Ultrasound imaging (ultrasonography)

Outline

Basic principle

- Same idea of radar
- Acoustic properties of tissues

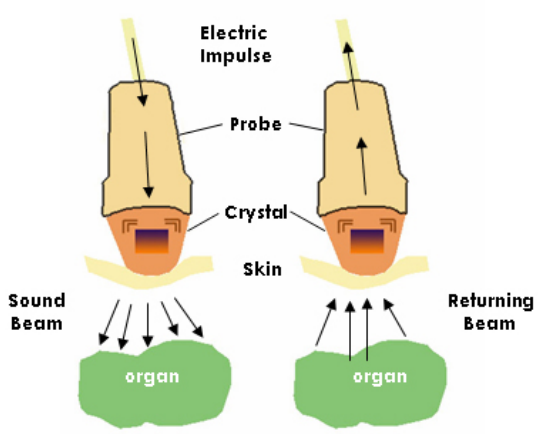
Details

- Ultrasounds generation/detection
- Interaction of ultrasounds with body
- Scanning modes, especially doppler

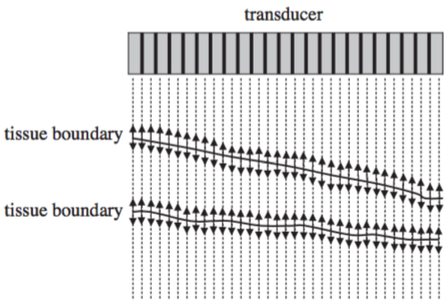
Clinical applications

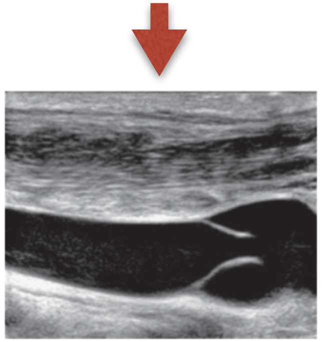
- Gynecology and obstetrics
- Cardiology

Same principle of **radar**



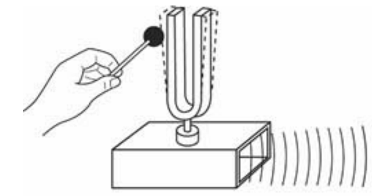
- A probe (*transducer*) sends **sound wave pulses** through body
- At each **boundary between tissues**:
  - small fraction of the wave is *reflected back* and *detected* by transducer (*echo*)
  - the remaining energy is *transmitted* past the boundary
- *Average* **speed of sound** in tissue is ≈1540 *m/s*
  - speed in air is ≈340 m/s
- *Depth of each boundary* is calculated from the **time between transmission and reception**
- The *stronger* the returning signal, the *brighter* it will be on the image



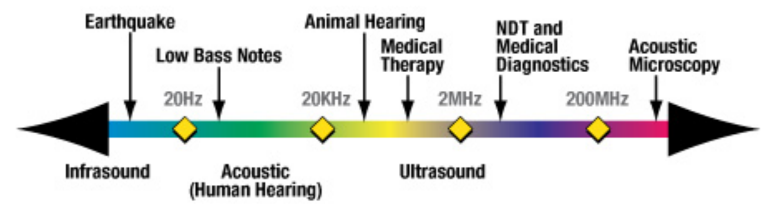


Notes

- **Sound** is a *pressure wave* which is created by a *vibrating object*



- **Ultra-high-frequency** sound waves (1-15 *MHz*) are used
  (human can hearing between 20 *Hz* to 20 *KHz*)



- Different **tissues** have different **properties**:
  - *Speed of propagation* in it (average is 1540 *m/s*)
  - *Acoustic impedance* (Z), i.e. attenuation
  - NB: values are similar but with **big exceptions**, e.g. *air* and *bone*

	$Z \times 10^5$ $(g\ cm^{-2}\ s^{-1})$	Speed of sound $(m\ s^{-1})$
Air	0.00043	330
Blood	1.59	1570
Bone	7.8	4000
Fat	1.38	1450
Brain	1.58	1540
Muscle	1.7	1590
Liver	1.65	1570
Kidney	1.62	1560

- **Various beam shapes** for specific purposes

- Very fast image acquisition (**real time**)
- It is <u>NOT</u> an *ionizing radiation*!

