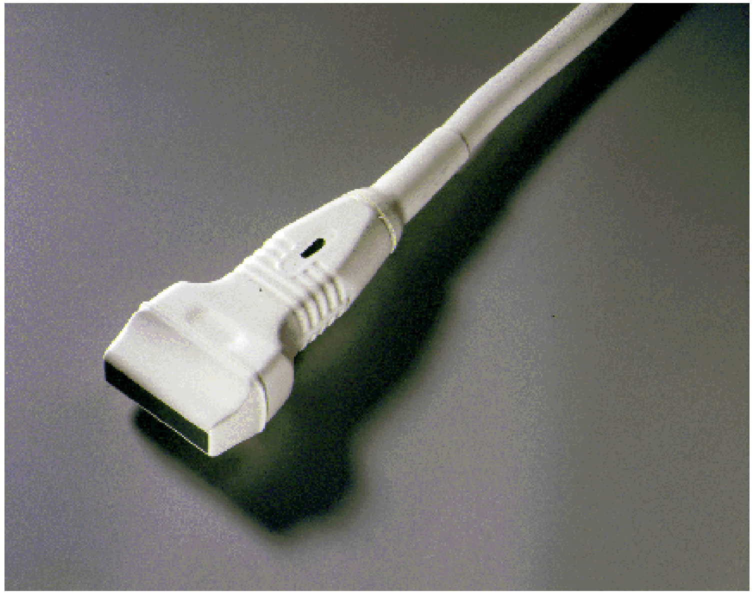
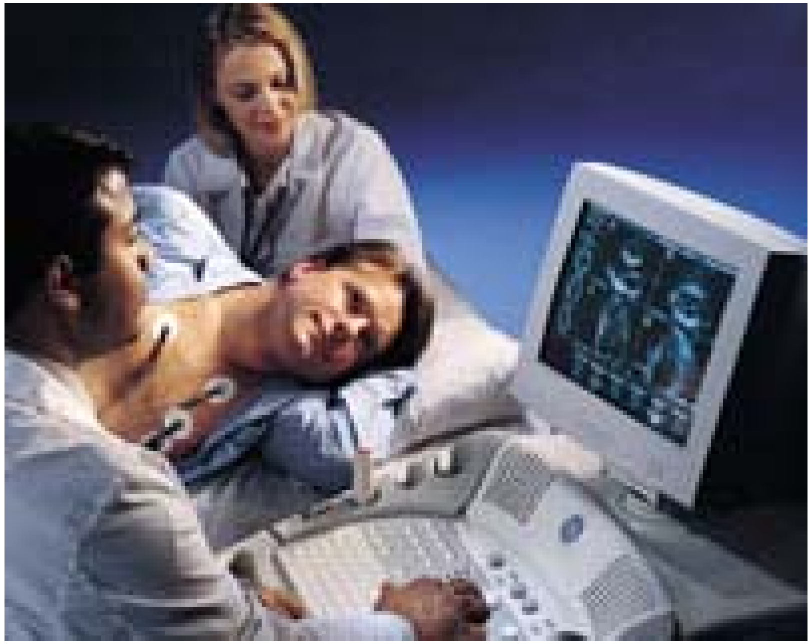
Medical Ultrasound Imaging



Sverre Holm
Digital Signal Processing and
Image Analysis Group

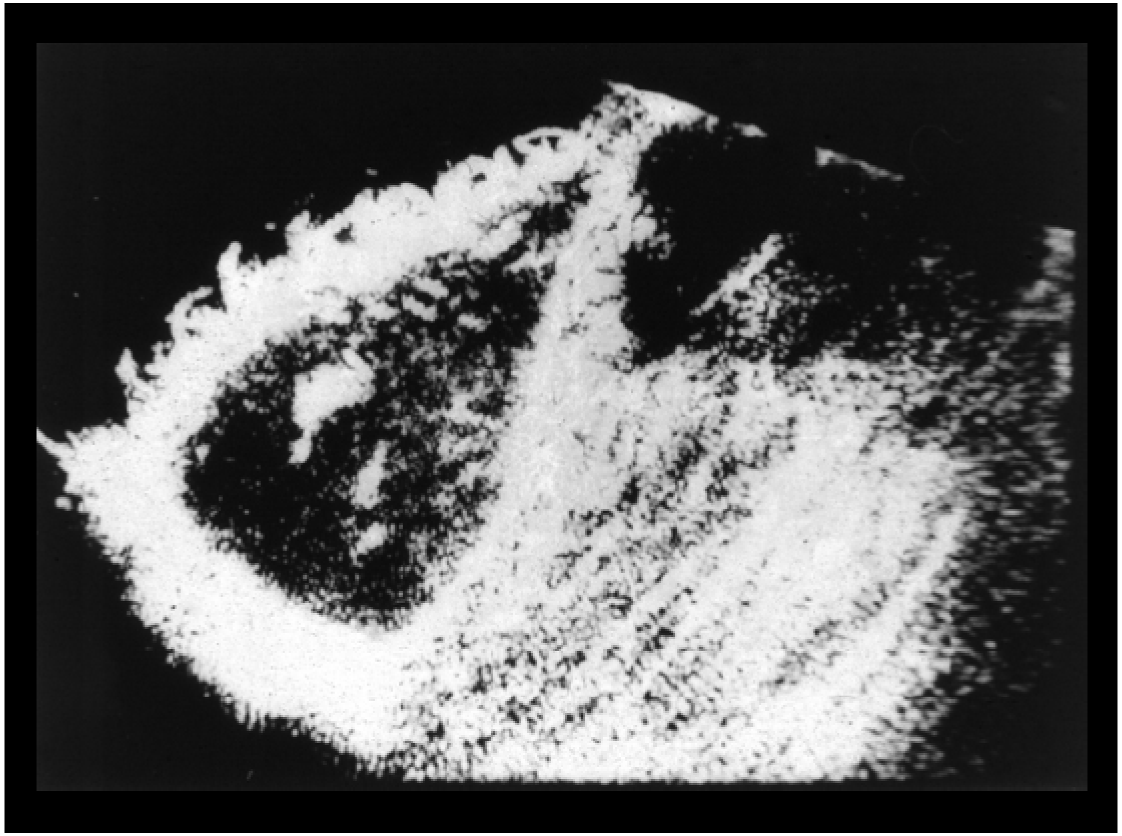
Medical Ultrasound

1. **Introduction**
2. Main principles
3. Imaging modes
4. Ultrasound instruments
5. Probe types and image formats



Medical Ultrasound uses

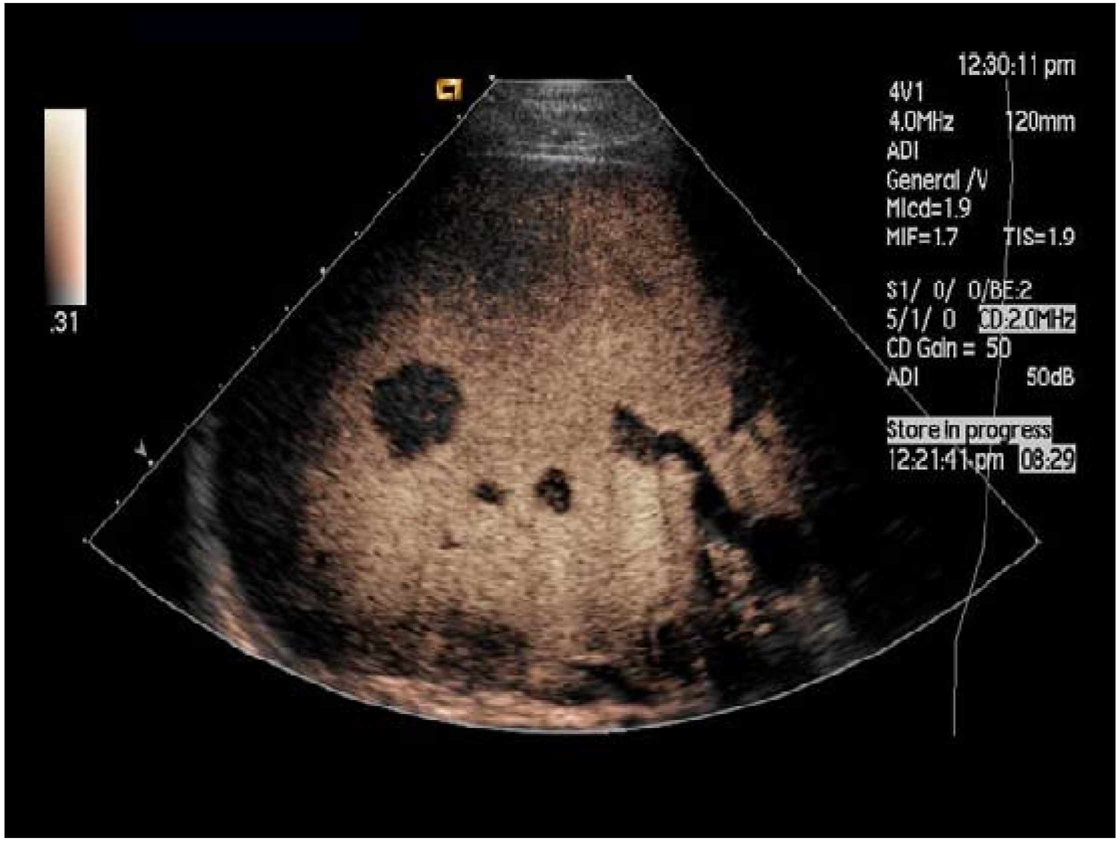
- Soft tissues
  - Fetal, liver, kidneys
- Dynamics of blood flow
  - Heart, circulatory system
- Avoid bone, and air (lungs)



