22485 Medical Imaging Systems

Lecture 1, September 2024

Introduction to course and ultrasound physics

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Department of Health Technology

DTU Health Technology

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Outline for Today

- Teachers
- Outline of course
  - Purpose
  - Course content and web-site
  - Books and notes
  - Exercises
- Medical ultrasound systems
  - History
  - Anatomic imaging
  - Blood flow imaging
  - Examples
- Physics of ultrasound after break

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Practical details

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Practical details – Teacher for lectures

- Jørgen Arendt Jensen
- DTU Health Technology
- Build 349, room 222
- Phone: 45 25 39 24
- E-mail: jaje@dtu.dk
- Web:

  home.healthtech.dtu.dk/jaj/

- Responsible for all practical details

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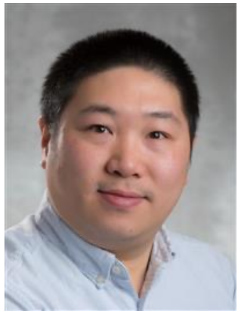
Practical details – Teacher for lectures



- Billy Yiu
- DTU Health Technology
- Build 349, room 232
- E-mail: yshyi@dtu.dk

- Handles part of the ultrasound, exercises and assignments

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Teacher for the MR part

- Hans Magnus Henrik Lundell

- DTU Health Technology
- Build 349, first floor
- E-mail: hmag@dtu.dk

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Guest lecturers

- Chief physicist, Cand.scient Søren Holm,
  Klinisk fysiologisk og nuklearmedicinsk klinik Rigshospitalet
- Professor, dr.med. Liselotte Højgaard,
  Klinisk fysiologisk og nuklearmedicinsk klinik Rigshospitalet
- Senior researcher, PhD Jakob Sauer Jørgensen, DTU Compute
- Senior Research Officer Carsten Gundlach, Department of Physics, DTU
- PhD, MD Thomas Kristensen,
  Diagnostisk Center, Radiologisk klinik afsnit 2023, Rigshospitalet
- Associate professor, PhD Borislav Tomov, DTU Health Technology
- PhD student, MD Nathalie Panduro, Rigshospitalet, Radiologisk Afdeling

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Practical details – Teachers for exercises

- PostDoc Lasse Thurmann Jørgensen

- DTU Health Technology
- Build 349, room 208
- E-mail: latjo@dtu.dk

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Practical details – Teachers for exercises

- PostDoc Lars Emil Haslund
- DTU Health Technology
- Build 349, room 224
- Phone: 45 25 39 02
- E-mail: lahas@dtu.dk

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The purpose of the course is …

- to obtain a thorough understanding of diagnostic imaging systems
- to give an understanding of the relation between different medical imaging systems and other measurement systems
- to relate the physical measurement situation with the applied signal processing
- to give an understanding for "good" (robust/accurate/sensitive) measurement and processing methods
- to give an active knowledge of the signal and image processing in modern imaging systems through exercises and project assignments.

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Prerequisites for following the course

- Assumes that the curriculum in Medicine & Technology has been followed:
  - 22052/31610 Applied signal processing
  - 22481/31540 Introduction to medical imaging
  - Courses in human anatomy and physiology
  - Capable of programming in Matlab
  - Interest in Medical Imaging!

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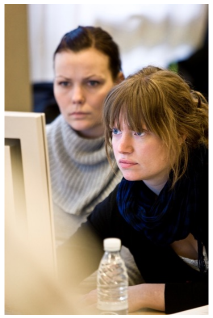
Teaching paradigm



- Discussion of reading material each Monday (13-15) in aud. 23, build. 341 and Thursday (9-11) aud. 11, build. 308
  - Discussion of Chapter and **Cold-call**
  - **Discussion assignment of the day**
  - Questions
  - Slides to support discussion
  - Small assignments
  - Matlab demonstration
- Exercises some Mondays (15-17) in E-data bar build. 341 room 015 (check plan)
- Two final assignments with hand-in of reports. Oral exam about the reports, exercises, and reading material (everything counts!)

