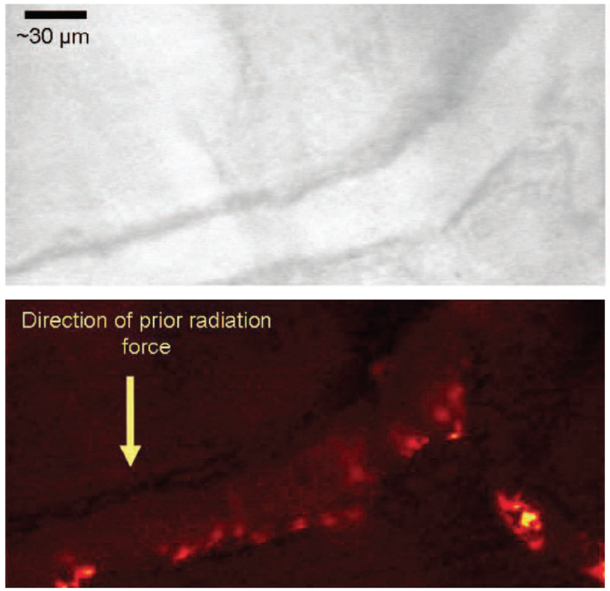




Delivery on cell plate



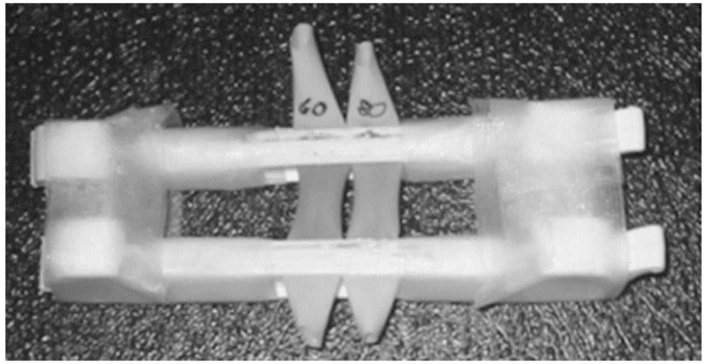
Delivery on mouse mouse vessel wall

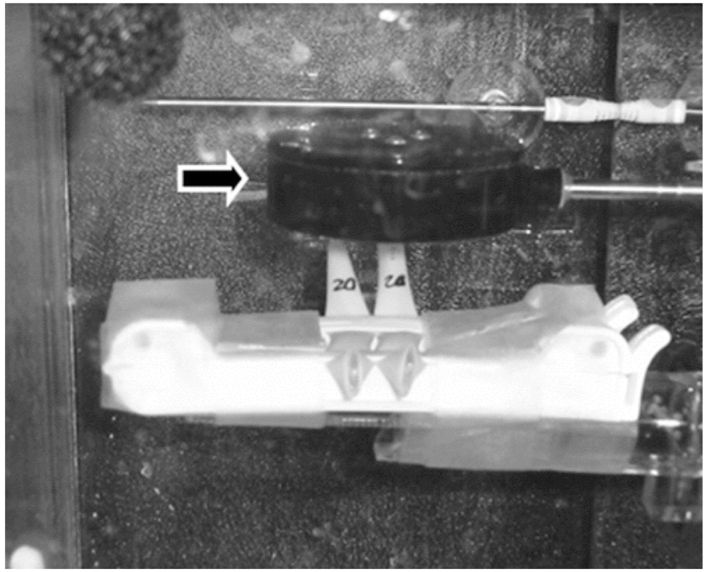


Shortencarier et al. 2004: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1320741