Liver: A scan which was considered to be of high quality in the **early 1970s** and which would have been interpreted as supporting the diagnosis of multiple metastases.
Wells, Ultrasound imaging, 2006

Metastasis = the spread of a disease from one organ or part to another non-adjacent organ or part. Concerned mainly with malignant tumor cells and infections (Wikipedia)

Liver: A scan made with **a modern system**, in which a metastasis can just be perceived towards the right side of the patient (i.e., towards the left of the image)
Wells, Ultrasound imaging, 2006



Liver, metastasis: a scan of the same patient, in which this lesion is clearly apparent following the administration of an ultrasonic **contrast agent**.
Wells, Ultrasound imaging, 2006

Medical Ultrasound

- Continuously improving image quality => increased clinical usage
- Relatively inexpensive compared to CT and MR
  - 25% of all imaging exams in hospitals is US
- Many clinical applications
- Requires training and skill

Norway

- 30 years of ultrasound development
- 70’s: Started at NTNU, continued R&D since then
  - L. Hatle og B. A. J. Angelsen, Doppler Ultrasound in Cardiology, Lea & Feibiger, Philadelphia, 1985.
  - B. A. J. Angelsen, Waves, Signals, and Signal Processing in Medical Ultrasonics, Vol I & Vol II, Institutt for fysiologi og biomedisinsk teknikk, NTNU, april 1996 +
  - 2006: Medical Imaging, Centre for Research-based Innovation http://www.ntnu.no/milab
- 80’s: Vingmed Sound
- 1998: GE Vingmed Ultrasound,
  - Now center of excellence for cardiology ultrasound in GE Healthcare:
  - More than 2 billion NOK turnover controlled from Horten, Norway
- Other companies:
  - Medistim (quality control in surgery) on Oslo Stock Exchange
  - Sonowand (image-guided surgery based on fusion of ultrasound and MR)
  - Neorad (ultrasound-guided injection of CT contrast agent in vein)

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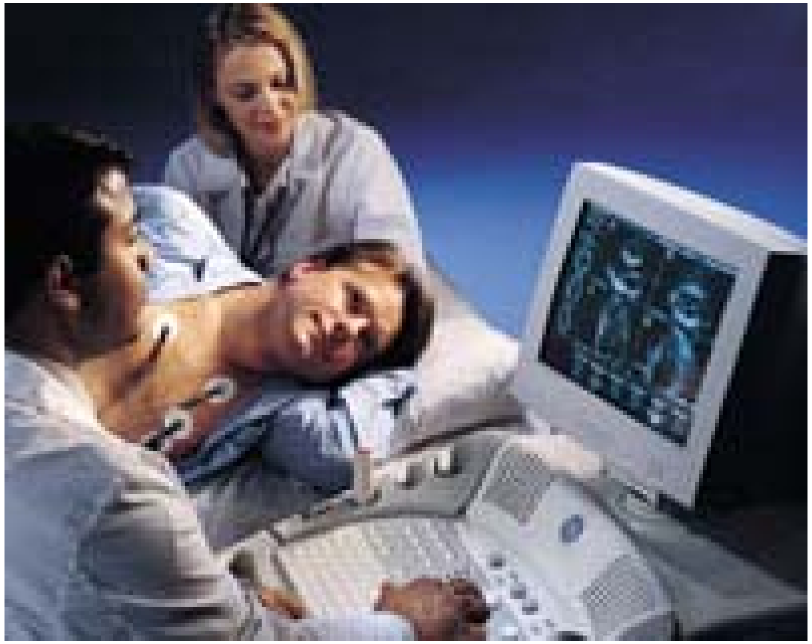
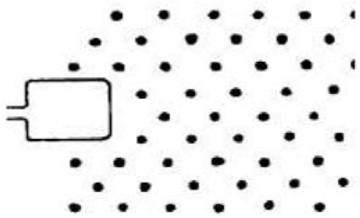
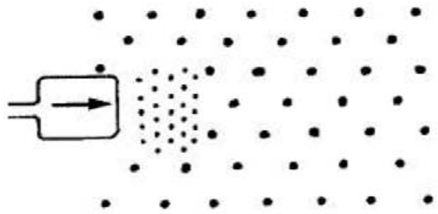
6. Emerging technology



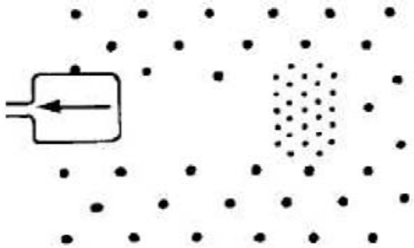
Longitudinal Waves



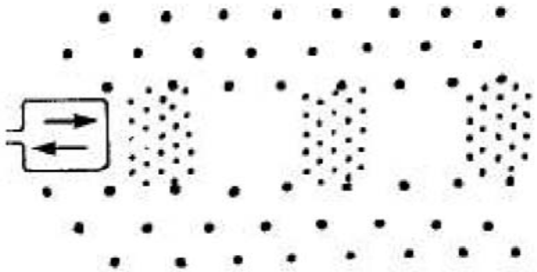
Uniform distribution of molecules in a medium



Movement of the piston to the right produces a **zone of compression**.



Withdrawal of the piston to the left produces a **zone of rarefaction**.



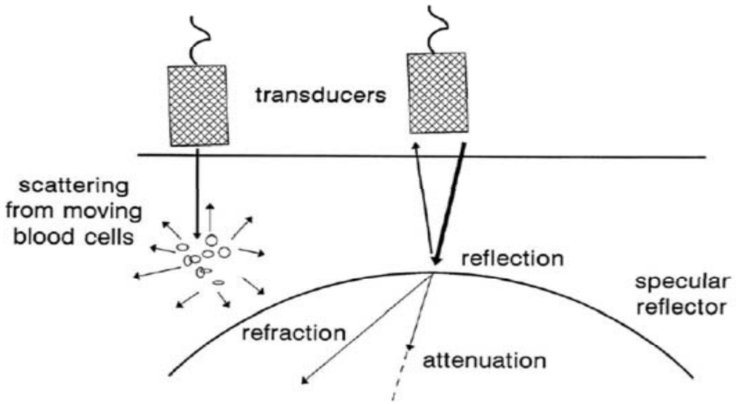
Alternate movement of the piston establishes a longitudinal wave

Sook Kien Ng, Ultrasound Imaging

Ultrasound: Interaction with tissue

Four major interaction mechanisms:

1. Reflection (Imaging)
2. Scattering (Imaging + Doppler)
3. Attenuation
4. Refraction

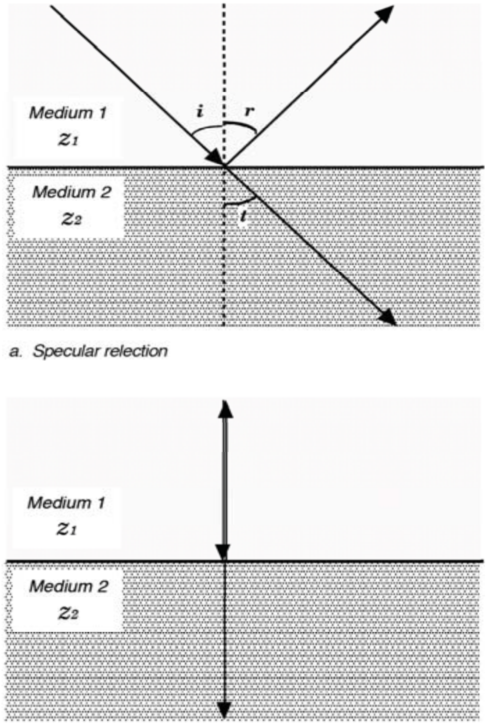


Lawrence, Physics and instrumentation of ultrasound, 2007.

Reflection

- Due to changes in acoustic impedance Z=ρ·c
- Specular
  - Like light striking a glass plate – Snell's law
- Echoes will only be received if beam is near perpendicular
  - Wall of an organ: heart, bladder

Burns, Introduction to the physical principles of ultrasound imaging and doppler, 2005



a. Specular relection

b. Specular reflection - normal incidence

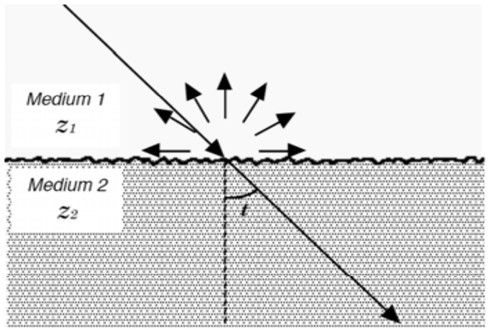
Scattering

A) Rough interfaces

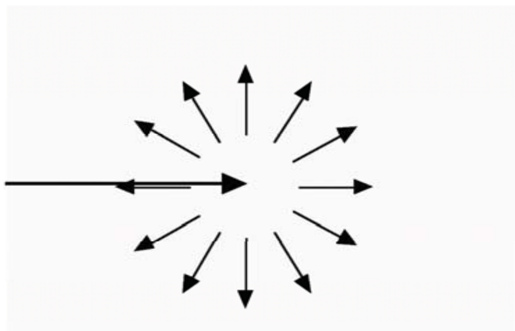
B) Inhomogenous medium (causing speckle in images)

C) Particles (red blood cells)