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Web-site and course plan

- Web-site at: courses.healthtech.dtu.dk/22485/
- Course plan in 4 themes:
  - Ultrasound imaging
  - X-ray and computer tomography (CT)
  - Radio isotopic imaging (PET, PET/CT, SPECT)
  - Magnetic resonance (MR)
- Slides are posted roughly 1 hour or less before the lecture
- All data and exercises can be found on the web site and on DTU Learn


TECHNICAL UNIVERSITY OF DENMARK

22485 Medical Imaging Systems

Main page | DTU Teaching | Center for Fast Ultrasound Imaging | Field II | JAJ

Plan
Teams 2022
Course material
Programs
Exercises
Ultrasound Data
CT Data
Papers
Teachers
Description
Learning objectives
News
About this site
Print Version

Welcome to the home page of 22485 Medical Imaging Systems!

On this home page you can find information about the course and you can download both the course plan for the autumn 2022, the data for the different exercises and assignments, and various programs used for demonstrations during the lectures. The site is being updated for 2022 and will be completed before the semester starts.

The lectures will take place in building 349, room 205 on Mondays and Thursdays. The exercises are performed in the E data bar in building 341, ground floor, room 015.

Aim: The purpose of the course is to give a thorough introduction to all modern diagnostic imaging systems. This includes the primary systems as X-ray, computer tomography (CT), ultrasound, and magnetic resonance (MR) as well as PET, PET/CT, and SPECT. Both the physics behind the imaging will be taught, as well as the signal processing performed in the systems. A number of computer exercises must be made during the course.

A number of international leading experts in medical imaging will also give guest lectures, and the course includes visit to radiology departments along with demonstrations.

The grading in the course is based on two projects about CT reconstruction and ultrasound and an oral exam. For both a report must be made and handed in during the course. The reports, exercises, and reading material are discussed during the oral exam.

Contents: Physics of ultrasound imaging. B-mode imaging. Signal processing in flow estimation systems (Doppler Systems). X-ray physics and imaging. CT scanning and reconstruction. MR scanning and reconstruction. PET, PET/CT and SPECT scanning. Molecular Imaging. Implementation of signal processing. Exercises. Report writing. Oral exam.

News:
The latest addition to News is from August 8 on the revsion of thew site.

Biomedical Engineering Group | DTU Teaching | DTU Health Technology

/22485/main.html
Last updated: 15:35 on Mon, 08-Aug-2022

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Modern Medical Imaging Systems

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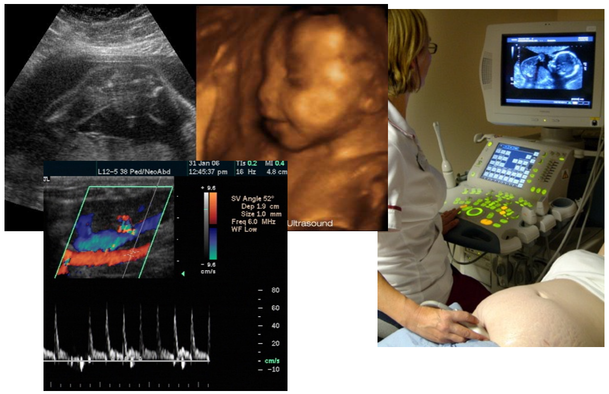

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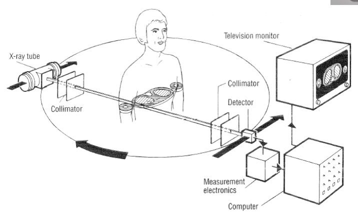
CT scanning



From Krestel (1988)

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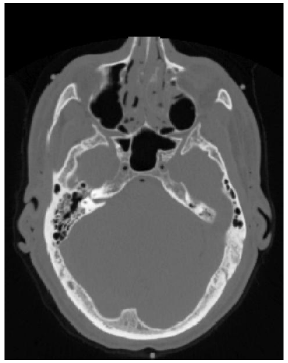
CT scans



