RUHR-UNIVERSITÄT BOCHUM

Physics of Ultrasound Imaging

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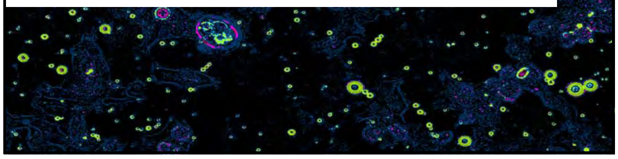
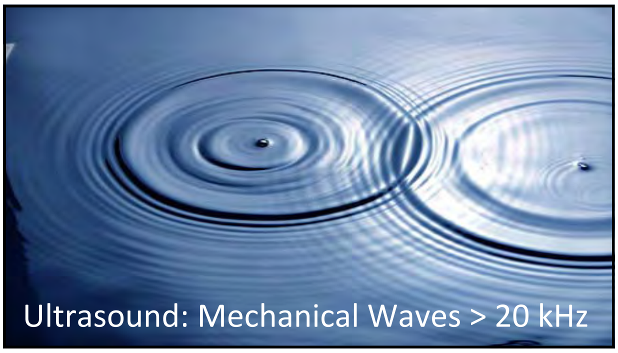


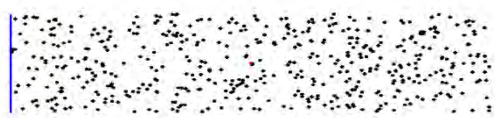
3 years curriculum

Year 1	Year 2	Year 3
HARDWARE – Ultrasonic Imaging		
Talk IIIA1: Physics of Ultrasound Imaging (30 - 45 mins)		
MAIN FOCUS: Basics of ultrasound wave propagation. Ultrasound imaging principle, resolution and penetration depth.	**MAIN FOCUS:** Flow Imaging with Doppler. Ultrasound contrast media and their sensitive detection and quantification.	**MAIN FOCUS:** Advanced beamforming for fast 2D and 3D imaging.
Topics: a) Ultrasound in fluids and tissue b) Pulse-echo imaging principle and beamforming c) Resolution, speckle noise and penetration depth d) Applications and examples	**Topics:** a) Doppler effect and spectral Doppler b) Color Doppler and Power Doppler imaging c) Physics of contrast media d) Non-linear imaging for contrast media detection and quantification e) Applications and examples	**Topics:** a) Plane wave imaging b) Synthetic aperture focusing c) Ultrasound tomography d) Applications and examples
Related Techniques: B-mode imaging	**Related Techniques:** Color Doppler, Power Doppler, Pulse Inversion, Harmonic Imaging, CPS, SPAQ	**Related Techniques:** 3D real time imaging, US tomography



Mechanical waves in fluids are longitudinal waves

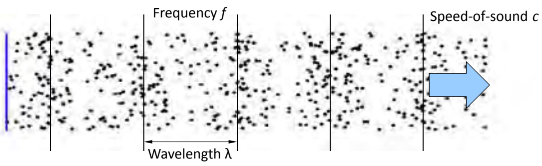
- In soft tissues at frequencies > 1 MHz only longitudinal waves are of interest
- Direction of particle motion = direction of wave propagation



Wave:	"Particle" velocity: $v = dx/dt = \dot{x}$	Pressure: p
Material:	Density ρ	Compressibility κ

Mechanical waves in fluids are longitudinal waves

$$MI = \frac{\text{maximum negative pressure in MPa}}{\sqrt{\text{Frequency in MHz}}}$$



- Pressure and frequency determine the Mechanical Index (MI) of the wave
- MI around 1.0: risk of cavitation / mechanical damage to tissue

Frequency and wavelength in water

$$\text{wavelength} \approx \text{spatial resolution}$$

$$\text{wavelength} = \frac{\text{sound speed}}{\text{frequency}} = \frac{1500\ \frac{m}{s}}{1500000\ \text{Hz}} = 1\ \text{mm}$$