Burns, Introduction to the physical principles of ultrasound imaging and doppler, 2005



a. Rough Interface



b. Inhomogeneous medium

Attenuation of ultrasound

- In water: usually increases with f^2
- In tissue: usually increases with f

- Typically α = 0.5-1 dB/cm/MHz
- Attenuation = $2d \cdot \alpha \cdot f$
- Examples 60 dB attenuation (α = 0.5 dB/cm/MHz):
  - f = 1 MHz: d=60 cm depth, λ=1.5 mm =>400 λ depth
  - f = 3 MHz: d=20 cm depth, λ = 0.5 mm => 400 λ depth
  - f = 10 MHz: d=6 cm depth, λ = 0.15 mm => 400 λ depth

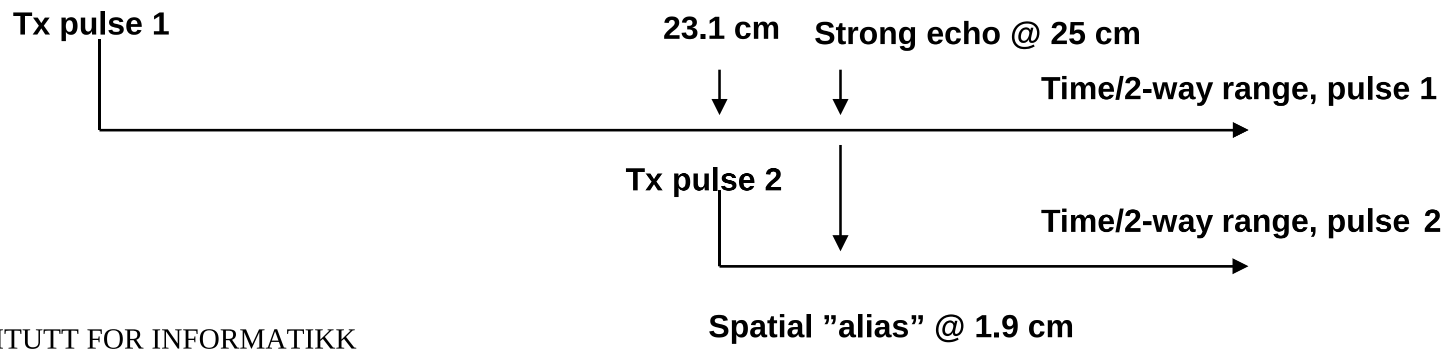
Max depth to image

- Depth where attenuation reaches ~60 dB
  - Attenuation = $2d\cdot\alpha\cdot f$ => d = Attenuation/$(2\cdot\alpha\cdot f)$

- Examples: 60 dB attenuation (α = 0.5 dB/cm/MHz):
  - f = 2.6 MHz: d = 23.1 cm depth
  - f = 3 MHz: d = 20 cm depth
  - f = 5 MHz: d = 12 cm depth
  - f = 10 MHz: d = 6 cm depth

Pulse Repetion Frequency

- Max depth, example: d=23.1 cm, c=1540 m/s
- Time to travel up and down: T = 2d/c = 0.3 ms
- Pulse Repetition Frequency PRF = 1/T = 3333 Hz
- PRF = Framerate for A- and M-modes
- Too high PRF => Spatial ”aliasing”:



Modeling of ultrasound propagation

- Lossless wave equation, u is displacement (or pressure):

$$\nabla^2 u - \frac{1}{c_0^2}\frac{\partial^2 u}{\partial t^2} = 0$$

- Standard viscous wave equation – attenuation prop. to ω^2

$$\nabla^2 u - \frac{1}{c_0^2}\frac{\partial^2 u}{\partial t^2} + \tau\frac{\partial}{\partial t}(\nabla^2 u) = 0$$

- Fractional wave eq. (Holm, Sinkus Journ. Acoust. Soc. Am, Jan 2010 + Holm, Näsholm. Journ. Acoust. Soc. Am, Oct. 2011.) – attenuation prop. to ω^{z0+1} as in medical ultrasound

$$\nabla^2 u - \frac{1}{c_0^2}\frac{\partial^2 u}{\partial t^2} + \tau^{z_0}\frac{\partial^{z_0}}{\partial t^{z_0}}(\nabla^2 u) = 0$$

- Derivatives of order z_0 – not an integer - fractional derivatives:
  http://blogg.uio.no/mn/ifi/innovasjonsteknologi/content/bedre-diagnose-ved-bedre-derivasjon

Resolution vs penetration

- Both radial and lateral resolution are improved with frequency
- Attenuation also increases with frequency, i.e. penetration falls with frequency
- ~optimum for an organ of a given size and depth:
  - 2.5 – 3.5 MHz cardiology
  - 5 – 7.5 MHz cardiology children; peripheral vessels
  - 3.5 – 5 MHz fetal imaging

1D probe for 2D imaging

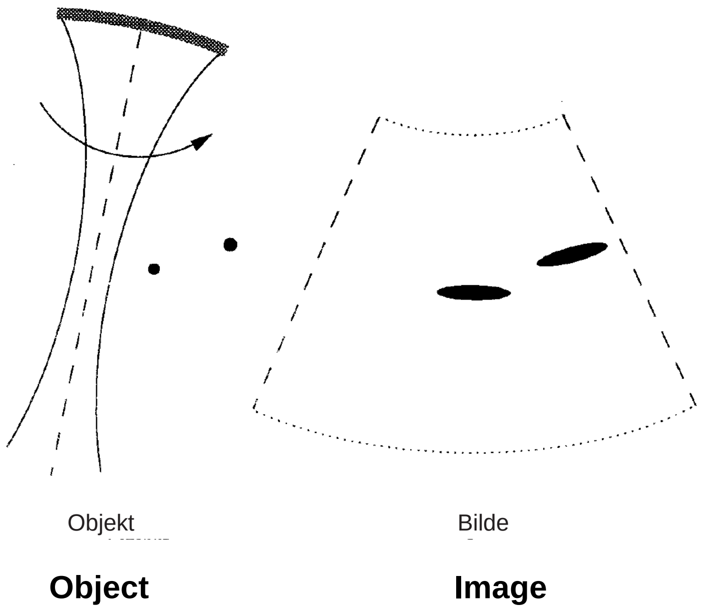
- 32-128 elements
- Beamforming in the azimuth plane for steering and control of the beam
- Acoustic lens for focusing in the elevation dimension

- Azimuth = in-plane = x
- Elevation = out-of-plane = y

Resolution

Two dimensions:

1. Radial or depth resolution
2. Azimuth or lateral resolution – orthogonal to beam direction.
   - Usually hardest to improve, as illustrated



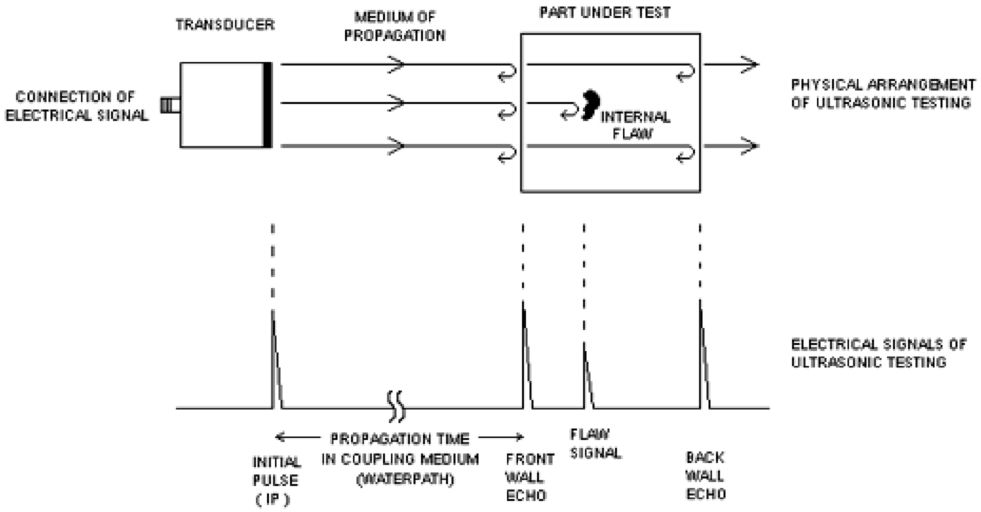
Ill.: B. Angelsen, NTNU

Radial resolution (as in sonar ...)

- Resolution = half the pulse length

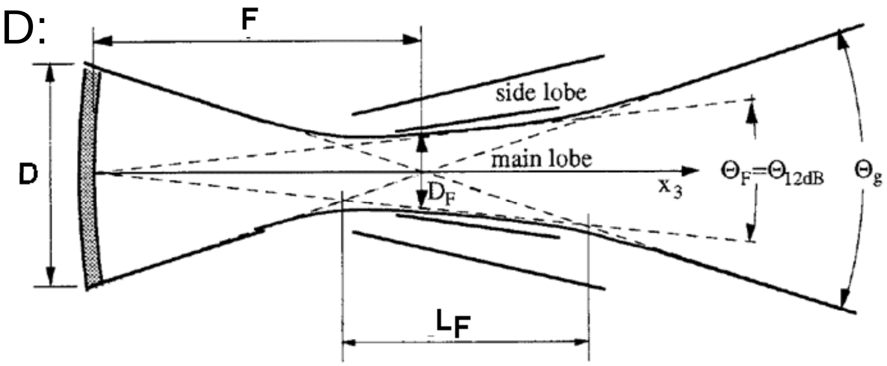
$$\Delta r = c\tau / 2 = c/(2B)$$

- Small value = good resolution = the ability to resolve two neighboring objects
- Also inverse proportional to bandwidth
- As bandwidth usually is a fraction of the center frequency, resolution is inverse proportional to centre frequency, e.g. B=50% of f_0
- Example f_0 = 3.5 MHz, B = 0.5 · 3.5 MHz => Δr = 1500 / (2*1.75e6) ≈ 0.43 mm