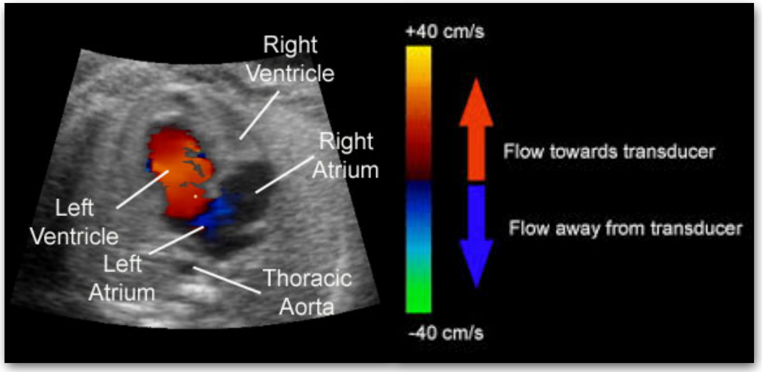
Clinical applications

Gynecology

- Especially useful during pregnancy to *image the fetus*
- *Non-invasive* for both mother and fetus

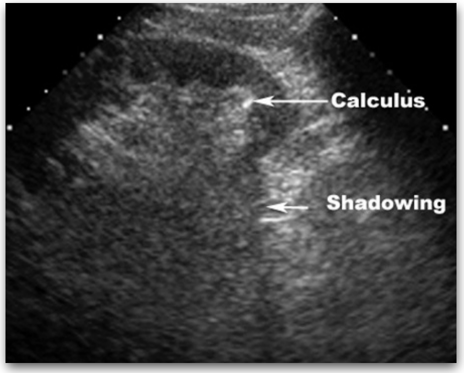
Cardiology

- The rapid acquisition allows **real time investigation** of *heart morphology and function* e.g. valve structure, ventricular function etc
- Also **blood flow** can be assessed



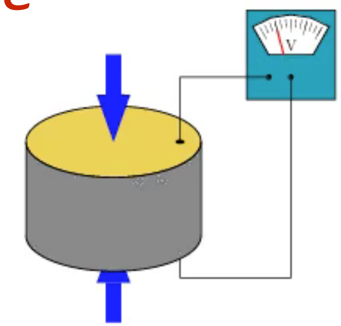
Diagnose *kidney stones* (alternative to CT)

- Cheap and noninvasive alternative to CT to easily spot the presence of kidney stones
- **Breathing etc** causes problems in other modalities



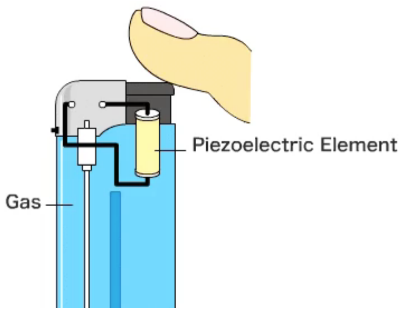
Ultrasounds generation/detection

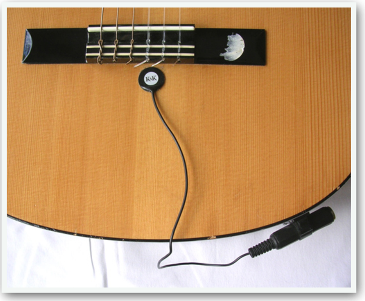
- **Piezoelectricity** = *"electricity resulting from pressure"*
  - Ability of certain materials to *generate electricity* in response to applied *mechanical stress*/pressure
  - Discovered in *1880* by **Jacques** & **Pierre Curie**



- **Piezoelectric transducer**: electronic device that…
  - On application of electric field ➜ deforms and generates a pressure wave
  - When hit/deformed by a pressure wave ➜ induces an electric field

- Piezoelectric transducers **found in everyday life**

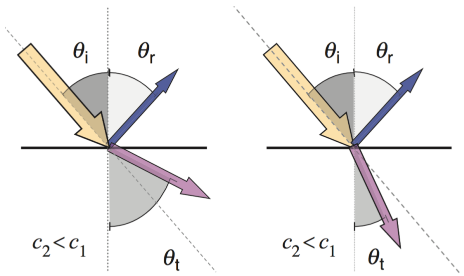


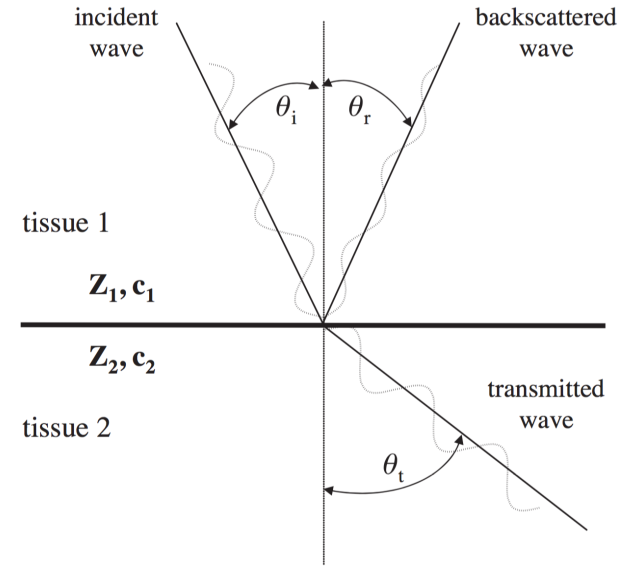


Interaction of ultrasounds with body (1/2)