Radiation force –induced thrombolysis

Blood clots in latex tubes



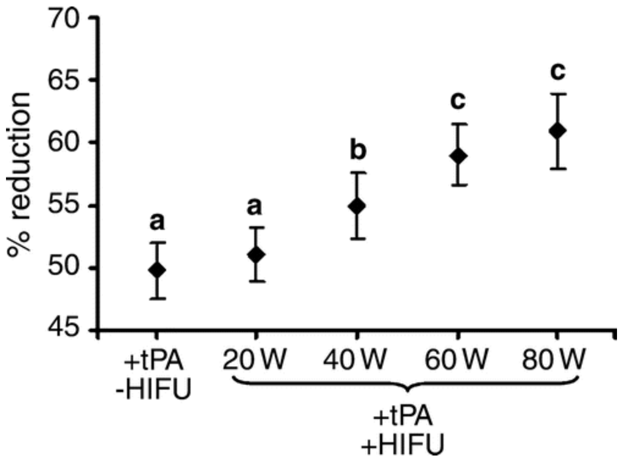


Goal: to improve tissue plasminogen activator (tPA)-mediated thrombolysis

Focus width (−3 dB) 1.38 mm, axial length (−3 dB) 7.2 mm.
100 ms bursts
1 MHz pulses
10% duty cycle (100 msec/1000 msec)
PRF 1 Hz

TAP (W)	Peak Axial Displacement (μm)
20	12.5
40	27.4
60	44.8
80	59.1

TAP = total acoustic power

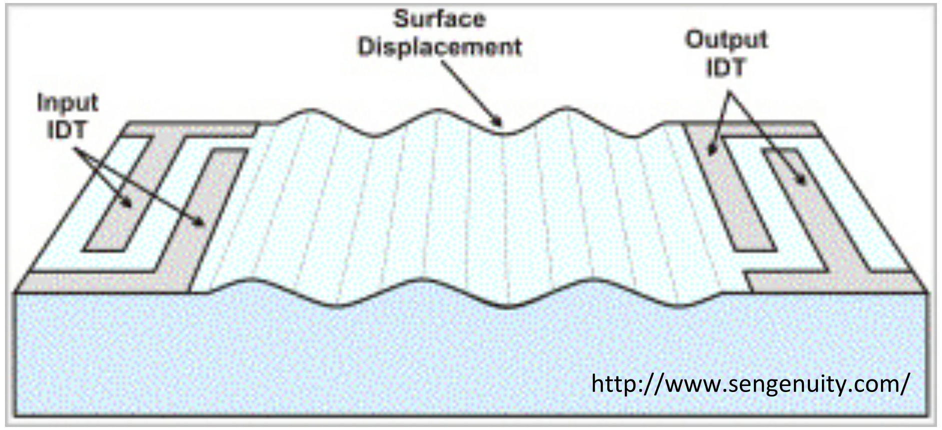


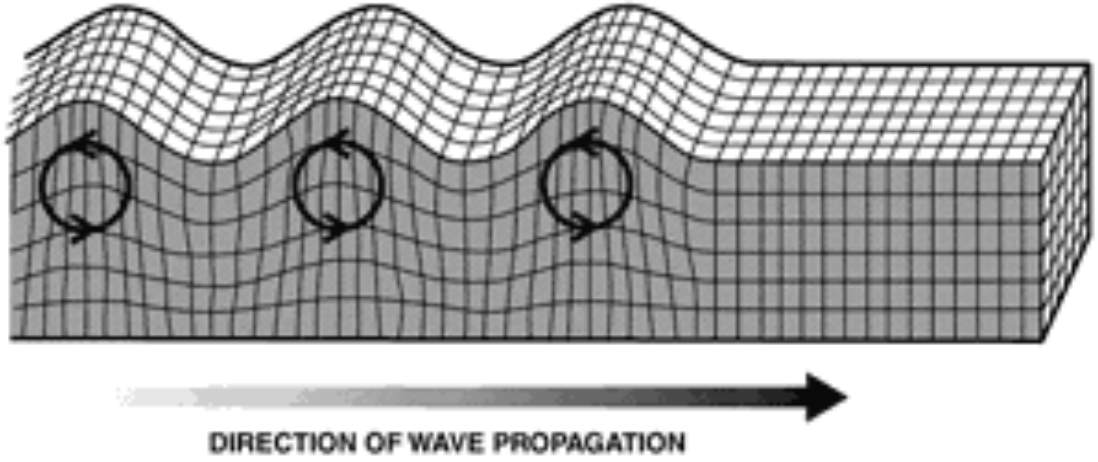
Widening of inter-cellular spacing resulting from acoustic radiation forces may enhance drug penetration