Lateral resolution

- Angular resolution for a source of size D:
  $$\Theta_F \approx \lambda / D$$
- At a distance F (small angles approx.):
  $$D_F \approx \Theta_F \cdot F = \lambda F / D = cF/(f_0 D)$$
- Res. best near the source (small F)
- Res. increases with frequency, f_0
- Ex: f_0=3.5 MHz, $\lambda=c/f_0$= 1500/3.5e6 ≈ 0.43 mm
- Cardiology: D=19 mm, Θ_F=0.43/19 = 0.023 rad = 1.3°. At depth 10 cm D_F=0.023*100 = 2.3 mm
- Abdominal: D=40 mm => Θ_F=0.62°
- Radial res. usually much better than lateral res. D_F= 2.3 mm >> Δr = 0.43 mm



Non-linear acoustics

The velocity of sound, *c,* varies with the amplitude, *s:*

$$\frac{dx}{dt} = c(t) = c_0 + (1 + \frac{B}{2A})s(t)$$

- A and B are the 1.and 2. order Taylor series coefficients for the pressure. B/A is a measure of the non-linearity.
- s(t) = pressure = $p_0 + p_1(t)$
  - p_0 = 1 atmosphere
  - $p_1(t)$ = applied pressure variation (= ”signal”)
- Two sources of nonlinearity:
  - Inherent in the material’s properties (equation of state): B/2A
  - Due to convection: the ’1’, exists even if material nonlinearity, B/2A = 0

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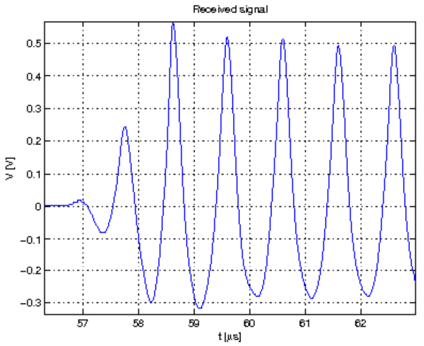
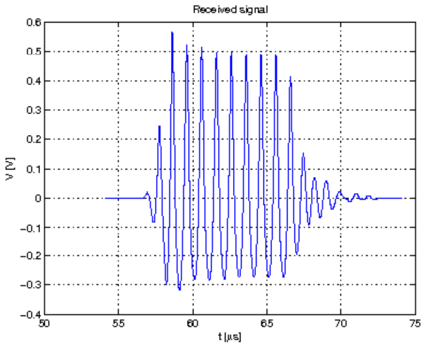
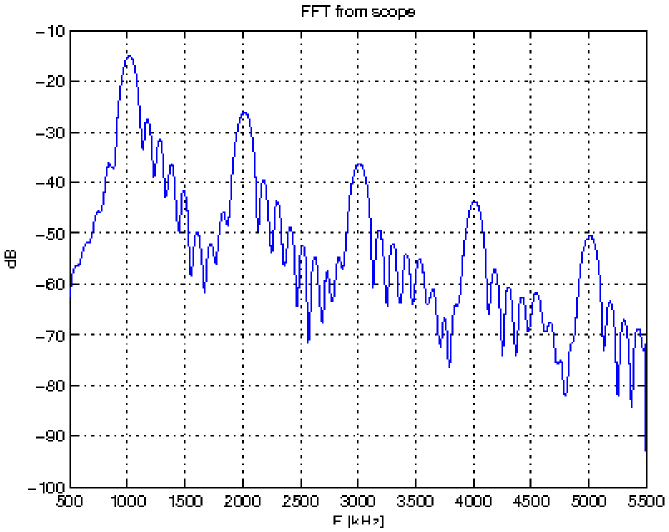
Nonlinear pulse shape measured in water tank in our lab





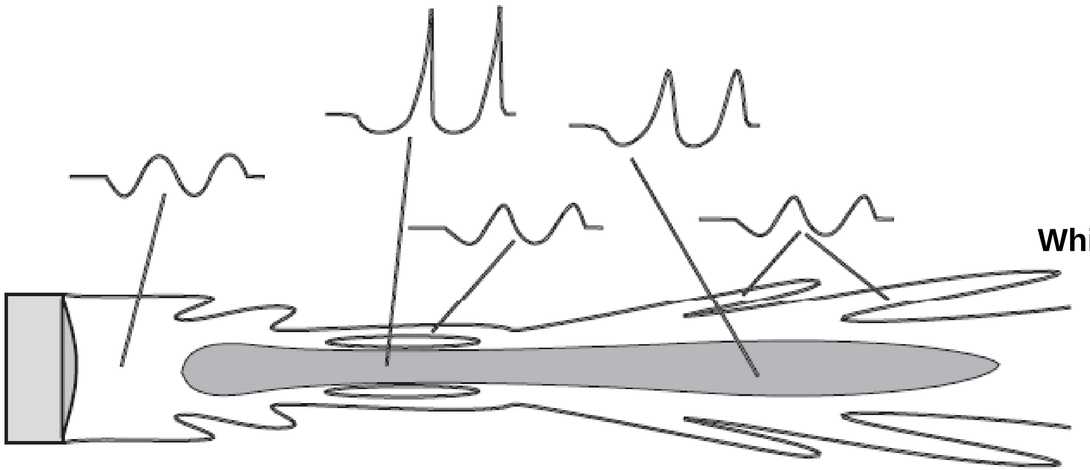


Fabrice Prieur, Sept. 2009

Non-linear acoustics

- Positive peaks propagate faster than negative peaks:
  - Waveform is distorted.
  - More and more energy is transferred to higher harmonics as the wave propagates.
  - Eventually a shock wave is formed.
- B/A:
  - Linear medium: B/A = 0
  - Salt water: B/A=5.2,
  - Blood and tissue: B/A=6,..., 10.

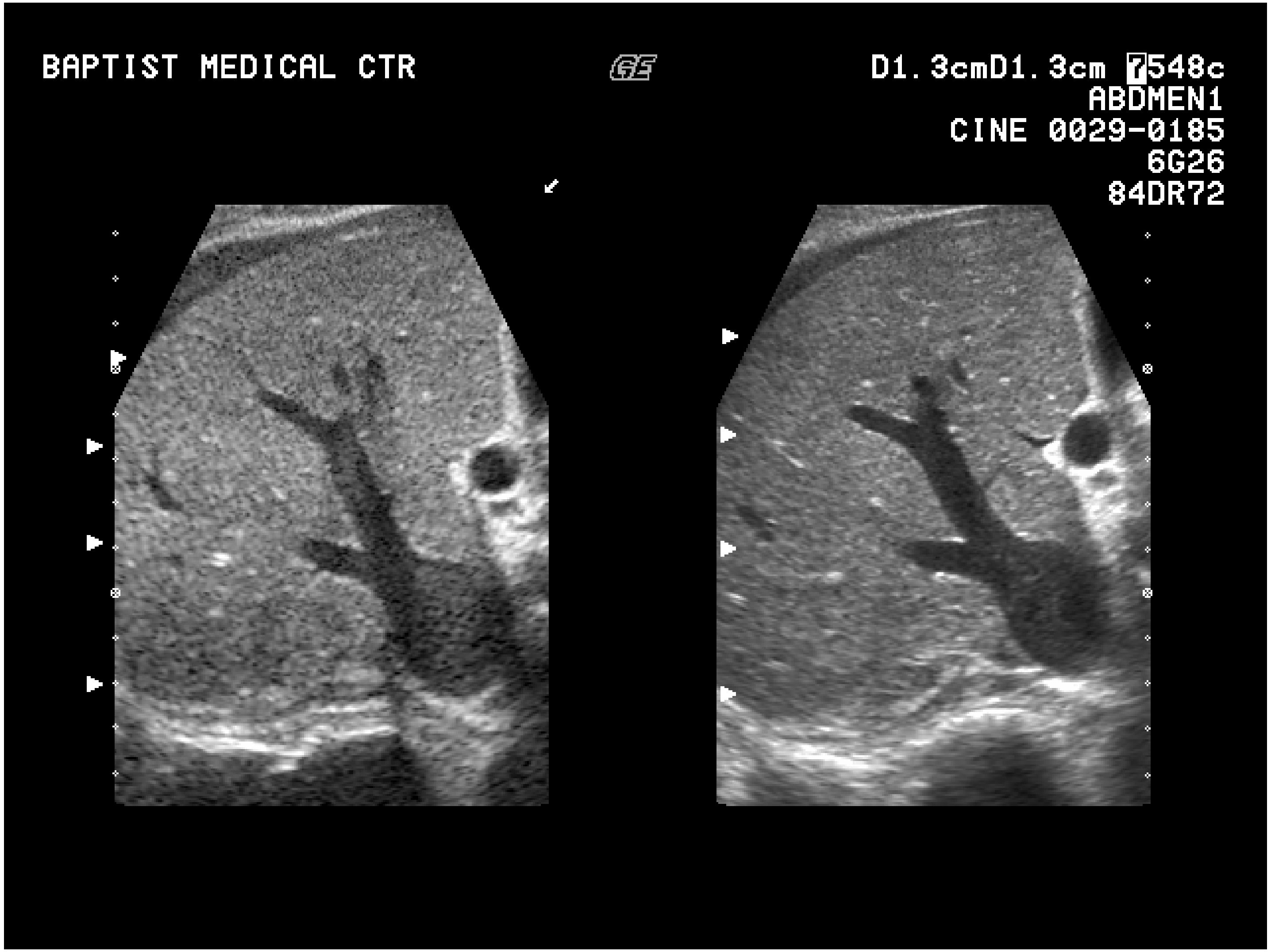
Non-linear acoustics



Whittingham, 2007

- Positive effect on images:
  - 2. harmonic beam is narrower => better resolution
  - Is not generated in sidelobes of 1. harmonic beam => less sidelobes
  - Is generated inside medium => avoids some of the aberrations and reverberations from chest wall
- Negative effect:
  - 2. harmonics attenuates faster => less penetration

