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Introduction to Medical Imaging (5XSA0)

Medical image acquisition and analysis: Ultrasound

Arash Pourtaherian
(a.pourtaherian@tue.nl)

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Ultrasound Introduction – (1)

* **Advantages**
  - Non-invasive
  - Inexpensive
  - Portable
  - Real-time
* **Disadvantages**
  - Low signal-to-noise ratio
  - Speckle noise, imaging artifacts

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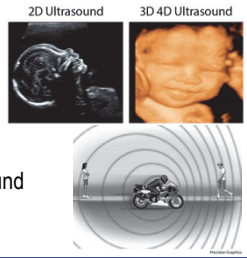
Ultrasound Introduction – (2)

* **Various clinical applications**
  - Echo ultrasound
    - Cardiac
    - Fetal monitoring
  - Doppler ultrasound
    - Blood flow
  - Contrast-enhanced ultrasound
    - Blood volume and perfusion
    - Cancer detection



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Ultrasound Introduction – (3)

* **What is ultrasound?**
  - High frequency sound (pressure) waves
  - Waves travel through tissue and with changes in the tissue acoustic properties, a fraction of pulse reflects
  - Echoes provide information about tissues along the path
  - Along a path, the depth of a structure is determined from the time between the pulse emission and echo return and the echo amplitude is translated to greyscale value.

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Outline

* **History**
* **Ultrasonic Waves and wave propagation**
* **Data acquisition**
* **Ultrasound Transducers**
* **Image reconstruction**
* **Image quality and artifacts**
* **Equipment and ultrasound applications**

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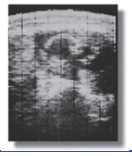
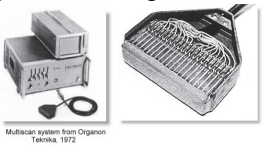
Ultrasound History – (1)

* **First clinical use in cerebral ventricles for locating brain tumors in 1942 (Dr. Karl Dussik)**
* **First greyscale image was produced in 1950**
  - in real time (15 fps) by Siemens Medical in 1965



Ultrasound History – (2)

* **First commercially available real-time array (20 sensors) in 1972 at Organon Teknika BV**

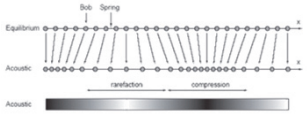


Multiscan system from Organon Teknika, 1972

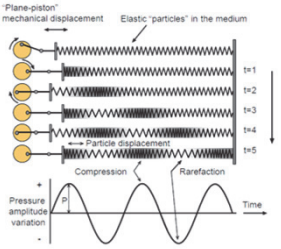
* **Popular technique since mid-70s**
* **Substantial enhancements since mid-1990**

Ultrasonic Waves – (1)

* **Progressive *longitudinal compression* waves**
  - Displacement of particles parallel to direction of wave
  - Transducer emits sound pulse that compresses material
  - Elasticity limits compression and extends to rarefaction
  - Rarefaction returns to a compression



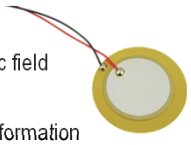
Ultrasonic Waves – (2)



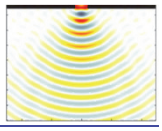
- Ultrasound waves in medicine > 2.5 MHz
- Humans can hear between 20 Hz and 20 kHz

Ultrasonic Waves – (3)

* **Piezoelectric crystals**
  - Deforms on application of electric field
    → Generates a pressure wave
  - Induces an electric field upon deformation
    → Detects a pressure wave
  - Such a device is called a *transducer*



  - Example of a produced pressure field



Wave propagation – (1)

* **Wave propagation in homogeneous media**
  - Characterized by medium specific acoustic impedance Z

$$Z = \rho c$$

ρ = mass density

c = acoustic wave velocity

$$\lambda = \frac{c}{f}$$

Substance	c (m/s)	$Z = \rho c$ (10^6 kg/m^2 s)
Air (25° C)	346	0.000410
Fat	1450	1.38
Water (25° C)	1493	1.48
Soft tissue	1540	1.63
Liver	1550	1.64
Blood (37° C)	1570	1.67
Bone	4000	3.8 to 7.4
Aluminum	6320	17.0