	Frequency	Wavelength	
	15kHz	10cm	
	150kHz	1cm	
clinical	1.5MHz	1mm	
clinical	15MHz	0.1mm	preclinical
	150MHz	10µm	preclinical
	1.5GHz	1µm	

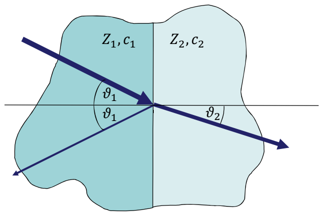
Speed of sound and acoustical impedance

- Speed of sound nearly constant in soft tissues
- Changes in acoustical impedance determine the echo strength

$$c = \frac{1}{\sqrt{\rho\kappa}} \qquad Z = \sqrt{\frac{\rho}{\kappa}} = \rho c$$

Material	Speed of Sound in m/s	Acoustical Impedance in MRayls=10^6 kg/(m²s)
Air	330	0.0004
Water (20°C)	1480	1.48
Fat	1450	1.38
Liver	1550	1.65
Muscle	1580	1.70
Bone	3500	7.80
Soft Tissue Average	1540	1.63

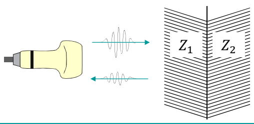
Reflection and Refraction



- **Impedance** difference determines strength of **reflection**
- Change in **speed of sound** causes **refraction** (change of wave direction)

Reflection and Scattering

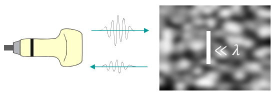
Reflection at tissue border

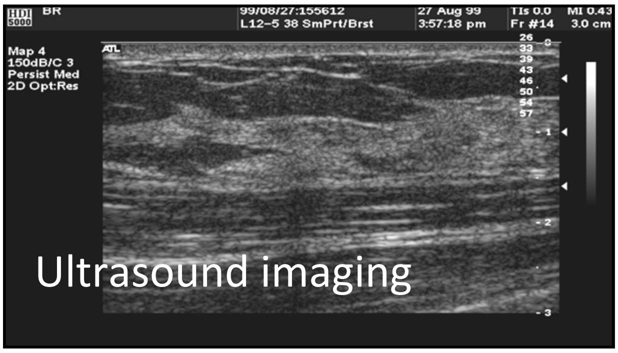


Reflection coefficient

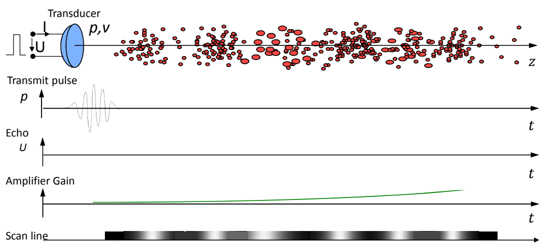
$$\Gamma = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Tissue variation at sub-wavelength scale: scattering occurs





Ultrasound imaging (2-30MHz): Pulse-Echo Principle



Standard ultrasound imaging assumes a constant speed of sound $z = c \cdot \frac{t}{2}$

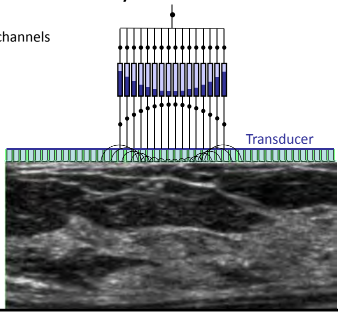
1st generation small animal imaging: Mechanical scan

- Mechanical sweep of a focused single element transducer
- Fixed focus (or sometimes annular arrays for electronic focusing)
- Non-optimal focusing, relatively slow acquisition, but also no array artifacts

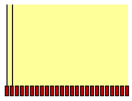
13.5 days mouse embryo imaged with Visualsonics Vevo 770
Foster FS et al., Ultrasound in Med and Biol, 28:1165-1172 (2002)