Depends on **acoustic properties** of tissues

- **Boundary** between two tissues: (Z_1, c_1) and (Z_2, c_2)
- Relationship between *incidence* (θ_i), *reflected* (θ_r) and *refracted* (θ_r) *angles* described by **Snell's law**





Reflected and **transmitted waves**

- **Reflection**
  - $\theta_i = \theta_r$ and speed c_1 is unaltered
  - Non-perpendicular echoes are reflected away from the source (thus won't be detected)
- **Transmission**
  - Both *angle* and *propagation speed* are **changed**

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{c_1}{c_2}$$

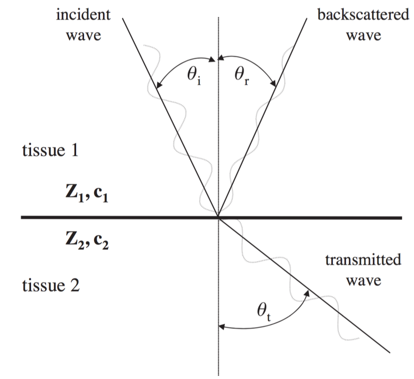
  - This phenomenon is called **refraction**

Interaction of ultrasounds with body (2/2)

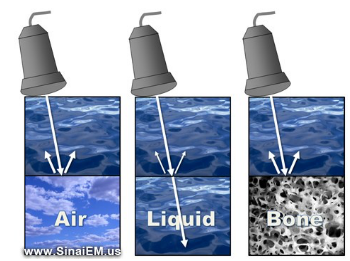
Reflection coefficient

- The **fraction** of sound intensity that is **reflected**

$$R_I = \frac{I_r}{I_i} = \frac{(Z_2 \cos\theta_i - Z_1 \cos\theta_t)^2}{(Z_2 \cos\theta_i + Z_1 \cos\theta_t)^2}$$

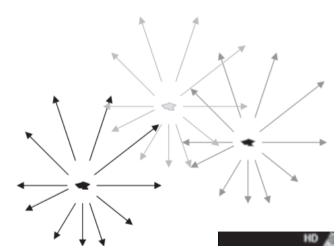


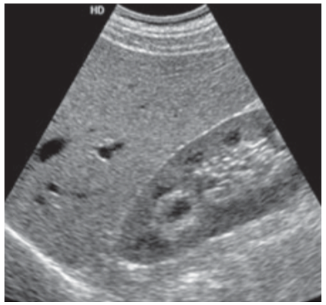
- Conservation of energy: $R_I + R_T = 1$
- *Examples* (assuming *perpendicular incidence*)
  - **Fat-muscle**: $R_I = (1.7-1.38)^2 / (1.7+1.38)^2 = 0.011$ ➜ ≈99% transmitted
  - **Muscle-air**: $R_I = (1.38-0.00043)^2 / (1.38+0.00043)^2 = 0.999$ ➜ ≈99% reflected
  - **Muscle-bone**: $R_I = (1.38-7.8)^2 / (1.38+7.8)^2 = 0.489$ ➜ ≈50% transmitted
  - NOTE$_1$: anatomy unobservable beyond an air-filled cavity (and bones)
  - NOTE$_2$: that's why *a gel is used* on the probe (to eliminate air pockets)!



Scattering at small structures

- When a wave hits structures with **size same/smaller than wavelength** ➜ wave is scattered in all directions
- The scattering of multiple objects generates complex **constructive/destructive interference** (*speckle* effect)