Frenkel et al: http://pubs.rsna.org/doi/full/10.1148/radiol.2391042181

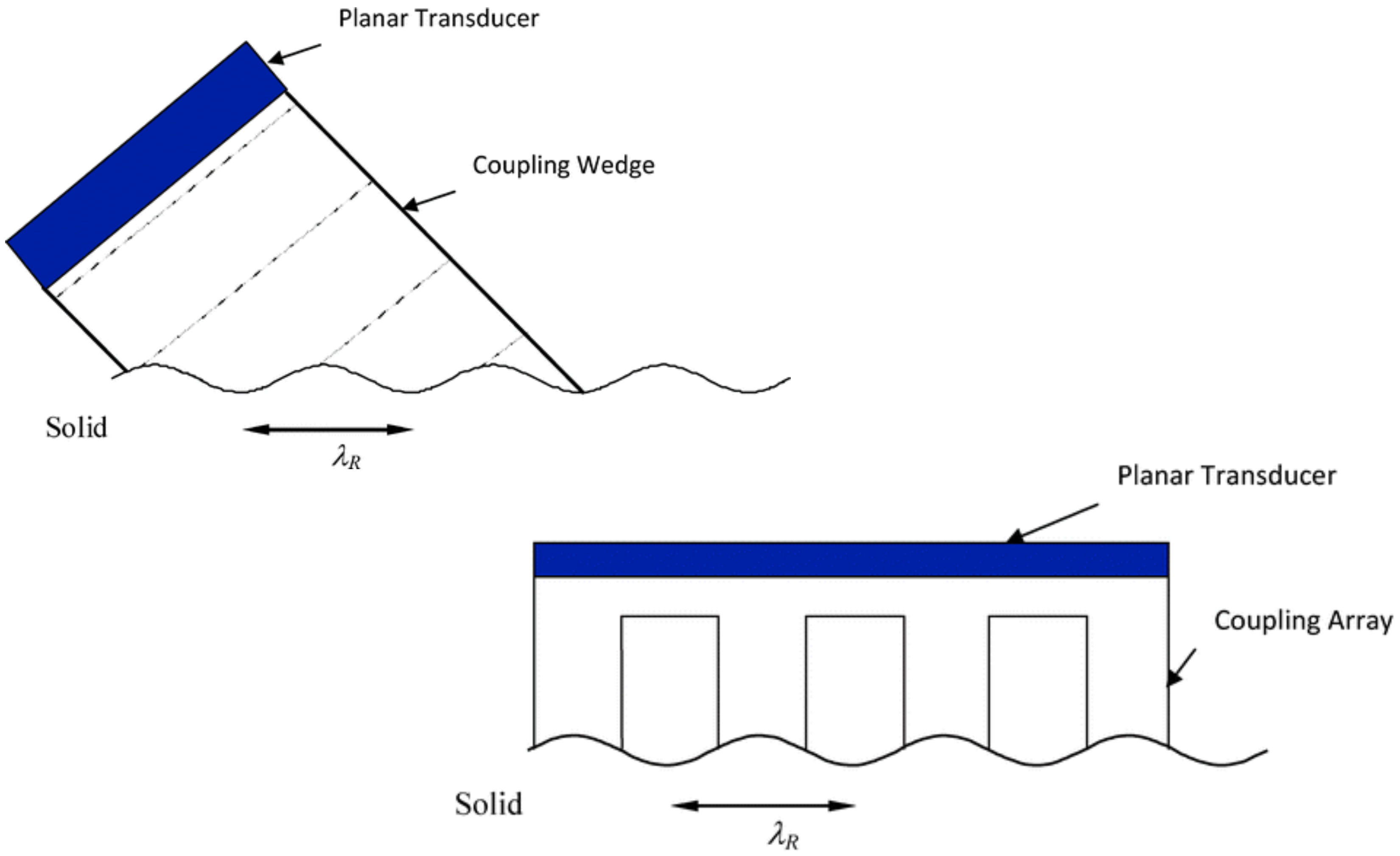
Radiation force
(travelling SAW)