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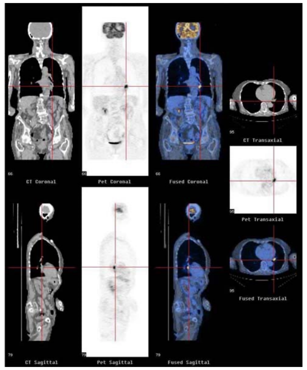
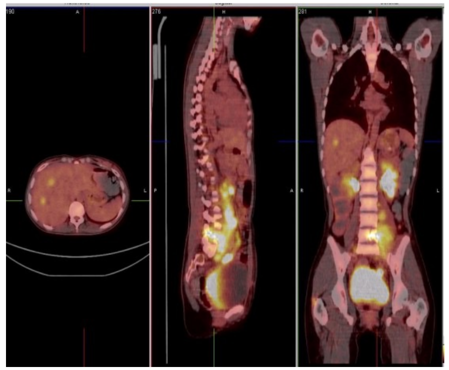
Radio isotopic imaging (PET/CT images)





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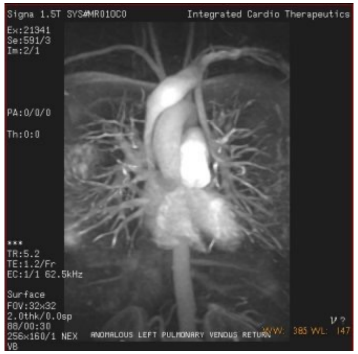
Magnetic resonance (MR)



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Books

- Two books are used:
  - Jørgen Arendt Jensen: *Estimation of Blood Velocities Using Ultrasound, A Signal Processing Approach, Cambridge University Press, 1996.*
    (third edition August, 2013 can be downloaded from DTU Learn. Note this is copyrighted material; For your Eyes only!)
  - P+L: J. L. Prince & J. M. Links: *Medical imaging signals and systems (second edition)*, Pearson Prentice Hall Bioengineering, 2015, ISBN: 978-0-13-214518-3 It can be bought from the PF bookstore with a discount. Is used from October 6.

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Exercises

- Seven exercises are made during the course
- Topics: Matlab programs for simulating the signal and image processing in medical imaging.
- Time: Monday 15-17 in the E-data bar, build. 341, ground floor room 015
- Made in groups of two (form groups today and Thursday)
- No reports hand-in, but you can be asked questions about it at the exam
- Lays the ground work for the two projects
- Prepare for the exercises!
- Tutors: Lasse Thurmann Jørgensen and Lars Emil Haslund

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Final assignments

- Two assignments are made:
  1. Ultrasound signal processing (hand in 28/10)
  2. Reconstruction and artefacts (hand in 5/12)
- Made in groups of two
- Evaluated with a grade that counts towards the final grade
- Hand-in time is strict
- Hand in as pdf and Urkund is used for plagiarism check

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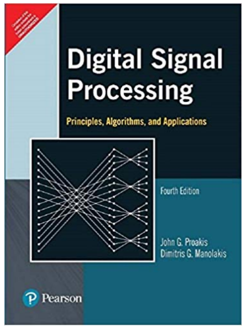
Quiz on signal processing next time

Topics:

- What is the spectrum of a square wave?
- Basic rules for signals and correlation functions
- What is the spectrum of a sinusoidal pulse with M oscillations
  - Sketch the signal
  - Sketch the spectrum
- What is the autocorrelation of a white, random signal?
- How do you plot in Matlab
- Takes 15 min and we will discuss it next time Monday



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Medical Ultrasound:

History and Systems

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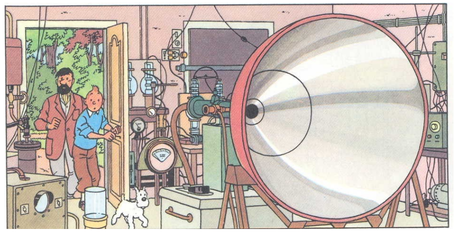
What is ultrasound?

- Ultrasound: Pressure waves with frequencies higher than 20 kHz, i.e. higher than the audible range of man. Compared to X-rays and CT, ultrasound is harmless unless very high intensities are used.



Tintin and Captain Haddock discovers Tournesol's deadly ultrasound device.

