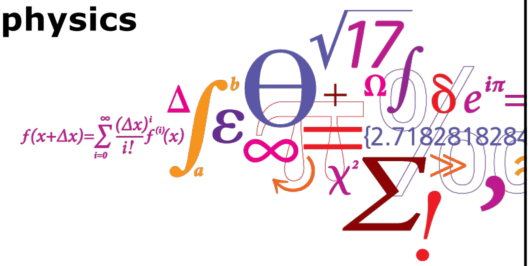
22485 Medical Imaging Systems

Lecture 1, August 2023

Introduction to course and ultrasound physics

Jørgen Arendt Jensen
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/

- Handles all practical details

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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

- Was Esben Thade Petersen which unfortunately passed away last week

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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

- PhD student: Lars Email 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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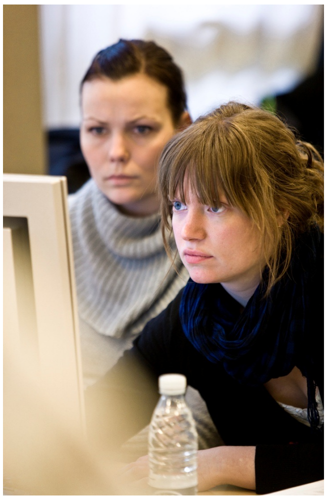
Teaching paradigm



- Discussion of reading material each Monday (13-15) in aud. 205, build. 349 and Thursday (9-11)
  - 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

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Modern Medical Imaging Systems

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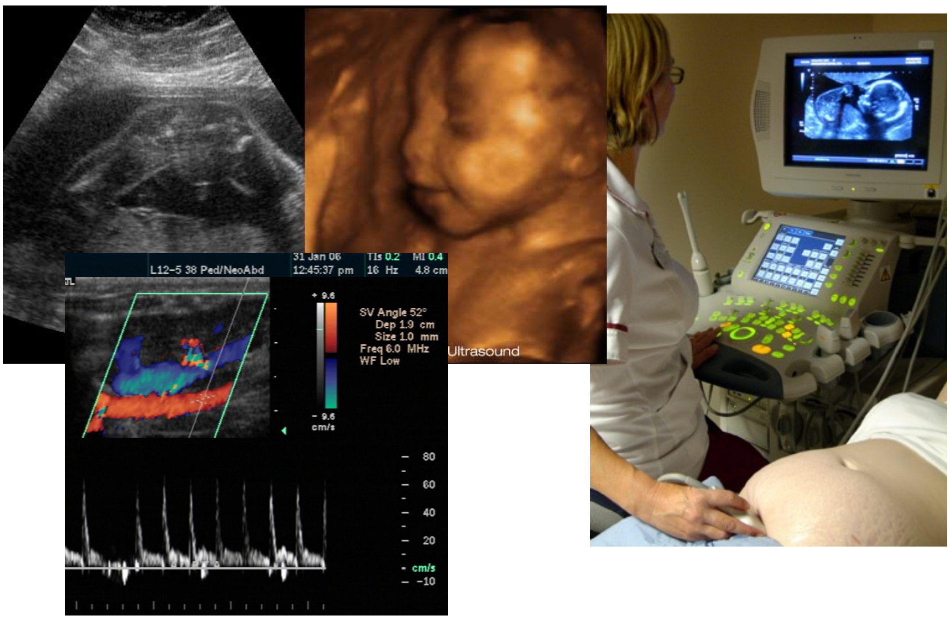

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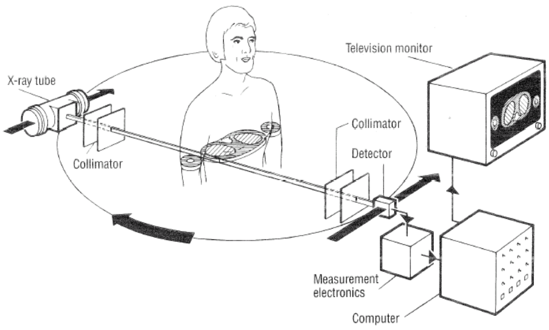
CT scanning



From Krestel (1988)

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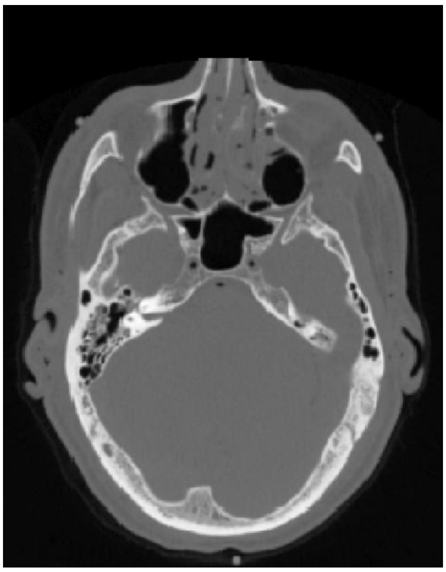
CT scans