Array Beamforming: Linear Array

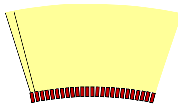
- Electronic delays on individual channels
  - 64-256 for linear arrays
  - up to 10000 for 2D arrays
- Electronic focusing for receive and transmit
- Ultrasound travels „along a line“
- Beam steering also possible (phased array)



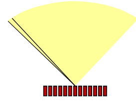
Scan geometries / array types



Linear array, linear scan



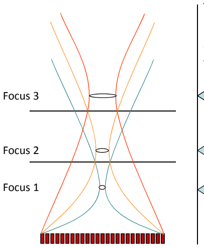
Convex array, convex scan



Phased array, sector scan

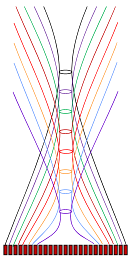
Annular array, (mechanical) sector scan

Transmit and Receive Focus



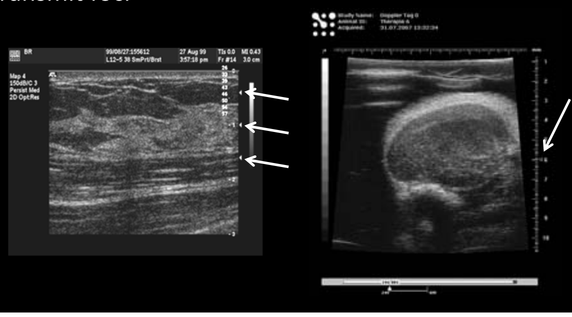
Transmit foci indicated by arrows on the screen

Transmit Focal Zones = Pulse/Echo Sequences

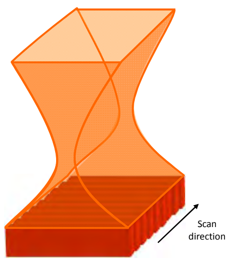


Receive: continuous adaptation, Dynamic Focus, Dynamic Aperture

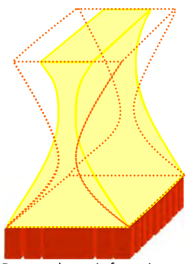
Transmit foci



Elevation Focus

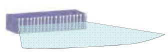


1-dimensional array: acoustic lens



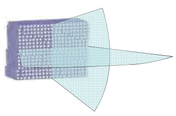
2-D array: dynamic focussing

3D imaging with 2D-arrays

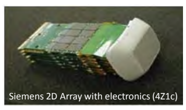


- 64-256 Elements
- Connected by coaxial cables
- Line for line imaging

GE linear transducer array



- E.g. 64 x 64 = 4096 Elements
- Multiline scanning needed (sound is too slow)
- Integrated electronics

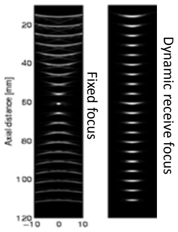


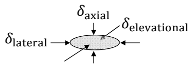
Siemens 2D Array with electronics (4Z1c)

Philips 2D Array with more than 9000 channels

Photography from companies' websites

Resolution





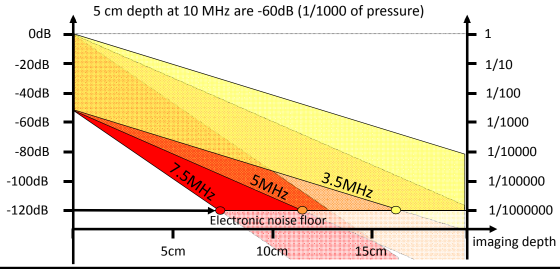
- axial: pulse length, bandwidth typically ca. wavelength
- lateral, elevational: focussing, aperture size, focal distance, wavelength
- higher frequency: better resolution
- lateral / elevational resolution not as good as axial