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Ultrasound history

- Used for many years by animals – bats and dolphins
- Piezoelectric effect discovered by the Curie brothers in 1888
- High frequency pressure waves in water (SONAR) was developed after World War I to detect submarines.
- The first ultrasound systems for medical imaging was made in the 1950s, mainly by Howry and Wild.
- The first velocity estimation system by Satomura in Japan, 1957

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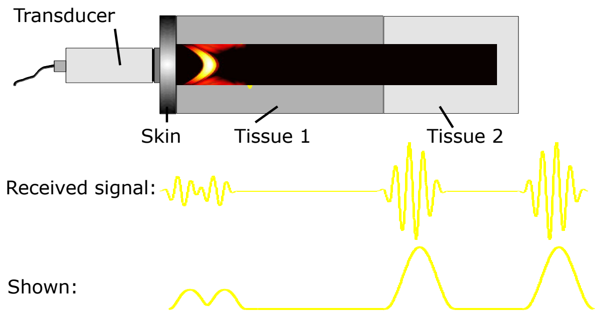
Pulse-echo principle for imaging



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Modern ultrasound system

- Speed of sound: 1540 m/s
- Time for one line is 200 μs for a depth of 15 cm
- Can yield 5,000 lines per second
- One image consists of 100-200 lines
- Frame rate is 10-50 images/s
- Electronic arrays transducers with 192 elements are used

Modern ultrasound scanner from B-K Medical

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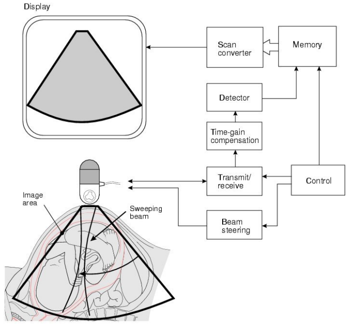
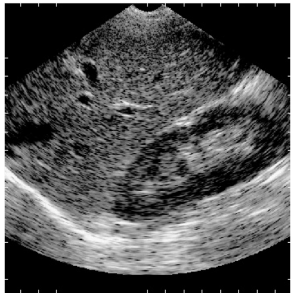
B-mode system





B-mode image of right liver lobe and kidney

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Example of ultrasound movie

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Medical Ultrasound:

Blood velocity Estimation

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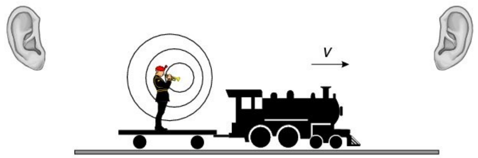
Doppler effect



$$f_r = f_0(1+\frac{v}{c})$$

f_r – Received frequency

f_0 – Emitted frequency

c – speed of sound (1540 m/s)

v – Train velocity

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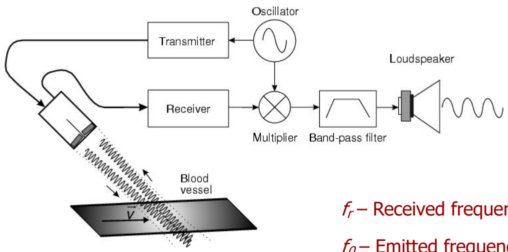
Velocity estimation system (Doppler system)



$$f_r = f_0(1+\frac{2v_z}{c})$$

f_r – Received frequency

f_0 – Emitted frequency

c – speed of sound (1540 m/s)

v_z – Axial blood velocity

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Audio generation

- Received and demodulated frequency is in the audio range:
  - Emitted frequency: 3-10 MHz
  - Blood velocity: 0-1 m/s
  - Resulting frequency example:
- Matlab example (snd_demo)

$$f_{doppler} = \frac{2v_z}{c} f_0 = \frac{2 \cdot 0.75}{1540} 5 \cdot 10^6 = 5\,\text{kHz}$$

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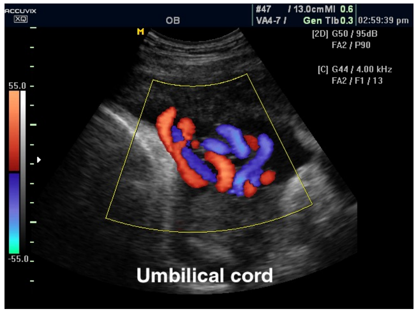
Color flow imaging (CFM)