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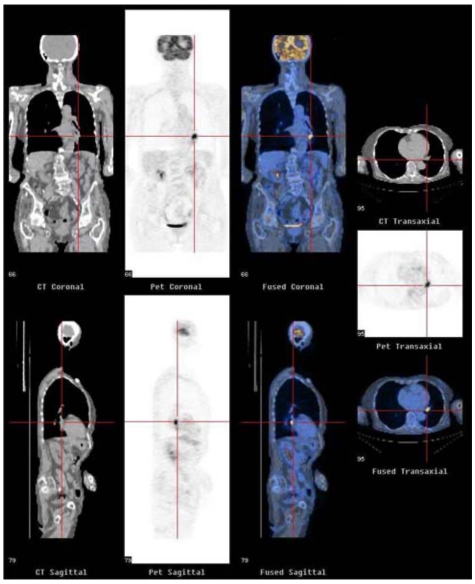
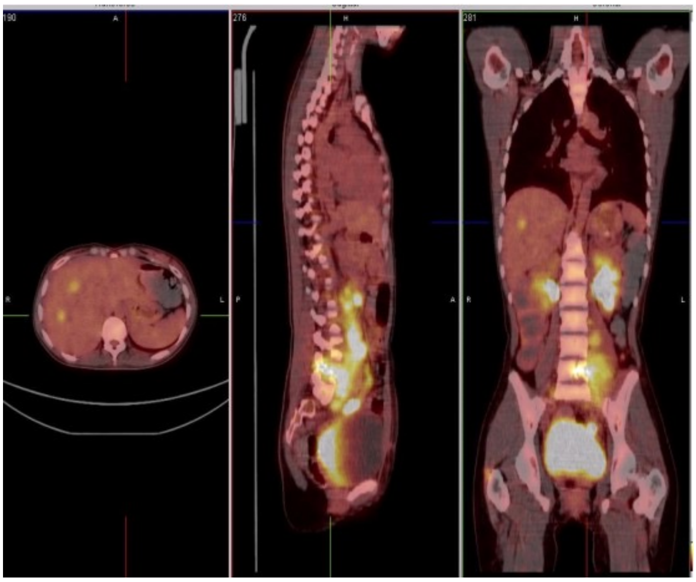
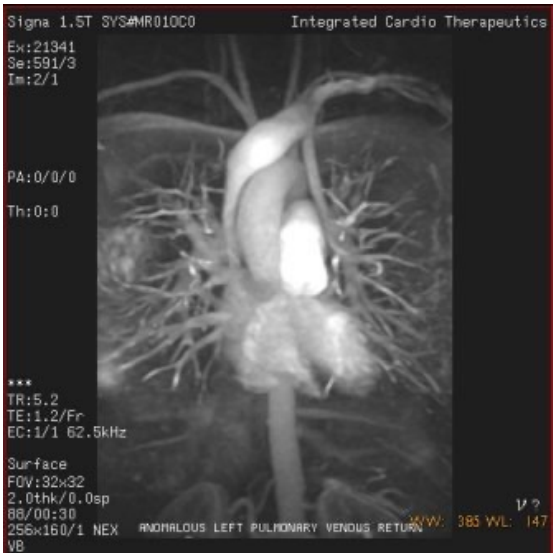
Radio isotopic imaging (PET/CT images)





Magnetic resonance (MR)



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 23/10)
    2. Reconstruction and artefacts (hand in 30/11)

- 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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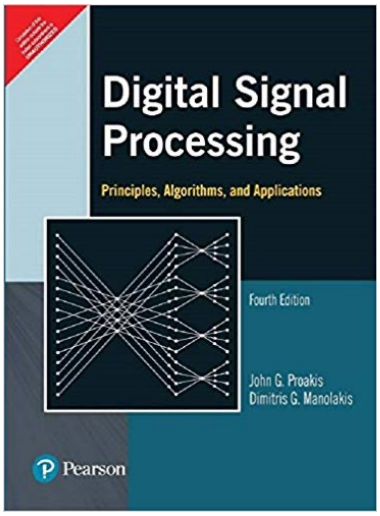
Quiz on signal processing next time

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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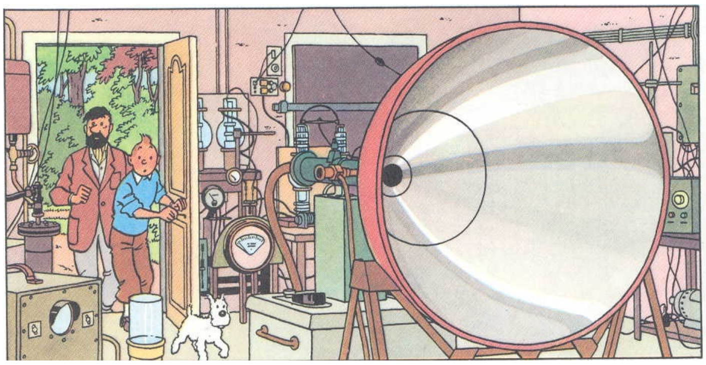
What is ultrasound?