Wave propagation – (2)

* **Attenuation**
  - Energy loss in propagation because of viscosity → heat

Tissue	Attenuation α_0 (dB / cm.MHz)
Lung	41
Bone	20
Fat	0.63
Blood	0.85
Water	0.0022

  - α_0 = 0.5 dB/cm.MHz, f=2MHz → amplitude/2 after 6cm

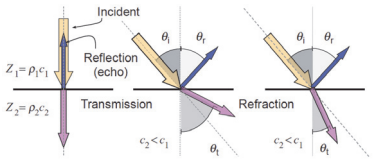
Wave propagation – (3)

* **Reflection and Refraction at smooth boundaries**
  - Reflection

$$\frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

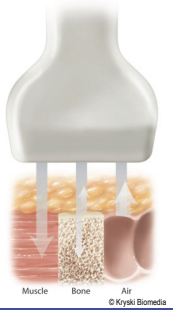
  - Refraction

$$\frac{\sin\theta_t}{\sin\theta_i} = \frac{c_2}{c_2}$$



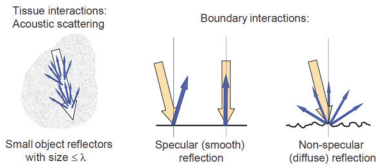
Wave propagation – (4)

- Intensity of reflected wave from a soft tissue interface is typically 0.1% of the incident intensity.
- The reflection on other interfaces, e.g. bones, can be stronger because of the higher $Z_2 - Z_1$.



Wave propagation – (5)

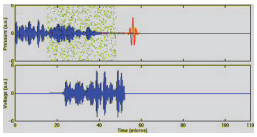
* **Scattering**
  - Arises from objects and interfaces that are about the size of the wavelength or smaller



Data acquisition A-mode

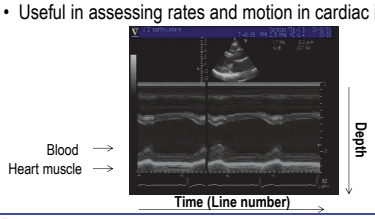
* **'A' for Amplitude**

$$\text{distance} = \frac{\text{time expired} \times \text{speed of sound}}{2}$$



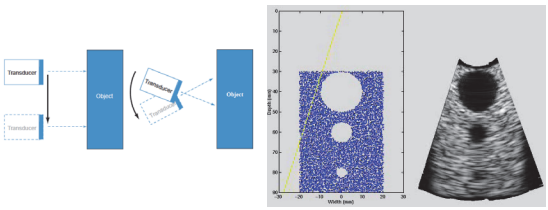
Data acquisition M-mode

* **'M' for Motion**
  - Repeated A-mode → greyscale image
    - Useful in assessing rates and motion in cardiac imaging



Data acquisition B-mode – (1)

* **'B' for Brightness**
  - An image is obtained by translating or tilting transducer



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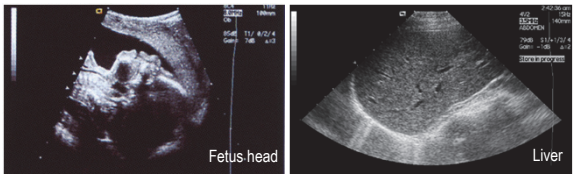
Data acquisition B-mode – (2)



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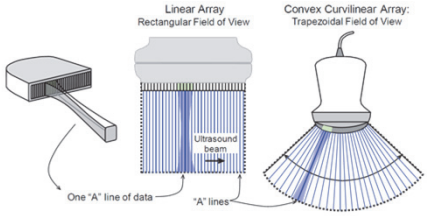
Ultrasound Transducers – (1)

* **Linear /curvilinear arrays**



64-256 piezoelectric (≈ 2x10mm) elements, activated in groups

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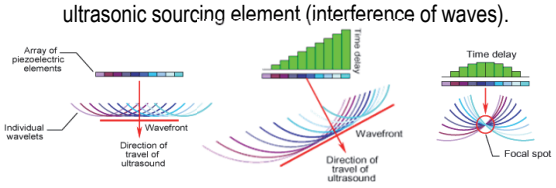
Ultrasound Transducers – (2)