- Ultrasound is emitted 8 to 16 times in the same direction
- The velocity is estimated along the image direction
- A blue color indicates velocity towards the transducer and red away
- Next slide is an example from the carotid artery and the jugular vein

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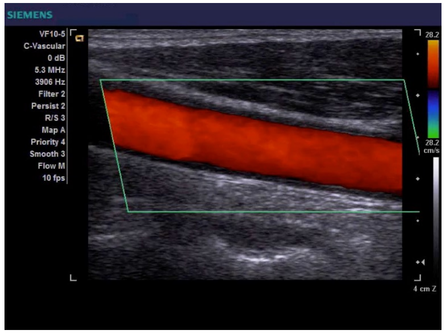
Modern color flow mapping



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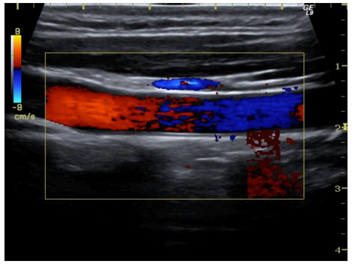
Conventional velocity estimation system

- Low frame rate (approx. 20 Hz)
- Angle dependent velocity estimation



- Velocity changes direction in the image
- Determination is dependent on angle between beam and flow:

  $V_z = |v| \cos(angle)$

- At 45 degrees:
  71% of velocity
- At 60 degrees:
  50% of velocity
- At 80 degrees:
  17% (!) of velocity
- At 90 degrees
  0%

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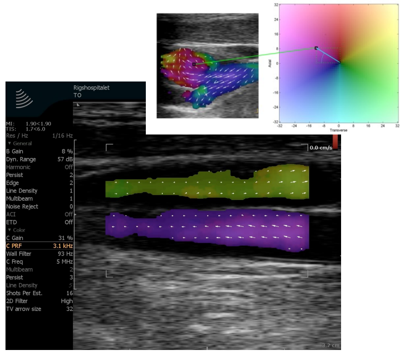
DTU developed vector flow method:
BK Medical ProFocus scanner
FDA approved January 2012



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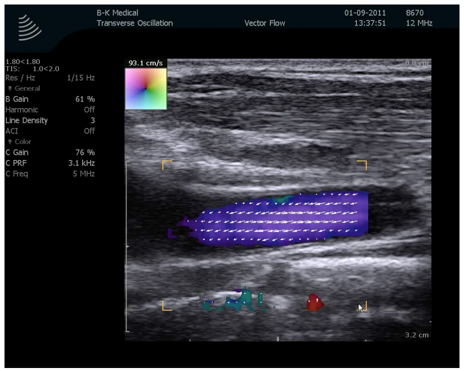
Scanning of the carotid artery



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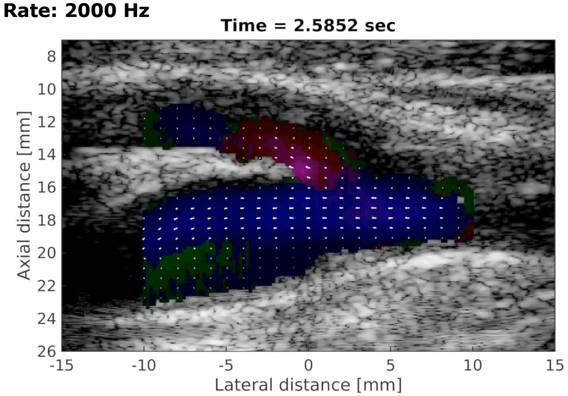
SA Vector Flow Imaging in Carotid bifurcation

Frame Rate: 2000 Hz



Villagomez et al, IUS 2015

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Medical Ultrasound:

Physics

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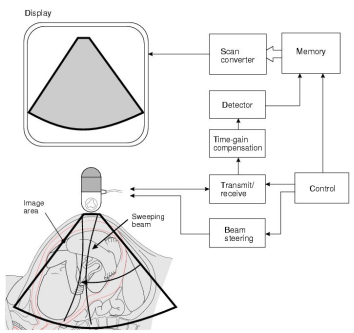
Ultrasound and scanning