- 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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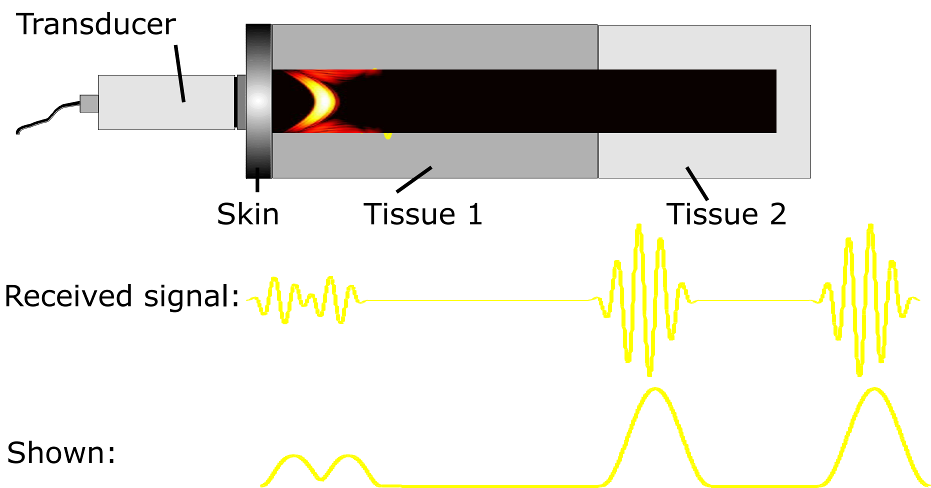
Pulse-echo principle for imaging



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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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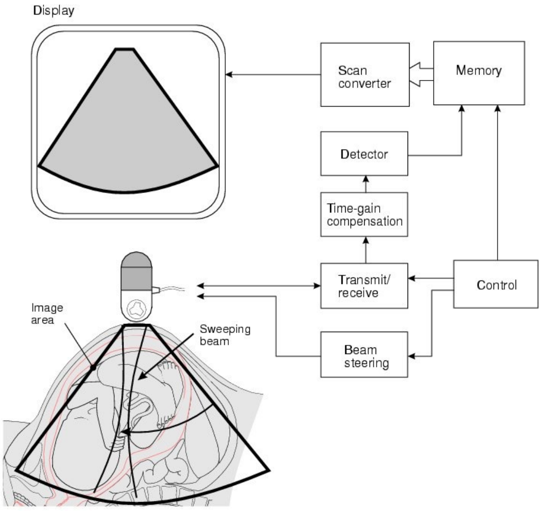
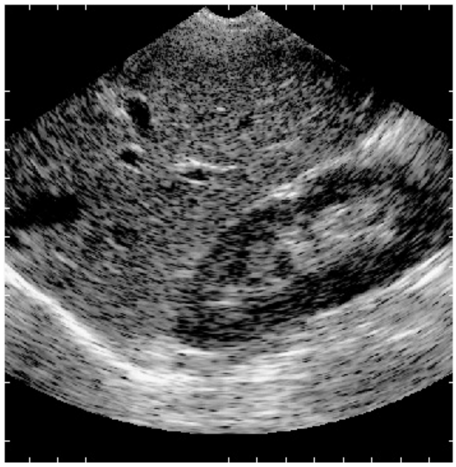
B-mode system





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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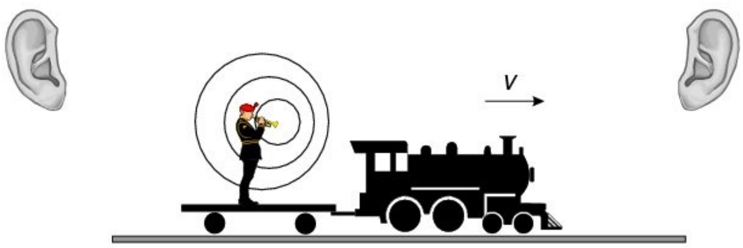
Doppler effect