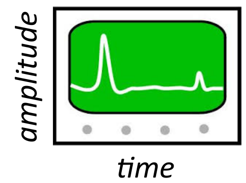


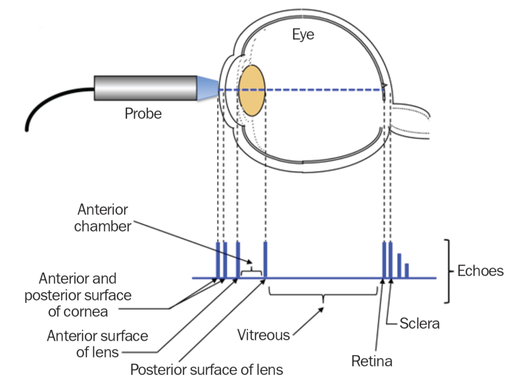


Scanning modes

A-mode *(Amplitude modulation)*

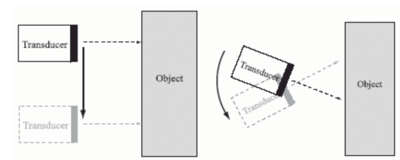
- Sends a *single pulse* and plots the amplitude of the echo as function of time
- Used to calculate lengths (mainly in *ophthalmology):*
  distance = (time elapsed * speed of sound) / 2

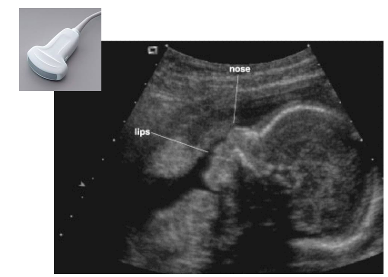


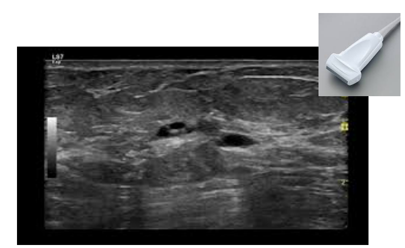


B-mode *(Brightness modulation)*

- *Most common* form of ultrasonography
- *2D images* created by steering the transducer
- *Brightness of a pixel* depends on the amplitude of the echo backscattered from that location