Schematic of SAW transducer



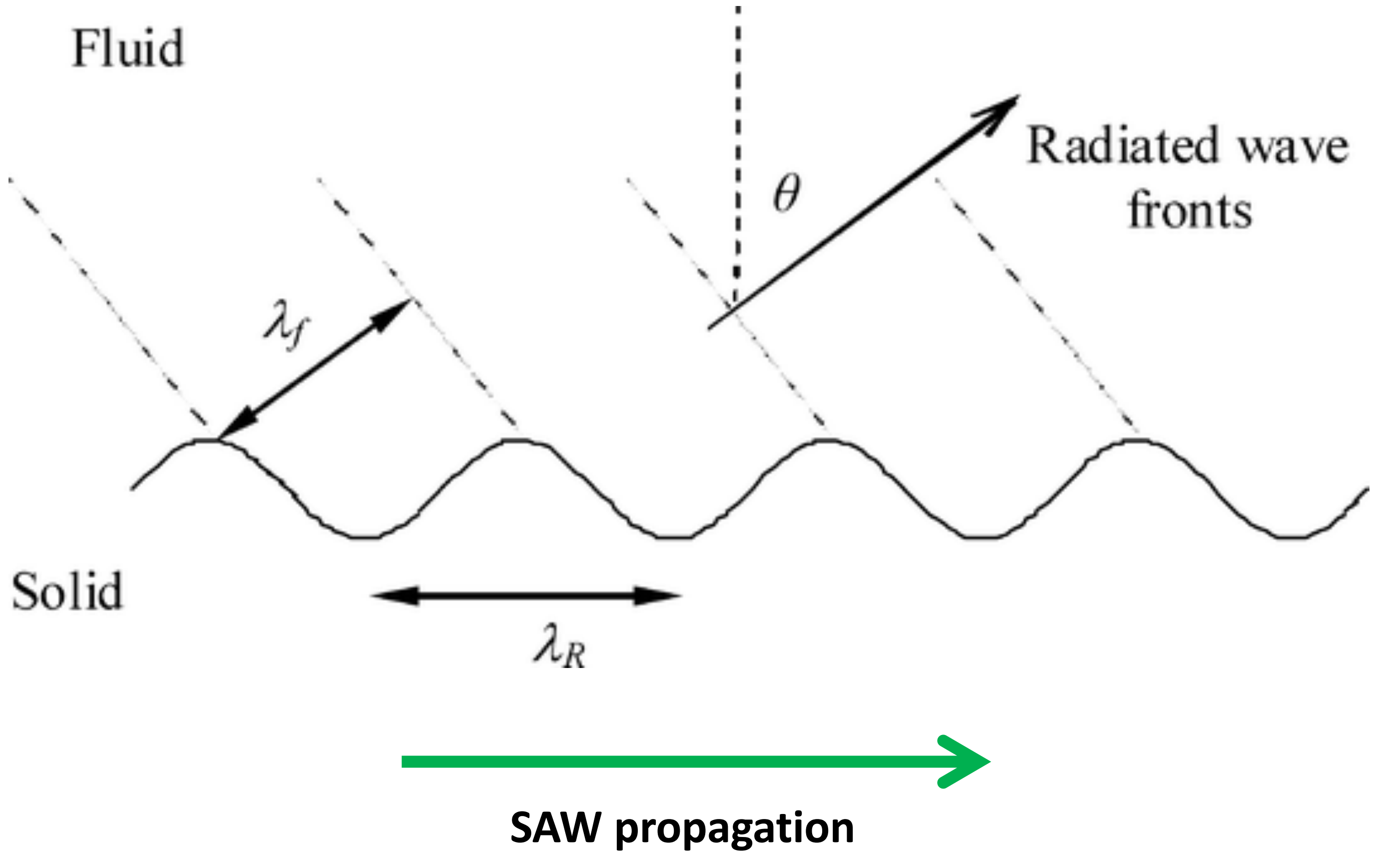


Other ways to generate SAWs



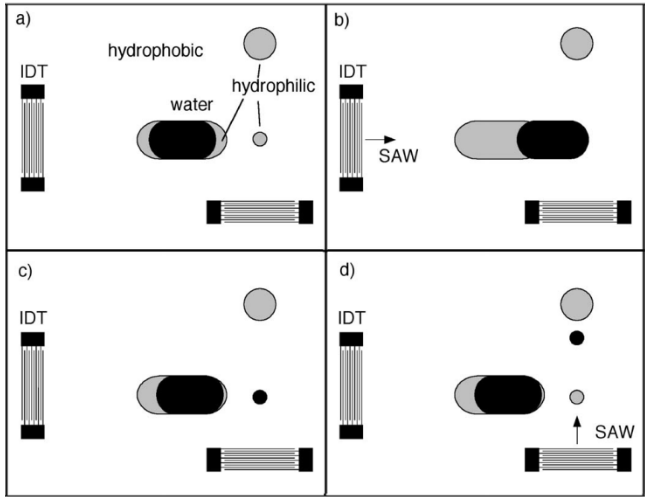
Gedge et al. 2012: http://pubs.rsc.org/en/content/articlehtml/2012/lc/c2lc40565b