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

f_r – Received frequency

f_0 – Emitted frequency

c – speed of sound (1540 m/s)

v – Train velocity

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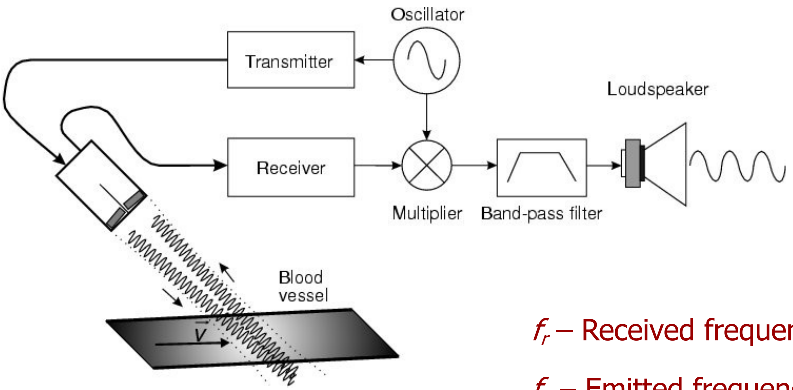
Velocity estimation system (Doppler system)



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

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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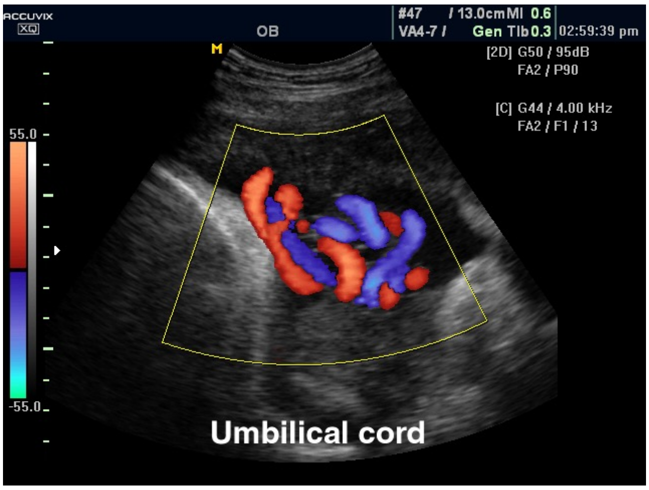
Color flow imaging (CFM)



- 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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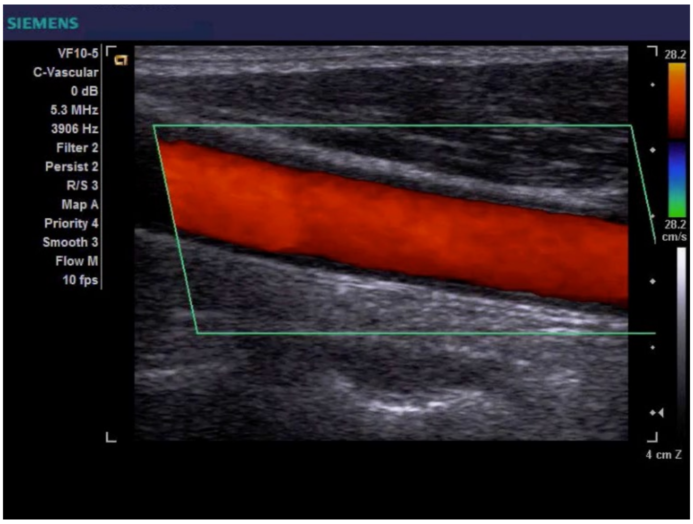
Modern color flow mapping



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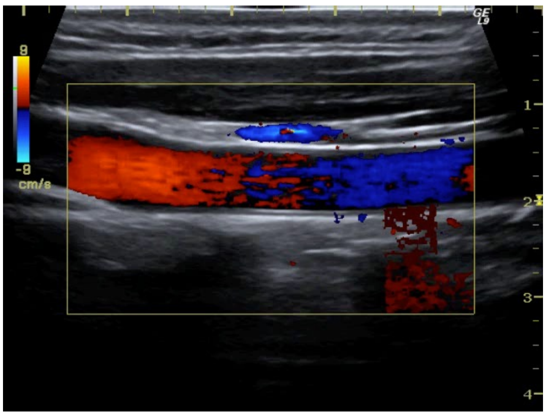
Conventional velocity estimation system