* **Beam steering and focusing**
  - Applying differential delays in the excitation of each ultrasonic sourcing element (interference of waves).



beam steering *beam focusing*

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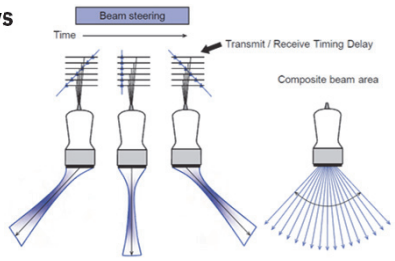
Ultrasound Transducers – (3)

* **Phased arrays**



30-128 (≈ 0.2x8 mm) elements activated together for focusing/steering

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Ultrasound Transducers – (4)

* **Array types**
  - **(a)** Linear sequential array
  - **(b)** Curvilinear array similar to (a), wider field of view
  - **(c)** Phased array, small footprint → cardiac imaging
  - **(d)** 1.5D elements in elevation allows for better focusing
  - **(e)** 2D array scans a 3D region

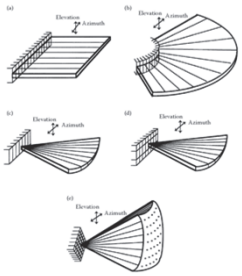

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Image reconstruction – (1)

* **Filtering**
  - Removing high frequency noise
* **Envelope detection**
  - Envelope ~ amplitude of signal ~ gray value in image

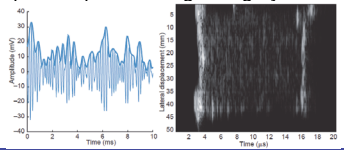


Image reconstruction – (2)

* **Attenuation correction (time-gain compensation)**
  - Different tissues ~ Different attenuation
    - Enabling the manual modification of gain at different depths

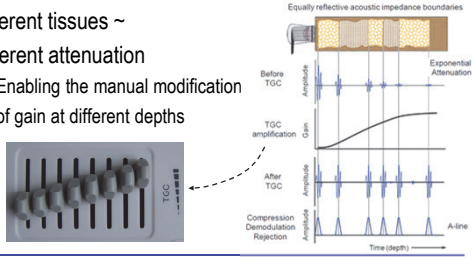
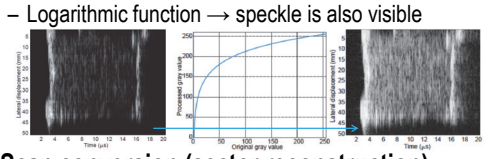


Image reconstruction – (3)

* **log-compression (gray scale transformation)**
  - Logarithmic function ⟶ speckle is also visible



* **Scan conversion (sector reconstruction)**
  - Interpolation: polar grid ⟶ rectangular grid
    - If image acquired by tilting the transducer instead of translating

Image reconstruction – (4)

* **Spatial compounding**
  - Several views acquired from the same target and combined to produce a single image

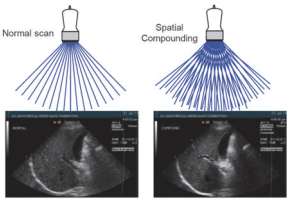


Image quality and artifacts – (1)

* **Speckle noise**
  - Overlapping of the echoes with scattered echoes results in a granular artifact known as speckle.

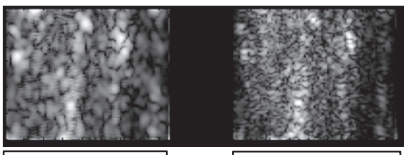


Image quality and artifacts – (2)

* **Shadowing**
  - Attenuation and reflection of the ultrasound beam cause intensity changes and shadowing.

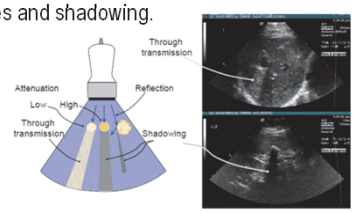


Image quality and artifacts – (3)

* **Anisotropy**
  - Acquired images depend on the position and orientation of the transducer with respect to imaged structures.