Liver



Fundamental **2. harmonic**

Nonlinear acoustics, wave equations

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}p + \frac{\delta}{c_0^4}\frac{\partial^3 p}{\partial t^3} = -\frac{\beta}{\rho_0 c_0^4}\frac{\partial^2 p^2}{\partial t^2}$$

- Westervelt equation: p is pressure, c_0 is speed of sound, ρ_0 is density, δ is loss factor, β =1+B/A is nonlinearity coefficient
- Viscous loss, attenuation prop to ω^2, good for water and air, not so good for medical ultrasound
- Prieur, Holm, ”Nonlinear acoustics with fractional loss operators,” Journ Acoust Soc Am, 2011 - other powers than 2

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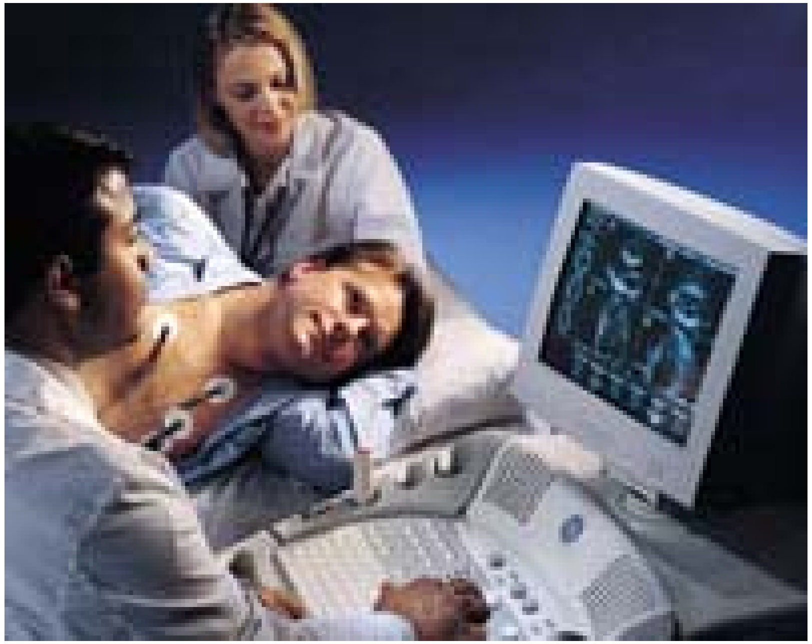
3. **Imaging modes**
4. Ultrasound instruments
5. Probe types and image formats



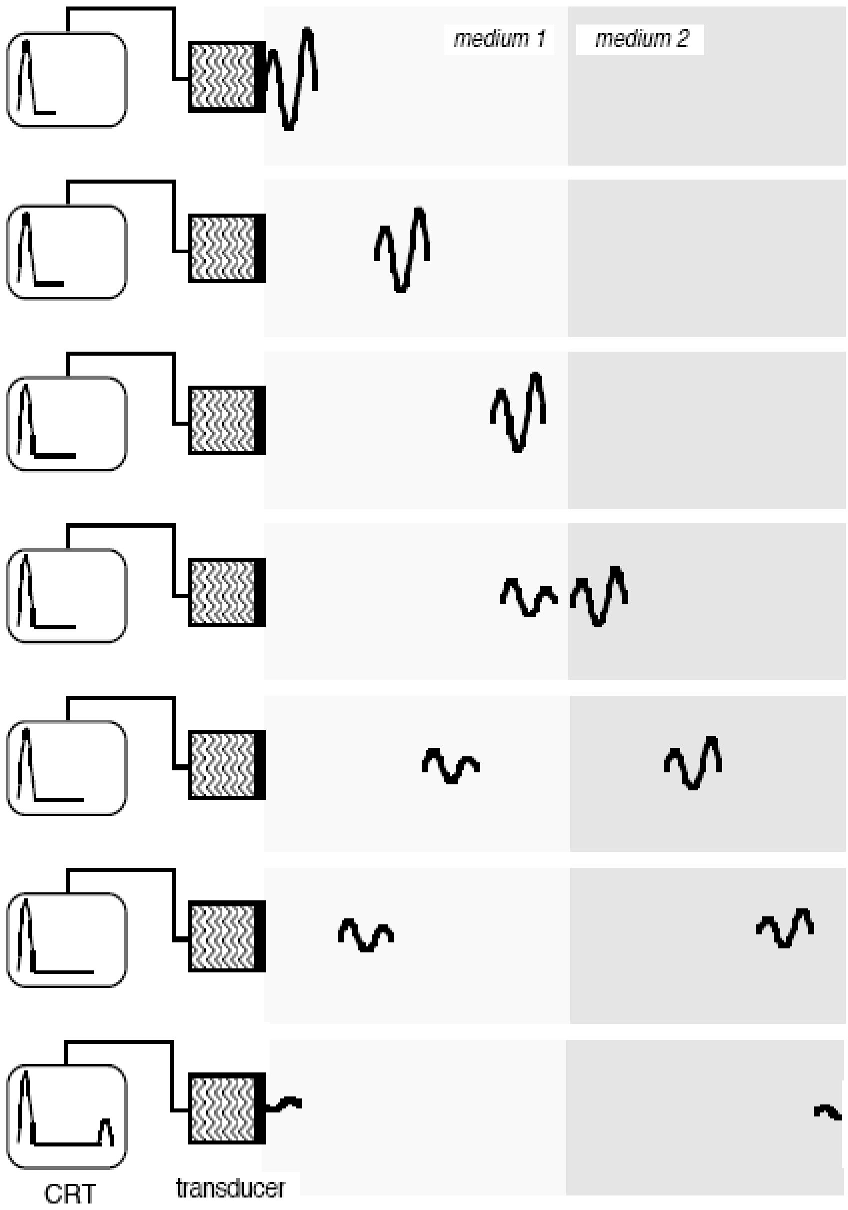
Medical Ultrasound Scanner

- Imaging modes:
  - A-mode (A = amplitude)
  - M-mode (M = motion)
  - B-mode 2D (B = brightness)
    - » Harmonic imaging – octave mode
- Doppler modes:
  - Doppler spectrum
  - Color doppler
  - (Strain)

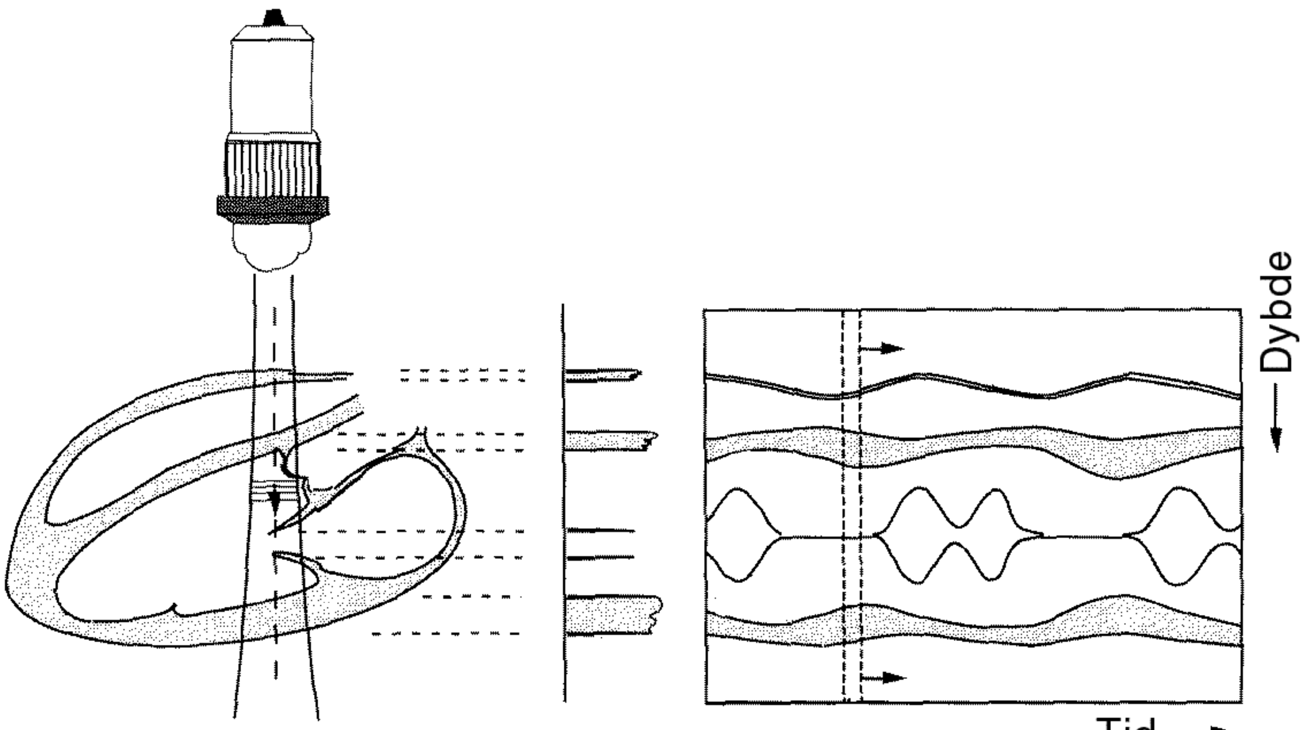
A-scan (obsolete)