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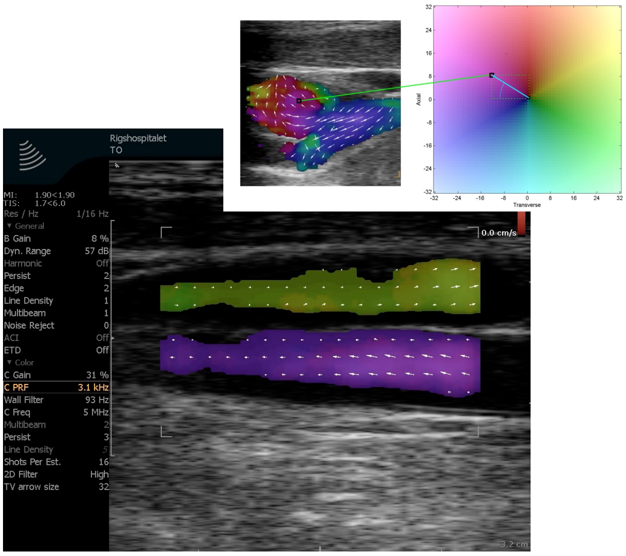
DTU developed vector flow method:
BK Medical ProFocus scanner
FDA approved January 2012



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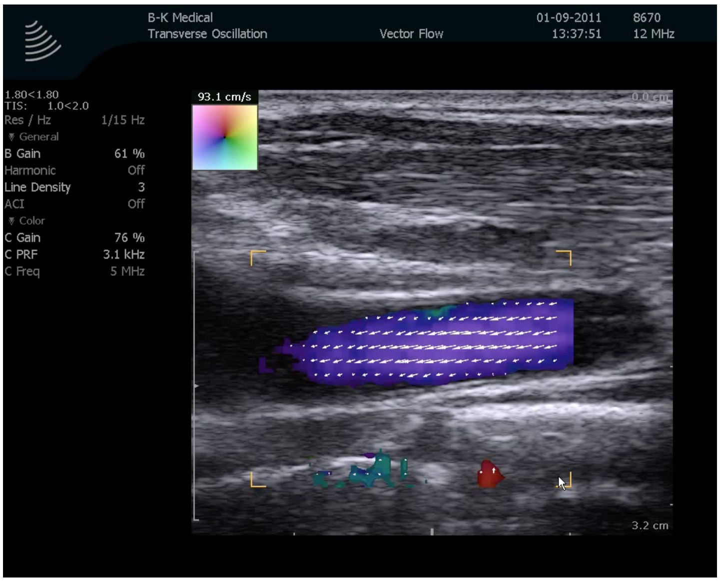
Scanning of the carotid artery



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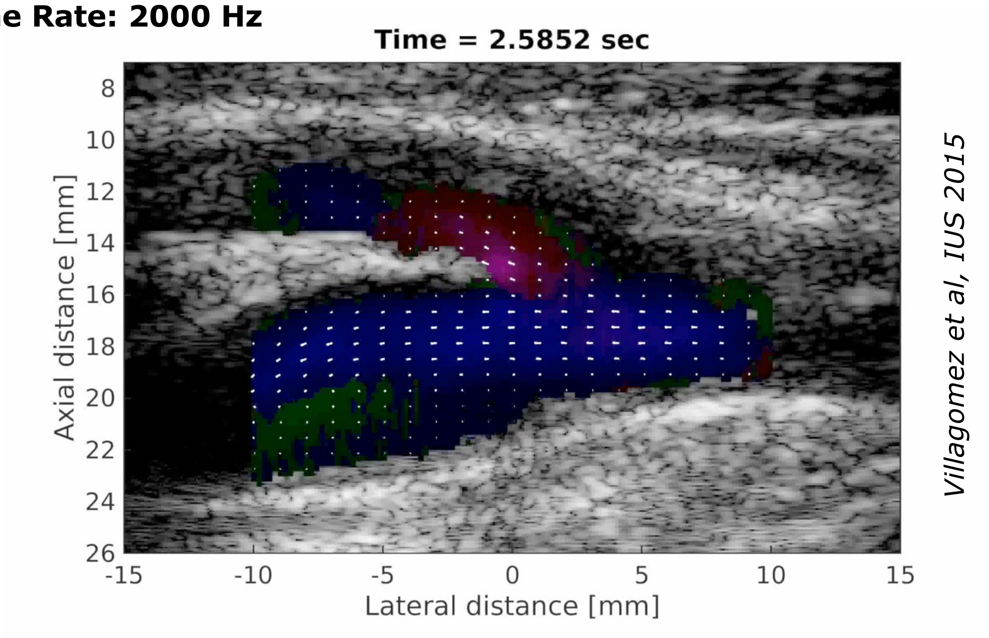
SA Vector Flow Imaging in Carotid bifurcation

Frame Rate: 2000 Hz



Villagomez et al, IUS 2015

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Medical Ultrasound:

Physics

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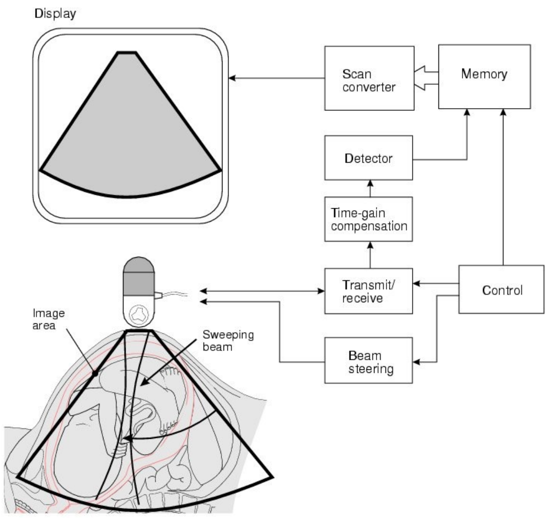
Ultrasound and scanning



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

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

- Wave length:

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

- 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:

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

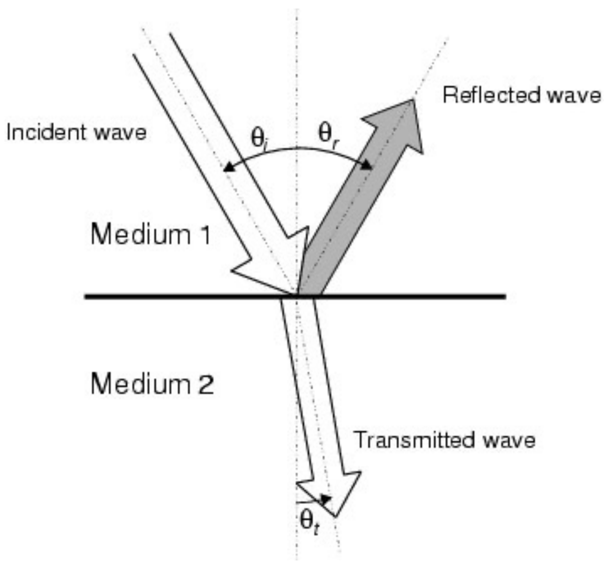

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Table with characteristic acoustic impedances

Medium	Density kg/m^3	Speed of sound m/s	Characteristic acoustic impedance $kg/[m^2 \cdot s]$
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? $z_1 = 1.66 \text{ MRayl}, z_2 = 1.33 \text{ MRayl},$
- Bone to fat? $z_1 = 7.38 \text{ MRayl}, z_2 = 1.33 \text{ MRayl},$
- Fat to air? $z_1 = 1.33 \text{ MRayl}, z_2 = 0.4 \text{ kRayl},$

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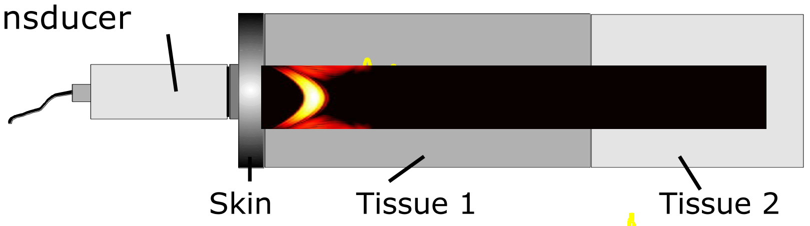
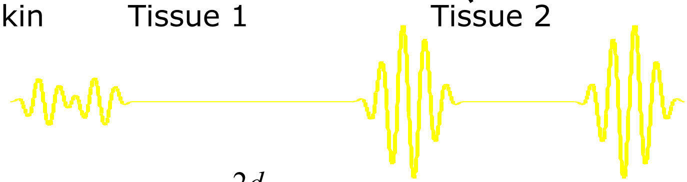
Reflection and reception



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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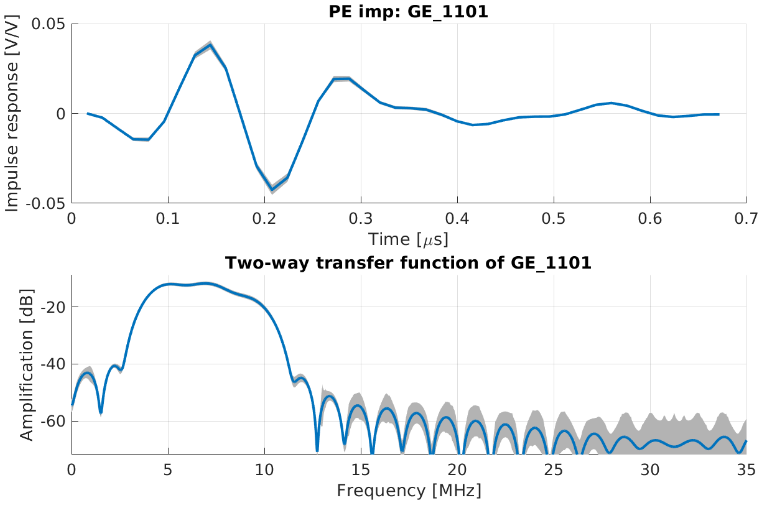
Measured ultrasound pulse