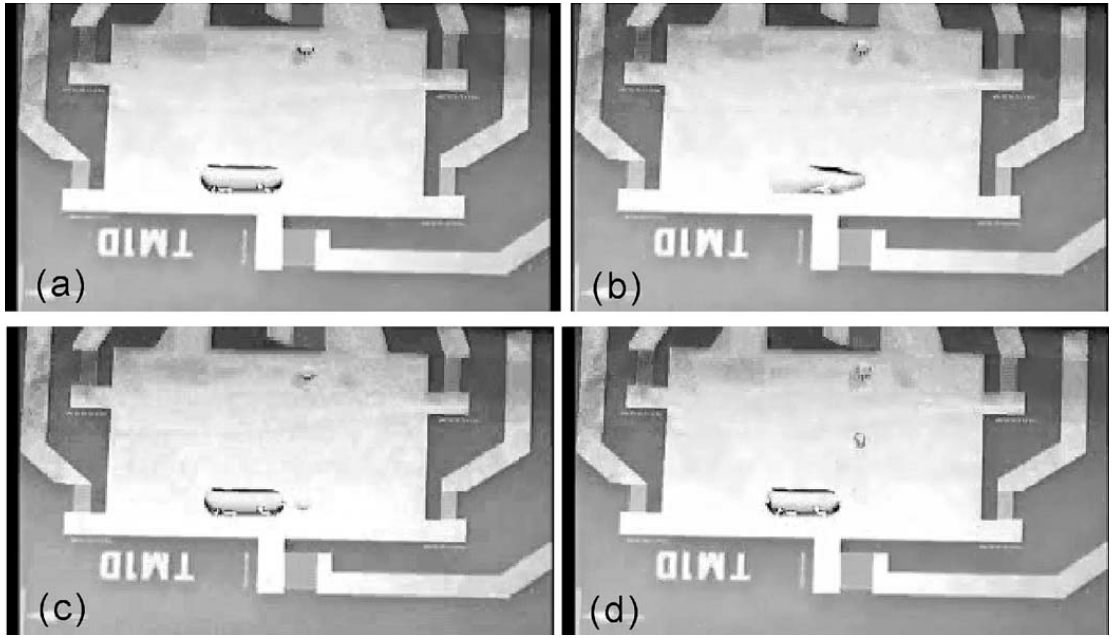
Leaky SAW



Gedge et al. 2012: http://pubs.rsc.org/en/content/articlehtml/2012/lc/c2lc40565b

Ultrasonic "pinball": SAW drive-in

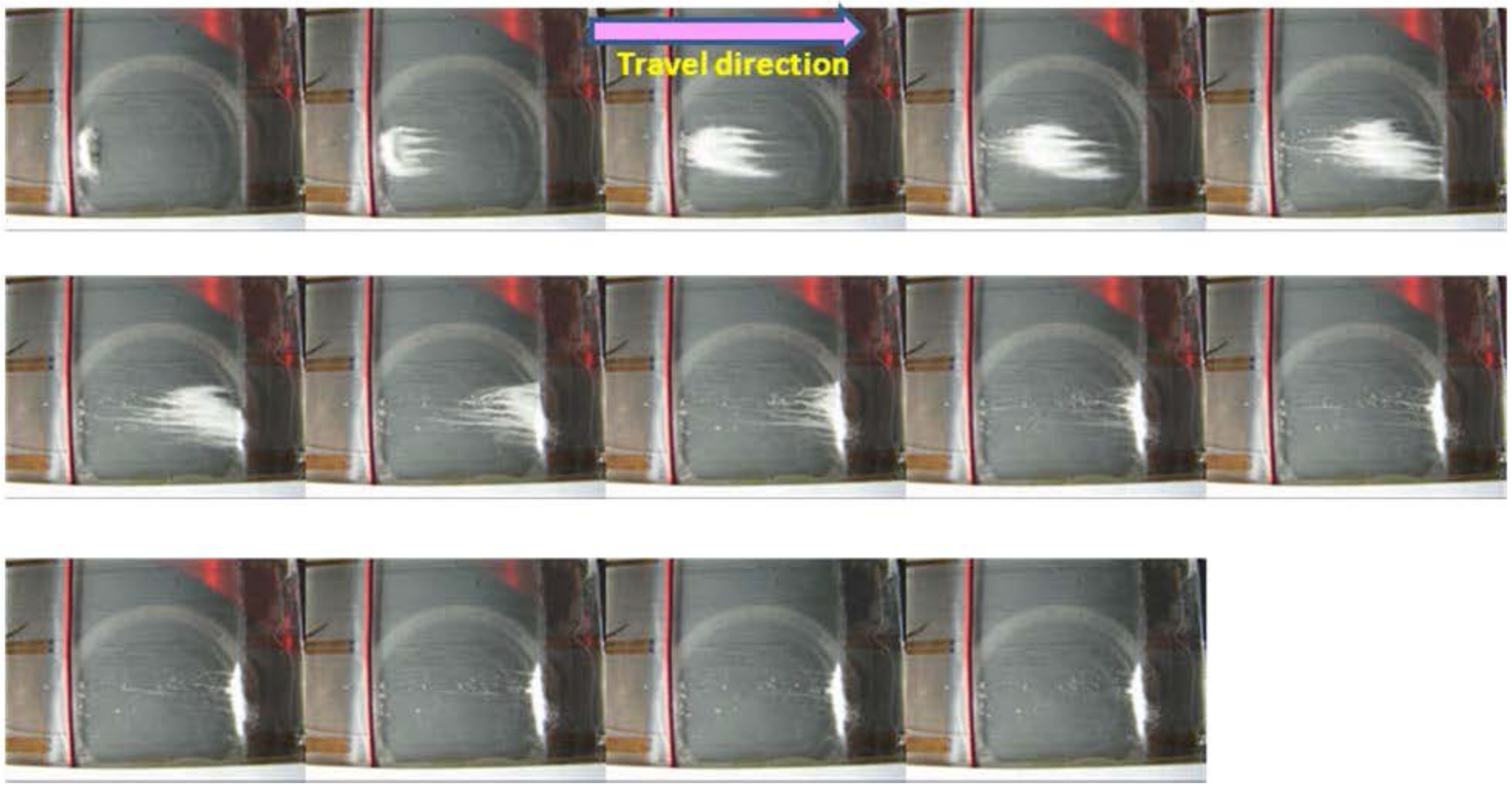




Sketch of the SAW-driven passive dispenser and time sequence of the dispensing process as explained in the text. In (a), the IDT on the left is activated to push the reservoir droplet towards the hydrophilic anchor. In (b), the hydrophilic anchor is wetted by