- ***Figure 1** The pulse-echo principle is used to produce an ultrasound A-scan.*
- *A pulse is emitted from the transducer at the same time as a dot is set in motion from left to right on the A-scan screen.*
- *When an echo reaches the transducer, the received signal causes a vertical deflection of the trace.*
- *The distance between deflections on the A-scan corresponds to the depth of the interface from the transducer.*

- Peter N Burns: INTRODUCTION TO THE PHYSICAL PRINCIPLES OF ULTRASOUND IMAGING AND DOPPLER, November 2005

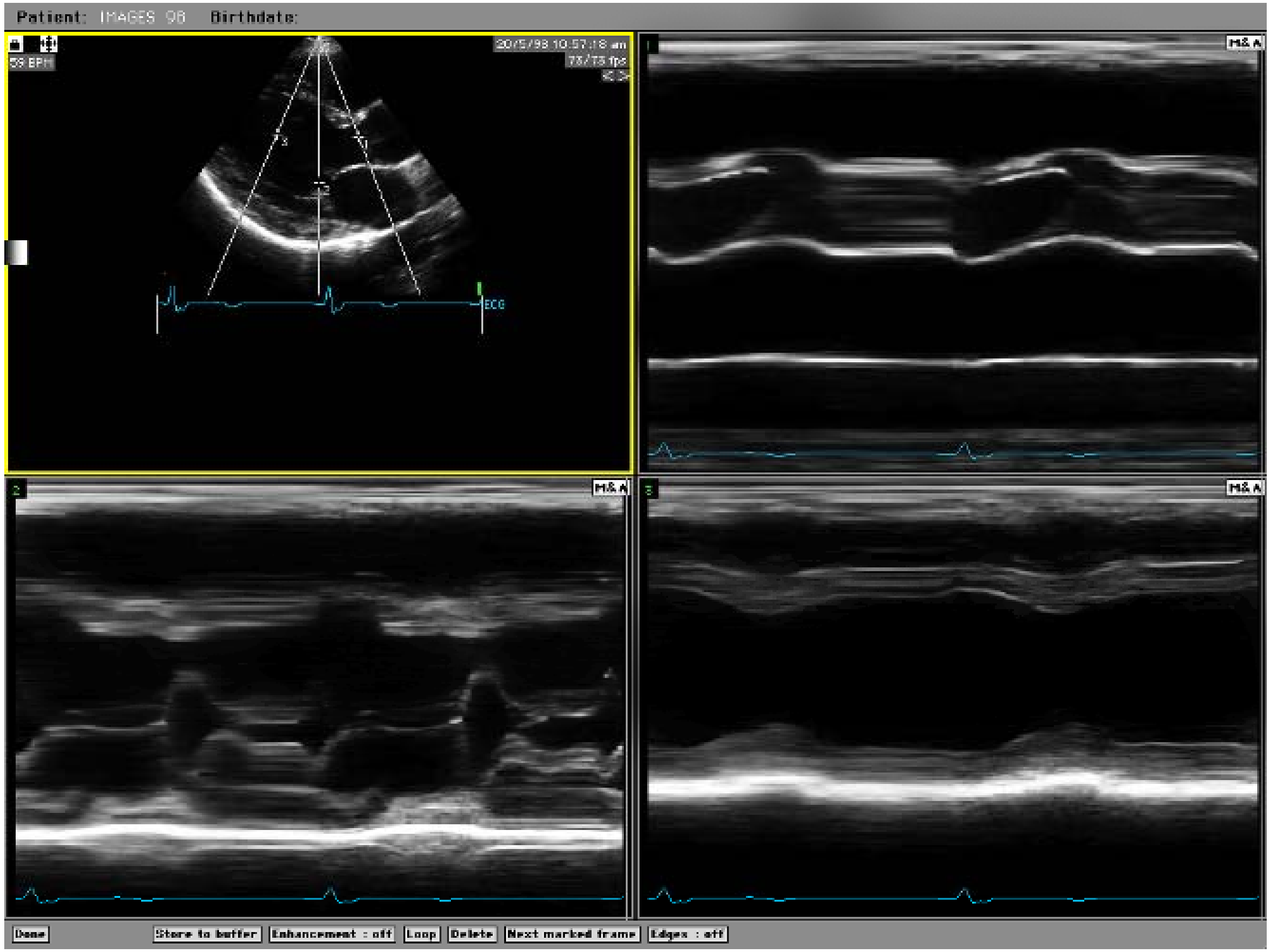


M-mode (M=motion) ≈ echo sounder

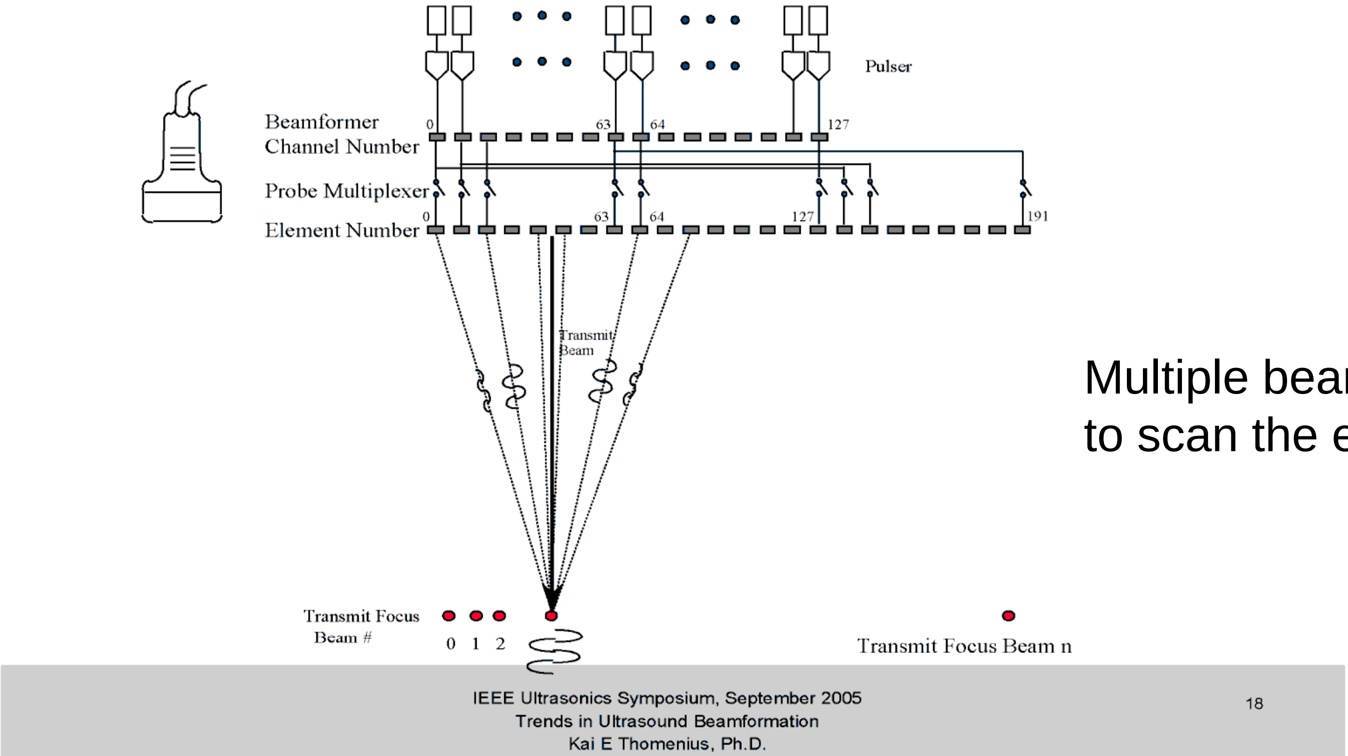


Ill.: B. Angelsen, NTNU

Heart
M-mode

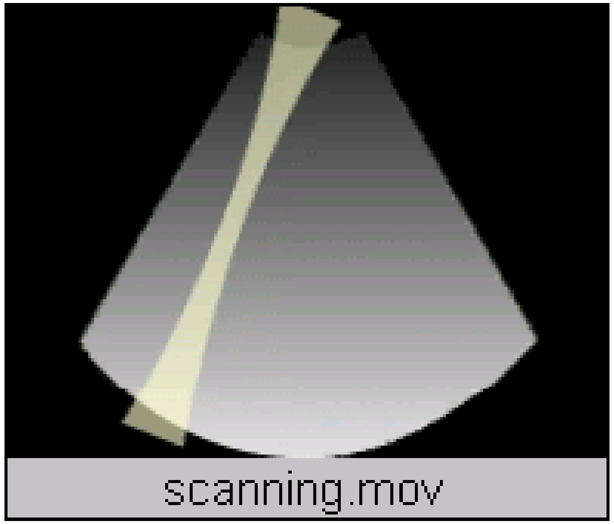

Patient: IMAGES 98 Birthdate:
ECG
Done
Store to buffer
Enhancement : off
Loop
Delete
Next marked frame
Edges : off

Linear Scan - Transmit Beamforming



Multiple beams are sent to scan the entire volume

Frame rate in 2D



- From before: A-scan:
  - Max depth d=23.1 cm, PRF = c/(2d)= 3333 Hz
- Typical beam width (cardiac probe):
  λ/d = 0.5mm/19mm = 0.026 rad = 1.5°
- Desired sector size: 90°
- Beam distance (typ 25-50% of beam width): 0.5°
- Number of beams per image: N=90°/0.5° = 180
- Frame rate: FR = PRF/N = 3333/180 = 18.5 Hz or fps (frames per second)
- Analog TV: 50 half-frames per second