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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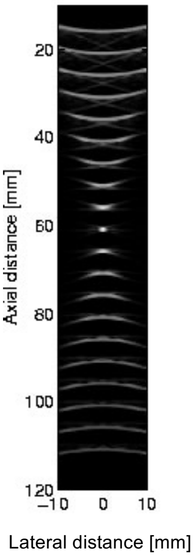
Resolution and point spread functions



- 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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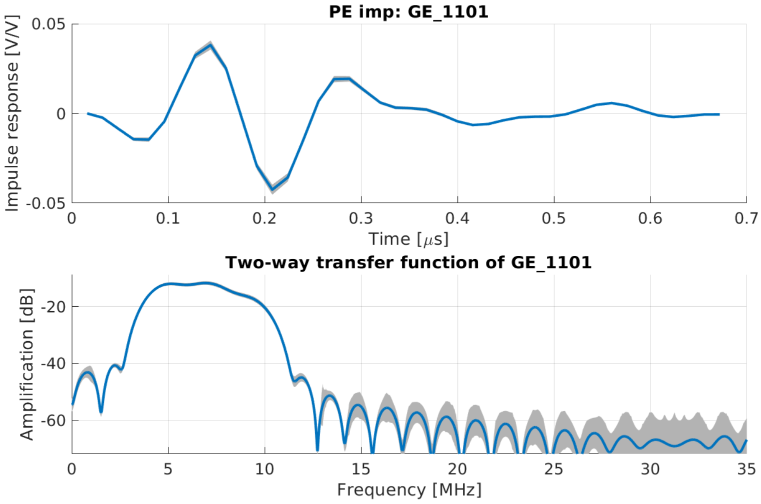
Measured ultrasound pulse



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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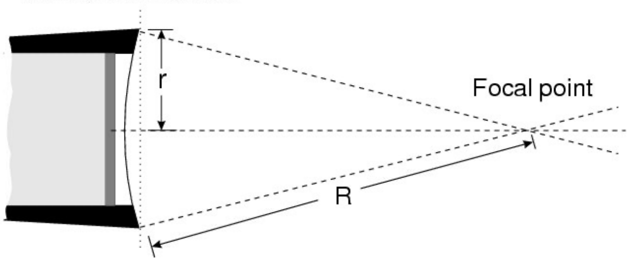
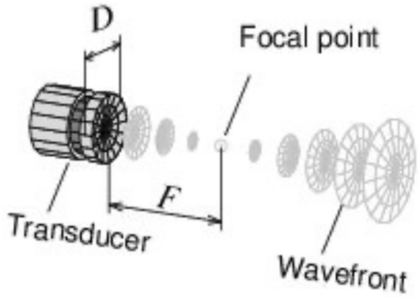
Lateral resolution



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

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

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



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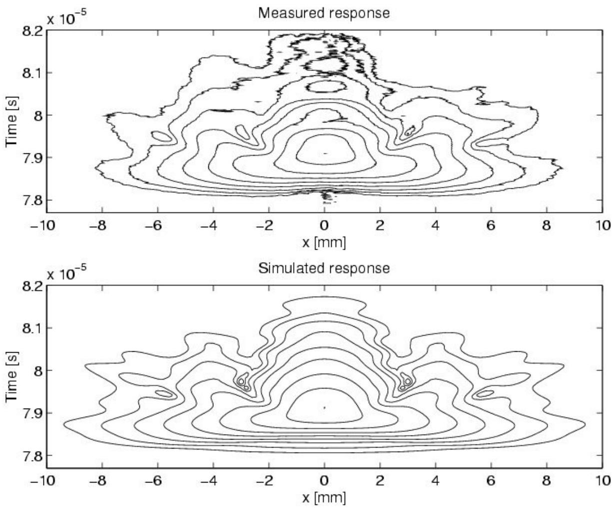
Point spread functions (measured and simulated)