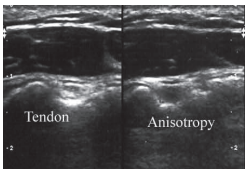
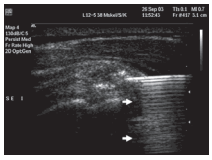
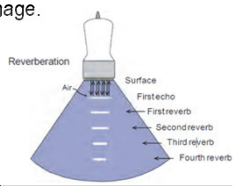


Image quality and artifacts – (4)

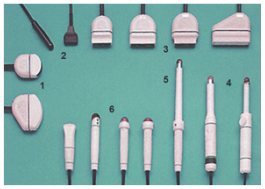
* **Reverberation**
  - Echoes bounce back and forth between the two boundaries and produce equally spaced signals of diminishing amplitude in the image.

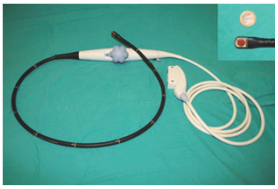




Equipment – (1)

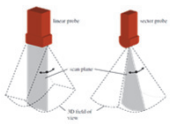
* **Special purpose transducers**

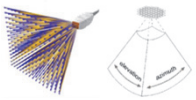




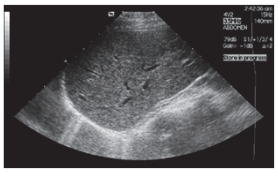
Equipment – (2)

* **Transducers for 3D imaging**
  - Mechanical motion of 1D array
  - 2D array (e.g. 64 x 64 crystals)

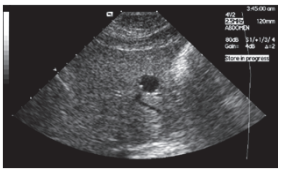




Ultrasound applications – (1)

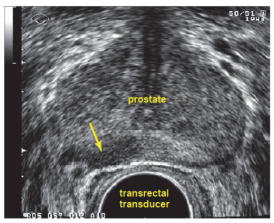


Normal liver

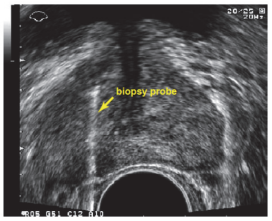


Liver with cyst

Ultrasound applications – (2)

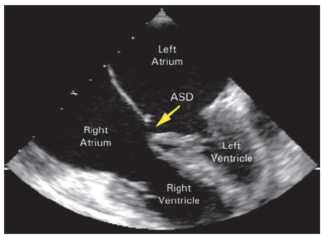


Prostate showing a hypoechoic lesion suspicious for cancer



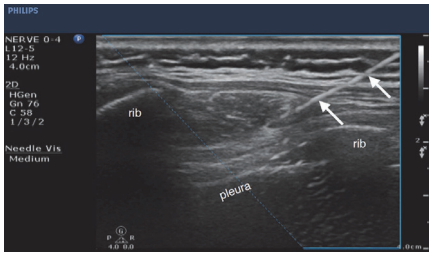
with biopsy needle

Ultrasound applications – (3)



Transesophegeal echocardiographic (TEE) image showing an atrial septal defect (ASD).

Ultrasound applications – (4)



Regional anesthesia (nerve block) Arrows = block needle

Ultrasound-guided needle intervention Automated needle tracking – (1)

* **Multi-fold coordination in handling devices and output**
  - Limited field of view in 2D ultrasound → Alignment of the needle and the visualization plane is challenging.
  - External guidance tools further complicate and raise costs.

* ***Image-based* needle tracking**
  - Without utilizing external tracking devices
  - No additional setup is required
  - Simplify manual skills because computer returns the best vision

Ultrasound-guided needle intervention Automated needle tracking – (2)

* **Minimum manual effort from the physician to find the needle**
  - Faster, easier and safer procedure
  - Within a few needle iterations, physician can identify target vessel/nerve and safely proceed the needle towards the target

* **Benefit: Only <u>half</u> of the anesthesia is required yielding <u>shorter</u> recovery time and <u>less</u> hospital days for the patient**

References

- J. T. Bushberg, "The Essential Physics of Medical Imaging," 3rd edition, 2012, Chapter 14.
- P. Suetens, "Fundamentals of Medical Imaging," 2nd edition, 2009, Chapter 6.