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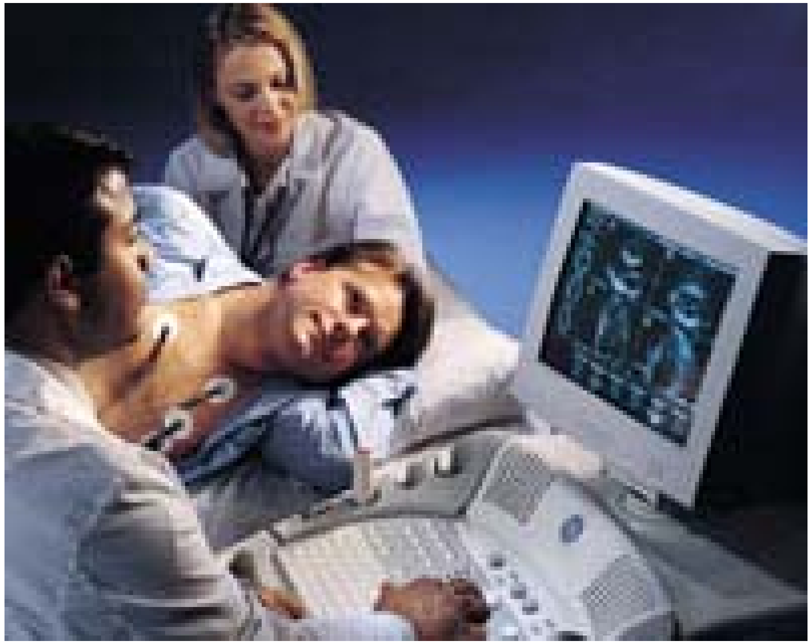
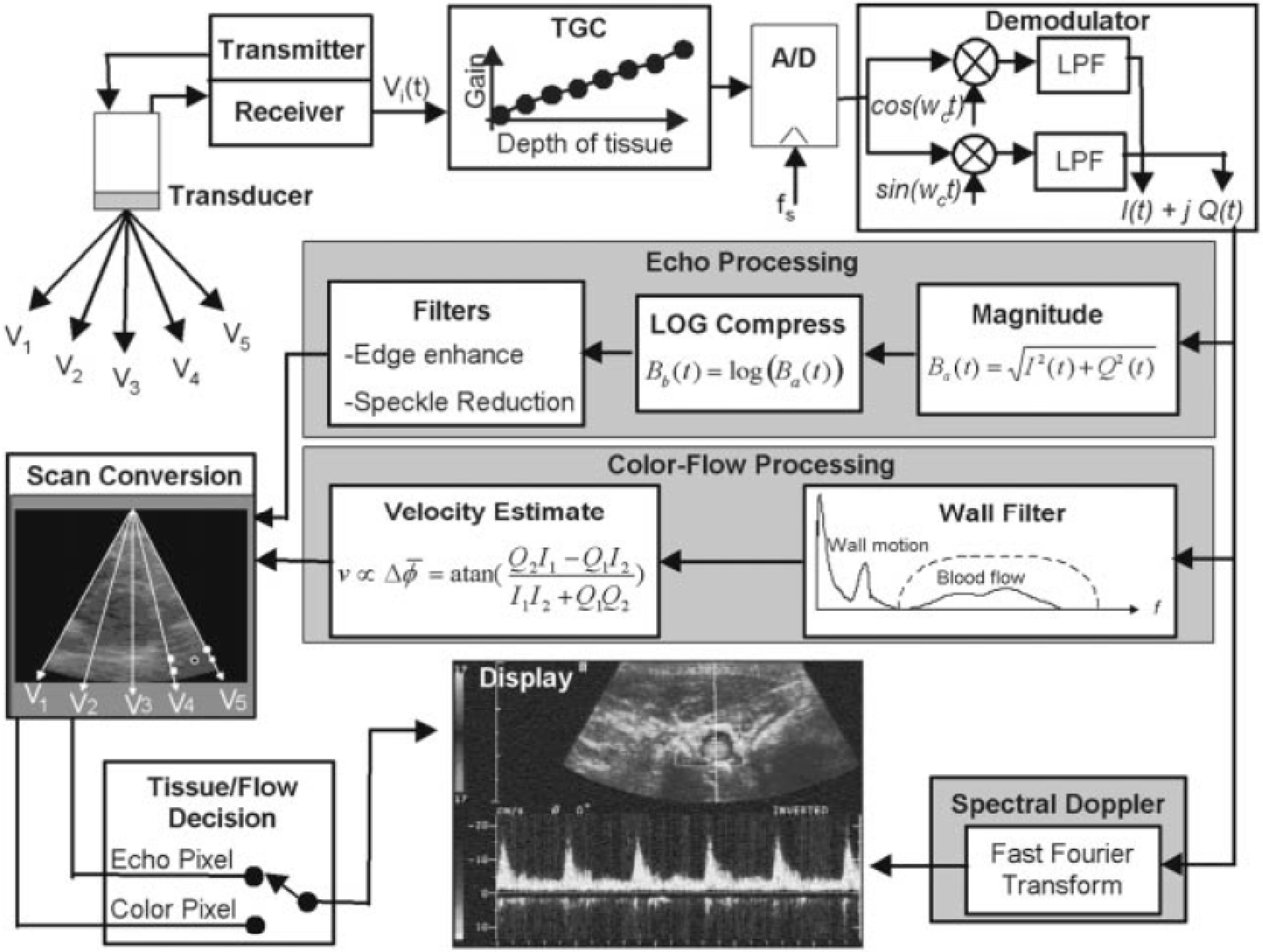




G. York, Y. Kim **,** Ultrasound Processing and Computing: Review and Future Directions Annu. Rev. Biomed. Eng. 1999

Medical Ultrasound Markets

- Cardiology (Heart) 25% of market
  - Field where Norwegian company Vingmed was established in the 80's as a startup from NTNU. Now GE Vingmed Ultrasound, center of excellence for cardiology ultrasound in GE Healthcare
  - Demo later in course
- Radiology (Inner organs) 40%
- Obstetrics/Gynecology 20%
- Niches
  - Vascular
  - Urology (B&K Medical, Denmark)
  - Surgery (Medistim AS and Sonowand AS)
  - Emergency medicine (driver for handheld ultrasound)
  - General practice
  - Dermatology (skin)
  - Veterinary
  - Small animals for medical experiments/testing
  - ...

High-end Ultrasound providers

- Philips
  - Acquired ATL ,Seattle WA, and HP/Agilent, Boston MA
- Siemens
  - Acquired Acuson, Silicon Valley
- GE Healthcare
  - Acquired Vingmed
- Japan: Toshiba, Hitachi, Aloka
- Emerging? France: Supersonic Imagine

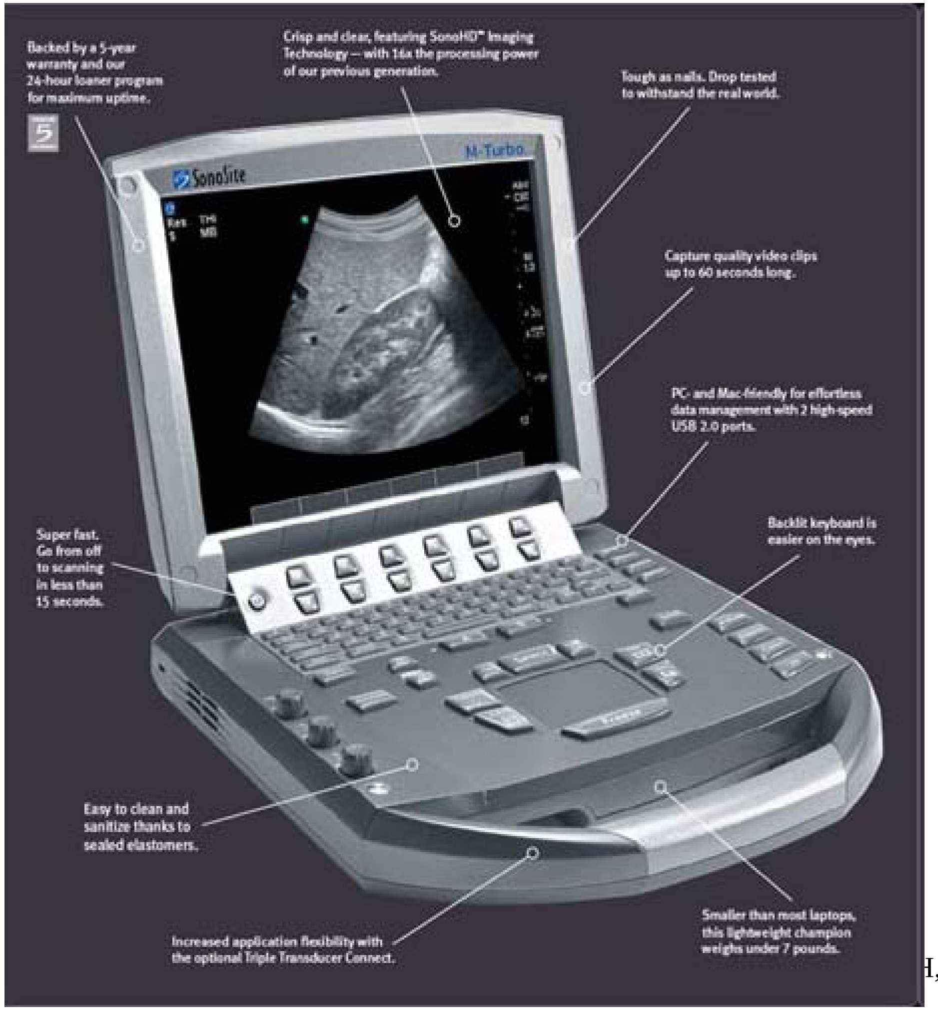
www.geultrasound.com

Laptop ultrasound

GE Logiq Book XP




Sonosite M-Turbo



Pocket Ultrasound: GE VScan

- Developed by GE Vingmed Ultrasound in Norway
  - For cardiologists or primary care
  - Liver, gall bladder, kidney, fetal position, cardiac, aorta
- No 14, Time Magazine's list The 50 Best Inventions of 2009
- Winner Årets ingeniørbragd, Norway 2009