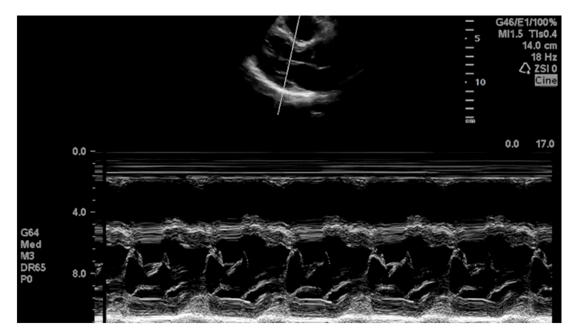






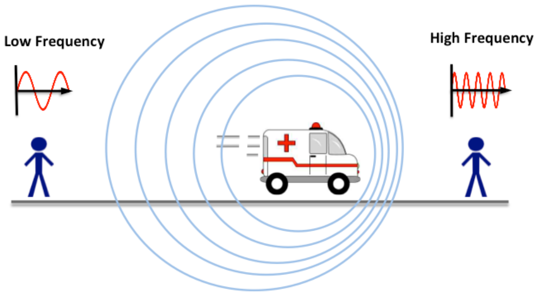
M-mode *(Motion mode)*

- Repeated A-mode or B-mode measurements
- Used mainly in *cardiology*

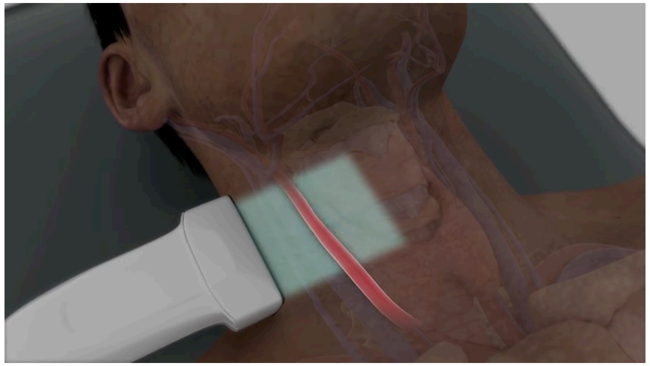


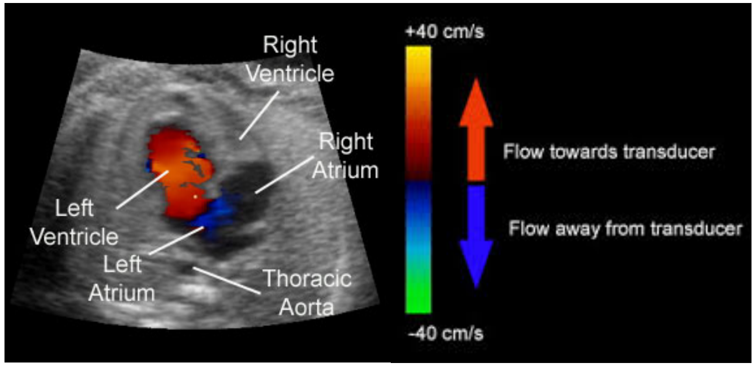
Doppler mode

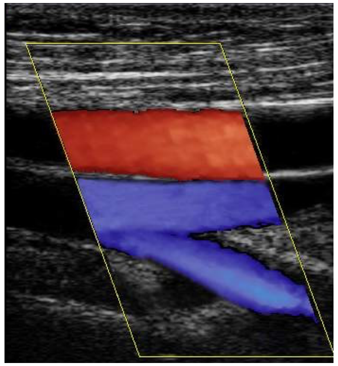
- What is the *doppler effect*?
  "…It's the **apparent change in the frequency** of a wave caused by relative motion between the source of the wave and the observer…"
- There's **no actual frequency change**, it's apparent
  - When the <u>source moves towards</u> the observer, each successive wave crest is emitted from a *position closer to the observer* than the previous wave
  - Each wave takes *slightly less time to reach the observer* than the previous one
  - Observer then *perceives a higher frequency*
  - Opposite when <u>source moves away</u>



Doppler effect to **measure blood flow**



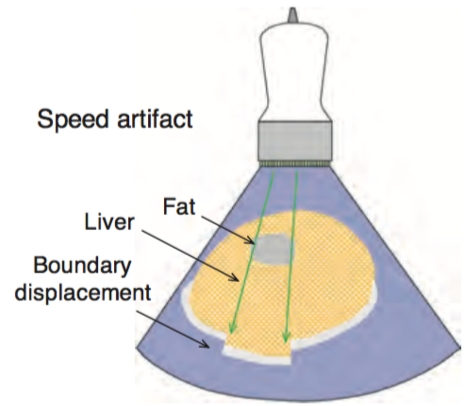


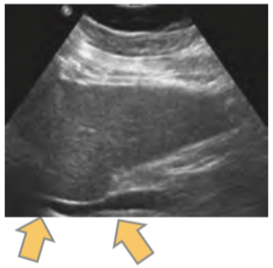


Main image artifacts

Speed displacement

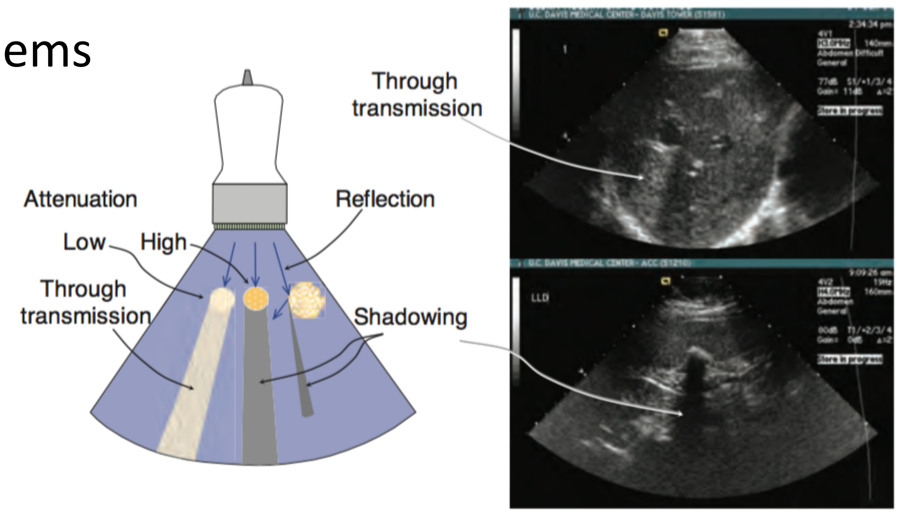
- *Variations in sound speed* in different tissues can cause **misplacement of the anatomy** (1540 *m/s* is only an average speed)
- Some echoes displaced from expected location in the image (discontinuities in borders)





Shadowing and **posterior enhancement**

- *Differences in attenuation* cause similar problems
- *Hypo-intensities* **behind structures that strongly absorb or reflect** sound waves
- Hyper-intensity areas arise from **increased transmission of sound** in objects having very low attenuation



NB: artifacts are not necessarily "bad" (e.g. *kidney stones* identified by artifact)

Summary

Pros

- **Noninvasive** and **not ionizing** radiation 
- **Low cost** and **high portability**
- Excellent temporal resolution (**real time**)

Cons

- Image quality: **noisy** and many **artifacts**
- Low **spatial resolution**

Applications

- Gynecology and obstetrics
  (only noninvasive modality to image fetuses)
- Cardiology
- Diagnose kidney stones