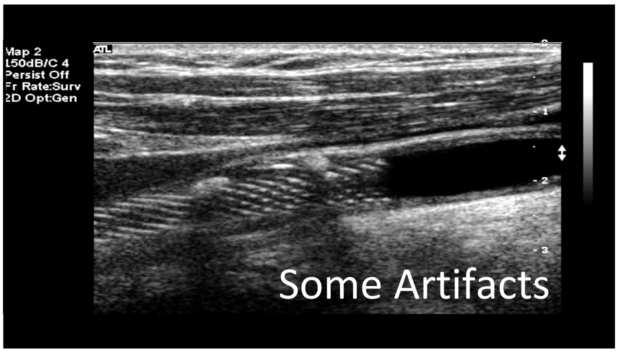
Field II calculations: J.A. Jensen

Dynamic range working against attenuation

Attenuation: Decay with $e^{-\alpha \cdot f \cdot 2z}$. Coefficient: $\alpha = 0.6 \, \frac{\text{dB}}{\text{MHz} \cdot \text{cm}}$

5 cm depth at 10 MHz are -60dB (1/1000 of pressure)





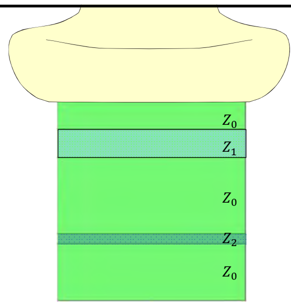
Reflection and Refraction

Ultrasound imaging assumes:

- Straight propagation paths
- Constant sound speed (c=1540 m/s =1,54 mm/µs)

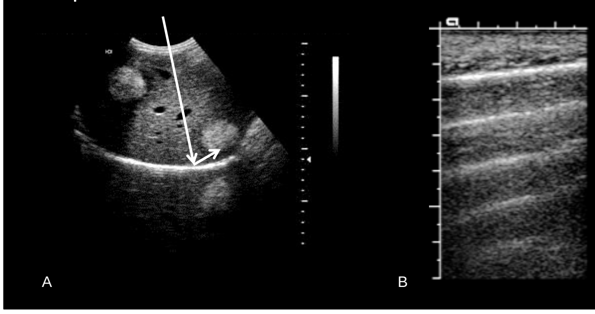
Ultrasound imaging ignores:

- Multiple reflections
- Different sound speeds
- Refraction of waves



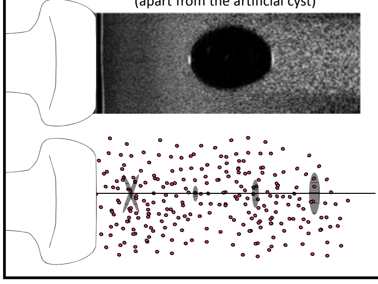
Simulation: PZFlex, www.youtube.com

Multiple reflection artifact



Speckle

Homogeneous phantom material (apart from the artificial cyst)

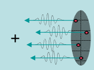


Speckle generation

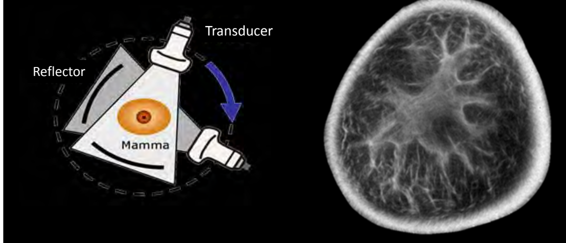
Echoes from one resolution cell add up in the transducer

- destructively (dark)
- constructively (bright)

A random pattern depending on the resolution cell shape and size appears



Reproducible 3D imaging for breast cancer diagnosis



Images by Prof. H. Ermert, Dr. C. Hansen

Array artifacts: grating lobes

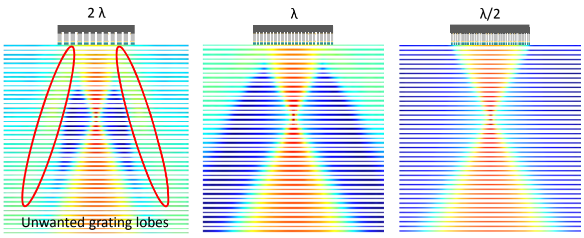
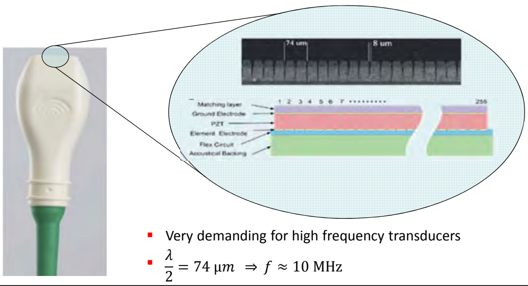