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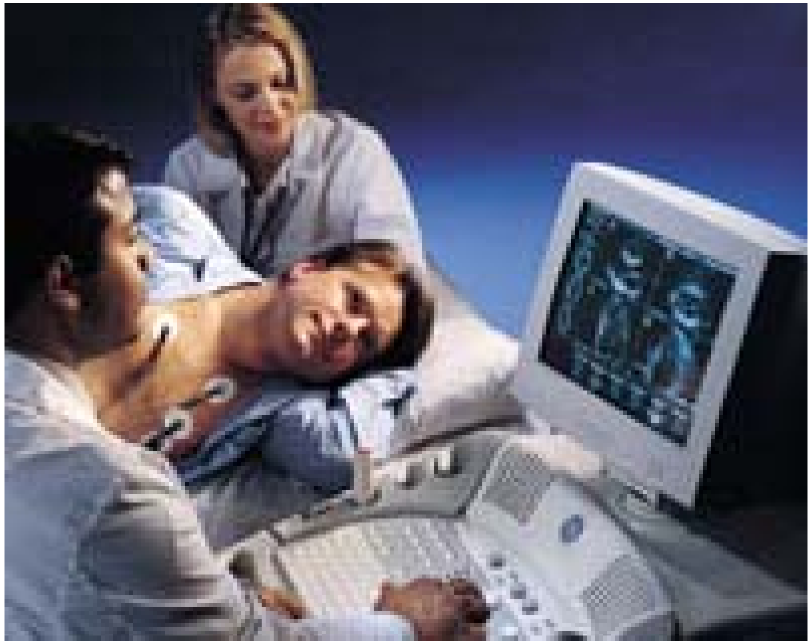
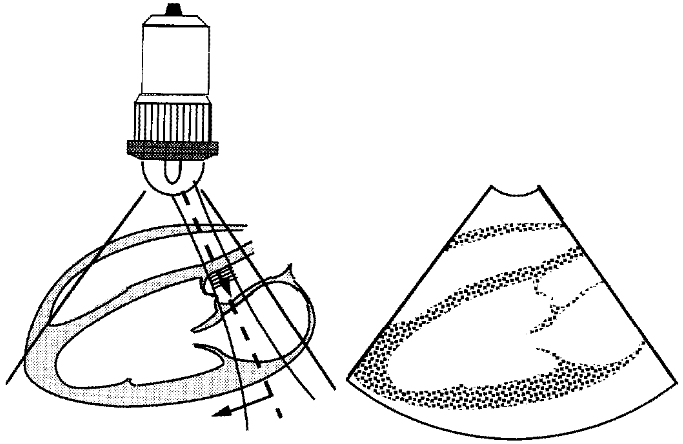


Sector scan

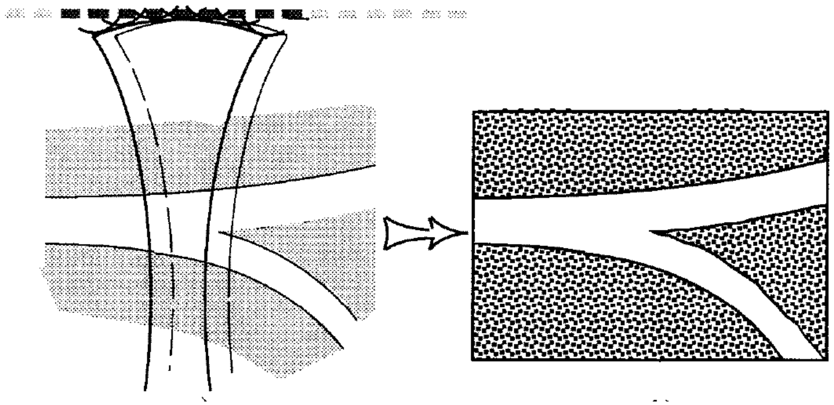
- Small footprint:
  - Access through ribs for cardiology
  - Typ: 19 mm adult, <12 mm pediatry
- Started with mechancially tilted probes (figure)
- Now: phased multi-element arrays and electronic tilting by means of digital delays



Ill.: B. Angelsen, NTNU

Linear scan

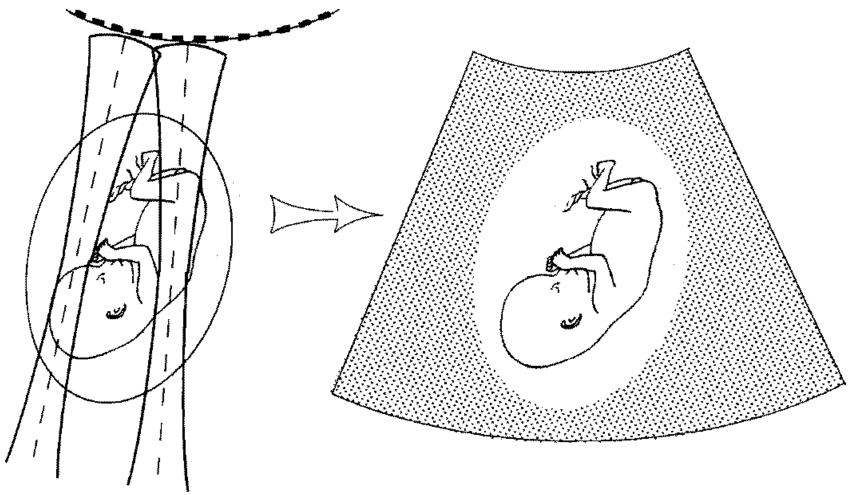
- Beam is moved along probe surface by switching elements in and out
- Can be done with simple electronics (important in the 80's)
- Suitable for organs with good access, e.g. external organs:
  - Artery in neck (halspulsåre)
  - Thyroid (Skjoldbrukskjertel)
  - Muscles, tendons



Ill.: B. Angelsen, NTNU

Curvilinear scan

- Beam is scanned along probe surface like linear scan
- Results in a large sector imaged with moderate requirements on access
- Used for
  - Fetal imaging
  - Internal organs: kidney, liver ...



Ill.: B. Angelsen, NTNU

Bioeffects and Safety

- Thermal effects: heating of muscles, tendons (physiotherapy)
- Mechanical effects: crushing of kidney/gall stones, surgery
- Every instrument displays TI and MI
- TI – Thermal Index: estimate of heating in hottest part of beam
  - TIS - Thermal Index Soft tissue: the most usual one
  - TIB - Thermal Index Bone: for bone in focal point (fetal scan)
  - TIC - Thermal Index Cranial: bone at probe surface (cranial imaging)
  - TI <1.5 centigrade is considered safe regardless of exposure time
- MI - Mechanical Index. $MI = p_-/f^{0.5} < 1.9$
  - Risk of cavitation (sometimes called cavitation index)
  - Peak negative pressure in MPa
  - Frequency in MHz

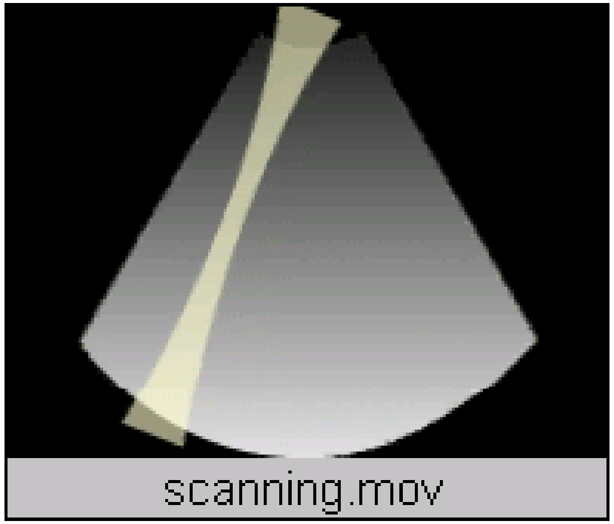
Factors which determine frame rate

- Depth where attenuation reaches ~60 dB
  - Attenuation = $2d \cdot \alpha \cdot f$
  - Example: 60 dB attenuation (α = 0.5 dB/cm/MHz):
    - » f = 2.6 MHz: d = 23.1 cm depth
- Speed of sound
- Number of transmit beams in M-, 2-D, or 3-D modes
- Recap 1-D and 2-D framerate on next slides

Pulse Repetion Frequency

- Max depth, example: d=23.1 cm, c=1540 m/s
- Time to travel up and down: T = 2d/c = 0.3 ms
- Pulse Repetition Frequency PRF = 1/T = 3333 Hz
- PRF = Framerate for A- and M-modes

Frame rate in 2D



- Previous A-scan:
  - Max depth d=23.1 cm, PRF = c/(2d)= 3333 Hz
- Typical beam width (cardiac probe): λ/d = 0.5mm/19mm = 0.026 rad = 1.5°
- Desired sector size: 90°
- Beam distance (typ 25-50% of beam width): 0.5°
- Number of beams per image: N=90°/0.5° = 180
- Frame rate: FR = PRF/N = 3333/180 = 18.5 Hz or fps (frames per second)
- Analog TV: 50 half-frames per second