the reservoir. In (c), switching off the SAW retracts the reservoir droplet leaving a small droplet at the anchor site. In (d), a second SAW is used to push the dispensed droplet toward a container anchor (larger gray area to the upper right).

Strobl et al. 2004 http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1367483

Powder transportation



Transportation of Al_2O_3 particles (~50µm size particles). Translation speed 60-180 mm/s (30 fps)

Bao et al. 2014: http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/44651/1/09-1466_A1b.pdf

Sand-water mixture transportation

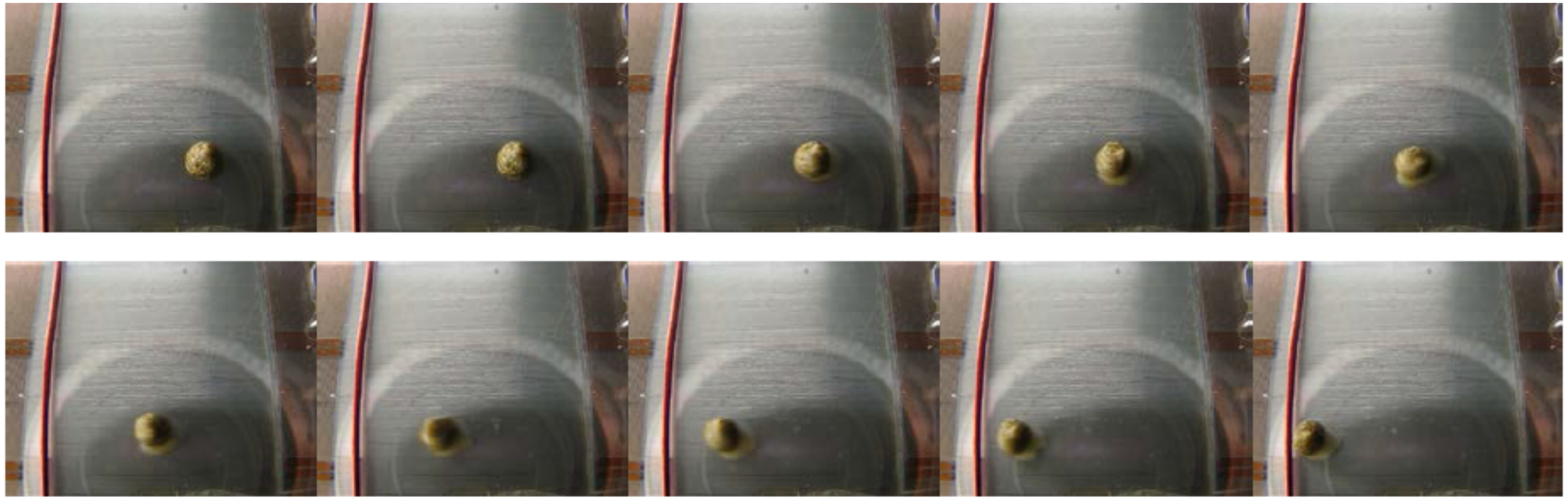


FIGURE 10: Sequence frames from the video of sand-water mixture traveling along the propagating direction of the SAW (from right to left). The frame rate is 30 f/s. The distance between the opposite IDT electrodes is 25 mm.

Bao et al. 2014: http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/44651/1/09-1466_A1b.pdf