Image information from out-of-focus areas is overlayed: low contrast of e.g. cysts

Element spacing and grating lobes



- Very demanding for high frequency transducers
- $\frac{\lambda}{2} = 74\ \mu m \Rightarrow f \approx 10\ \text{MHz}$

Graphics: www.visualsonics.com, Foster et al., Ultrasound in Medicine & Biology, 35(10), pp. 1700-1709, 2009

Topics covered today:

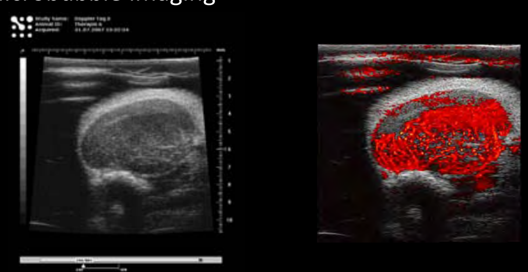
- Ultrasound in fluids and tissue
- Pulse-echo imaging principle and beamforming
- Resolution, speckle noise and penetration depth
- Applications and Examples

Goals:

- Know basic imaging principle and some artifacts
- Better understand system performance / settings

Questions: „Meet the experts" 15:15, in this room

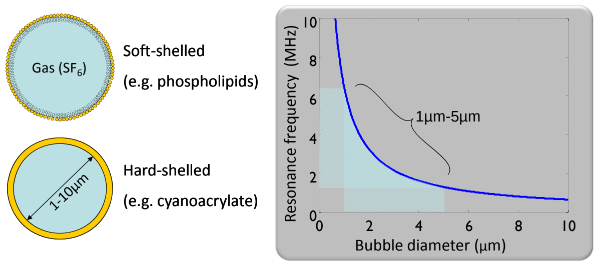
Microbubble imaging



A431 xenograft tumor implanted in CD1 nude mice, cooperation with Fabian Kießling, RWTH Aachen

Microbubble tracking and resulting traces

Why can we see single microbubbles?



They can be detected, but they cannot be resolved

… to be continued next year

Single microbubble detection and tracking in a tumor

Selected books and book chapters on the physical basics of medical ultrasound

[1] Angelsen, Bjørn A. J.: Ultrasound Imaging Vol. I. Emantec AS, Trondheim, 2001.

[2] Angelsen, Bjørn A. S.: Ultrasound Imaging Vol. II. Emantec AS, Trondheim, 2000.

[3] Hill, Christopher Rowland / (Hrsg.): Physical Prinpiples of Medical Ultrasonics. Ellis Horward Ltd., Chichester, 1986.

[4] Oppelt, A. (Ed.): Imaging Systems for Medical Diagnostics. Publicis Corp. Publ. Erlangen, 2005.

[5] Schmitz, G.: Biomedical Sonography, in Biomedical Imaging: Principles and Applications (ed R. Salzer), John Wiley & Sons, Inc., Hoboken, NJ, USA. doi: 10.1002/9781118271933.ch11, 2012

[6] Shung, K. K.; Smith, M. B.; Tsui, B.: Principles of Medical Imaging. Academic Press, San Diego, 1992.

[7] Shung, K. Kirk: Diagnostic Ultrasound, Imaging and Blood Flow Measurements. Taylor & Francis Group, Boca Raton, 2006.

[8] Szabo, Thomas, Diagnostic Ultrasound Imaging: Inside Out. Academic Press, Burlington, 2004.