- Pulse emission
- Speed of sound c=1540 m/s in soft tissue
- Distance in tissue: $d = c \cdot t$
- Pulse send out:

$$p(t) = \sin(2\pi f_o t) \quad 0 \le t \le \frac{M}{f_0}$$

- Wavelength:

$$T_0 = \frac{1}{f_0}, \quad \lambda = T_o c = \frac{c}{f_0}$$

- Length of pulse = $M\lambda$
- Typical parameters:

$$f_0 = 5\text{MHz}, \quad \lambda = \frac{1540}{5 \cdot 10^6} = 0.3\text{mm}$$

$$\text{M} = 2 \Rightarrow \text{M}\lambda \approx 0.6\text{mm}$$

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Reflection

- Reflection of sound:

$$R_a = \frac{z_2 \cos\Theta_i - z_1 \cos\Theta_t}{z_2 \cos\Theta_i + z_1 \cos\Theta_t} = \frac{p_r}{p_i}$$

- Characteristic acoustic impedance: $z = \rho c$
- Snell's law: $\frac{c_1}{c_2} = \frac{\sin\Theta_i}{\sin\Theta_t}$
- Transmission of sound:

$$T_a = \frac{2 z_2 \cos\Theta_i}{z_2 \cos\Theta_i + z_1 \cos\Theta_t} = \frac{p_t}{p_i}$$

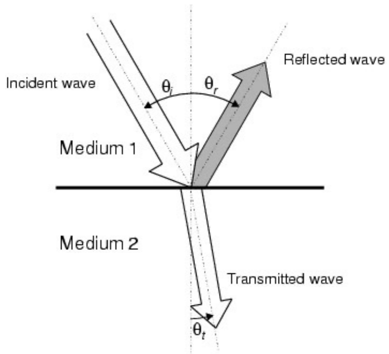

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Table with characteristic acoustic impedances

Medium	Density kg/m^3	Speed of sound m/s	Characteristic acoustic impedance kg/[m^2·s]
Air	1.2	333	0.4×10^3
Blood	1.06×10^3	1566	1.66×10^6
Bone	$1.38 - 1.81 \times 10^3$	2070 – 5350	$3.75 - 7.38 \times 10^6$
Brain	1.03×10^3	1505 – 1612	$1.55 - 1.66 \times 10^6$
Fat	0.92×10^3	1446	1.33×10^6
Kidney	1.04×10^3	1567	1.62×10^6
Lung	0.40×10^3	650	0.26×10^6
Liver	1.06×10^3	1566	1.66×10^6
Muscle	1.07×10^3	1542 – 1626	$1.65 - 1.74 \times 10^6$
Spleen	1.06×10^3	1566	1.66×10^6
Distilled water	1.00×10^3	1480	1.48×10^6

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What are the reflection coefficients?

- For normal incidence ($\Theta_i = 0 = \Theta_t$)

$$R_a = \frac{z_2 \cos\Theta_i - z_1 \cos\Theta_t}{z_2 \cos\Theta_i + z_1 \cos\Theta_t} = \frac{p_r}{p_i} = \frac{1 - \frac{z_1}{z_2}}{1 + \frac{z_1}{z_2}}$$

- Liver to fat?
- Bone to fat?
- Fat to air?

- Use the previous table to calculate the values.

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What are the reflection coefficients?

- Liver to fat? $z_1 = 1.66$ MRayl, $z_2 = 1.33$ MRayl,
- Bone to fat? $z_1 = 7.38$ MRayl, $z_2 = 1.33$ MRayl,
- Fat to air? $z_1 = 1.33$ MRayl, $z_2 = 0.4$ kRayl,

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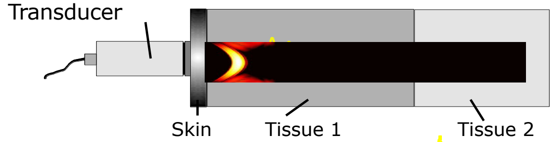
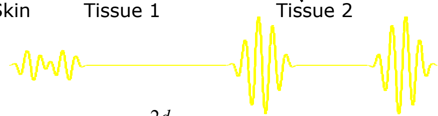
Reflection and reception



Received signal:



Depth-time relation: $2d = ct \Rightarrow t = \frac{2d}{c}$

For a number of reflections: $y(t) = r(t) * p(t)$ (Matlab con_demo)

Reflections *Pulse*

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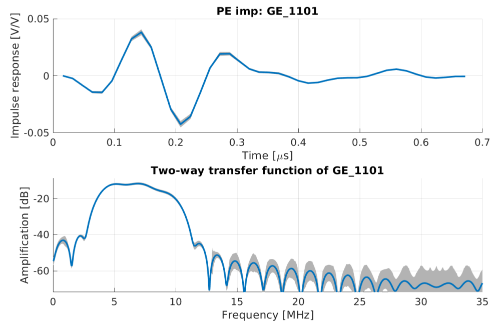
Measured ultrasound pulse



GE L8-18i-D, 8-18 MHz high frequency broadband transducer

Center frequency around 8 MHz, B=7 MHz at -20 dB

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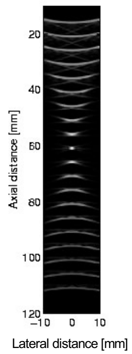
Resolution and point spread functions



- Resolution in the image is characterized by the point spread function (PSF)
- Spatially variant
- Axial resolution in depth
- Lateral resolution across ultrasound beam
- Azimuth – out of image plane
- Image model: $y(t) = r(t,\vec{r}) ** p(t,\vec{r})$
  - ** - 3D (spatial) convolution
  - *r* – Reflections
  - *p* – Point spread function

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Axial resolution

- Pulse emission
- Speed of sound c=1540 m/s in soft tissue
- Distance in tissue: $z = c \cdot t / 2$
- Pulse send out: $p(t) = \sin(2\pi f_o t) \quad 0 \le t \le \frac{M}{f_0}$
- Axial resolution: $\frac{M}{f_0}\frac{c}{2} = \frac{M}{2}\lambda$
- Transducer bandwidth = f_0/M
- Typical parameters:

$$f_0 = 5\text{MHz}, \quad \lambda = \frac{1540}{5 \cdot 10^6} = 0.3\text{mm}$$

$$M = 2 \Rightarrow res \approx 0.3\text{mm}$$

$$T = \frac{M}{f_0} = \frac{2}{5 \cdot 10^6} = 0.4\mu s$$

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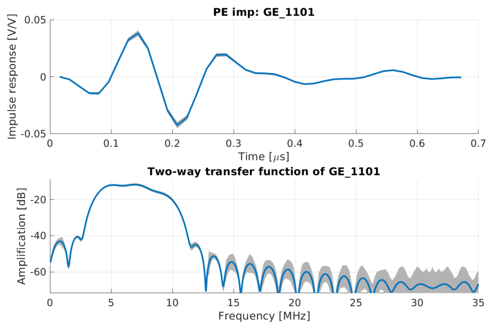
Measured ultrasound pulse



Transducer: f_0= 8 MHz, λ = 0.19 mm, B=7 MHz at -20 dB

Axial resolution: -6 dB: 0.125 μs, d=C T/2 = 1.54 10^6 x 0.125 10^{-6}/2 = 0.096 mm ~λ/2

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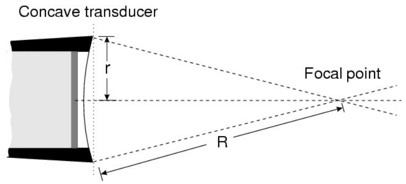
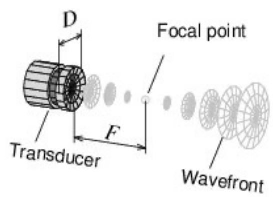
Lateral resolution



- Approximate resolution at focus at Full Width Half Max (FWHM, -6 dB):

$$d_{3dB} = FWHM = \lambda \frac{R}{2r} = \lambda F_\#$$

$$F_\# = \frac{R}{2r} = \frac{F}{D} \quad \text{F} - \text{number (typically 1-5)}$$