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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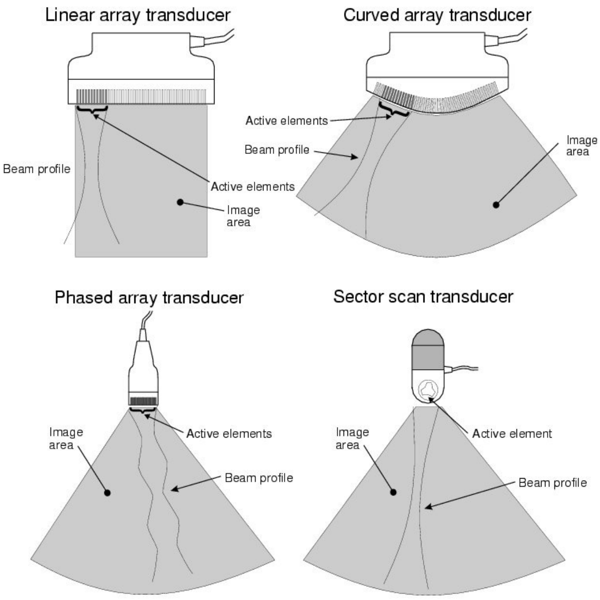
Different array transducers and imaging types



Linear array

Convex array

Phased array

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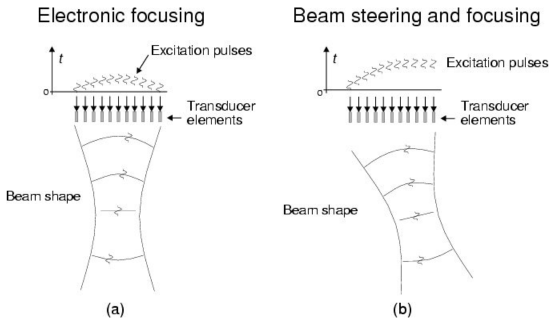
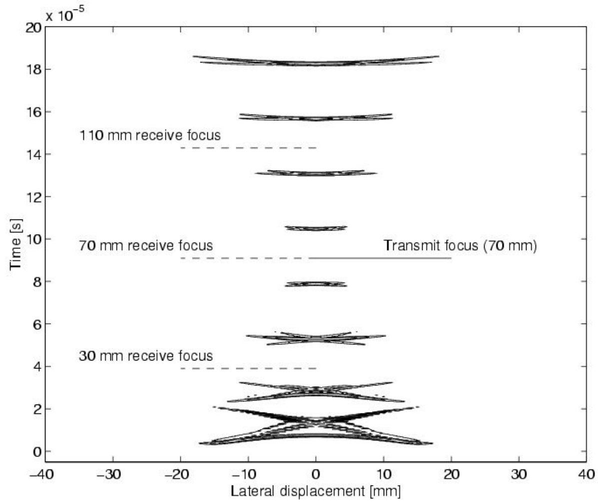
Transducers and focusing





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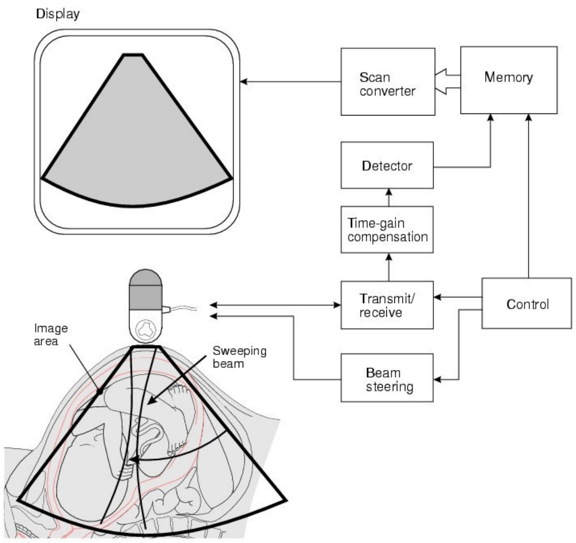
Signal processing in B-mode system



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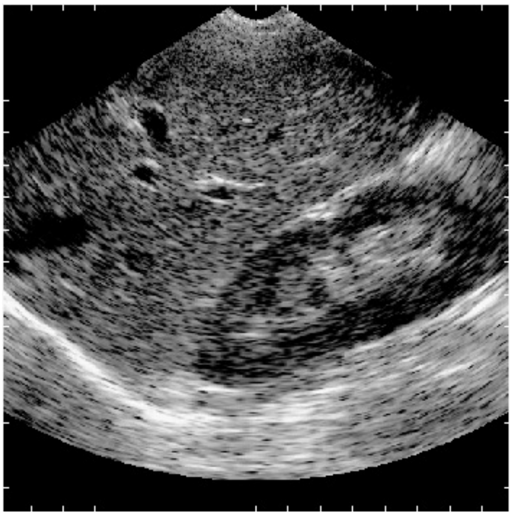
Signal processing in a B-mode system (Exercise 1)



B-mode image of right liver lobe and kidney

1 cm between markers (15 x 15 cm)

This is exercise 1
Monday September 11

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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