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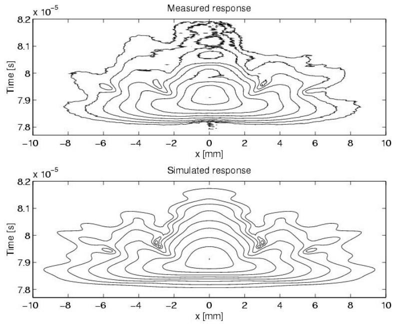
Point spread functions (measured and simulated)



PSF for concave 3 MHz transducer at 60 cm, diameter 2 cm, focus at 10 cm
6 dB between contours. Top – Measured, Bottom - Simulated

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Medical Ultrasound: Imaging

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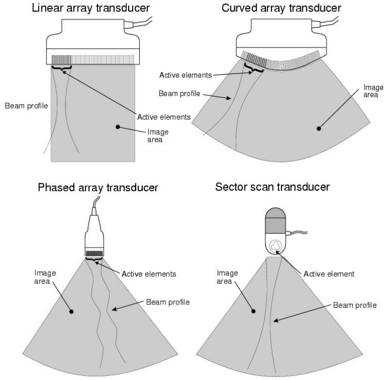
Different array transducers and imaging types



Linear array

Convex array

Phased array

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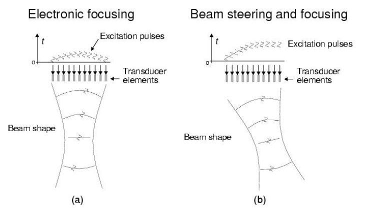
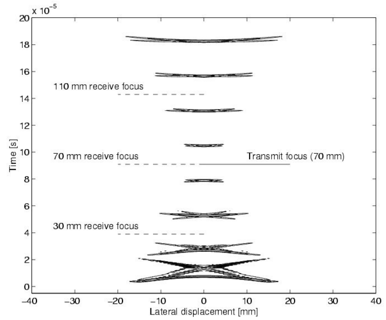
Transducers and focusing





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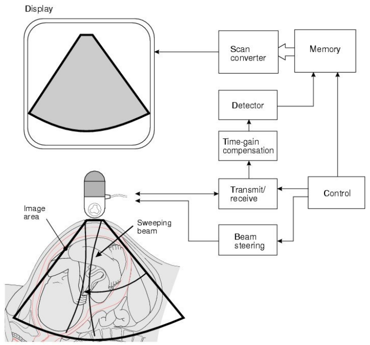
Signal processing in B-mode system



- Transmit pulse
- Receive and amplify in TGC amplifier
- Sample signal

$$y(t) = r(t) * p(t)$$

- Calculate envelope through Hilbert transform

$$e(n) = \sqrt{y^2(n) + H[y(n)]^2}$$

- Compress dynamic range

$$e_{disp}(n) = 20\log_{10}(e(n))$$

- Scale to color map
- Make rectangular-to-polar mapping

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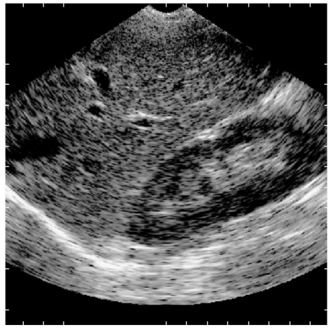
Signal processing in a B-mode system (Exercise 1)



B-mode image of right liver lobe and kidney

1 cm between markers

(15 x 15 cm)

This is exercise 1
Monday September 9

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Discussion assignment for Thursday

- Design an ultrasound B-mode system
- Assume that a system can penetrate 300 wavelengths
- It should penetrate down to 10 cm in a liver
  - What is the largest pulse repetition frequency possible?
  - What is the highest possible transducer center frequency?
  - What is the axial resolution?
  - What is the lateral resolution for an F-number of 2?

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Summary of today

- Practical details of course
- History of ultrasound
- Basic ultrasound
- Content of exercise 1

- For next time
  - Download and print book from DTU Learn
  - Read chapter 1 and 2, page 1-24 and look at your signal processing books – remember quiz questions
  - Make the discussion assignment
  - We will discuss Chapter 2
    - What are the key parameters of ultrasound?
    - Ultrasound propagation, intensity, reflection, and scattering
  - Next discussion Thursday, 9-12 on these topics
  - Read and prepare questions and discussion for exercise 1
  - Prepare for signal processing quiz

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