MIA – Medical Imaging Modalities

Master VIBOT – University of Girona

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Some definitions

- Medical Images:
  - Medical images are image **data** used in biomedical and health sciences
  - They can be either light images or non-light images.
  - They are daily used
    - For radiological diagnosis in radiology
    - For other medical fields (surgery, neurology, oncology, etc.)
    - For biomedical research and scientific discoveries

Some definitions

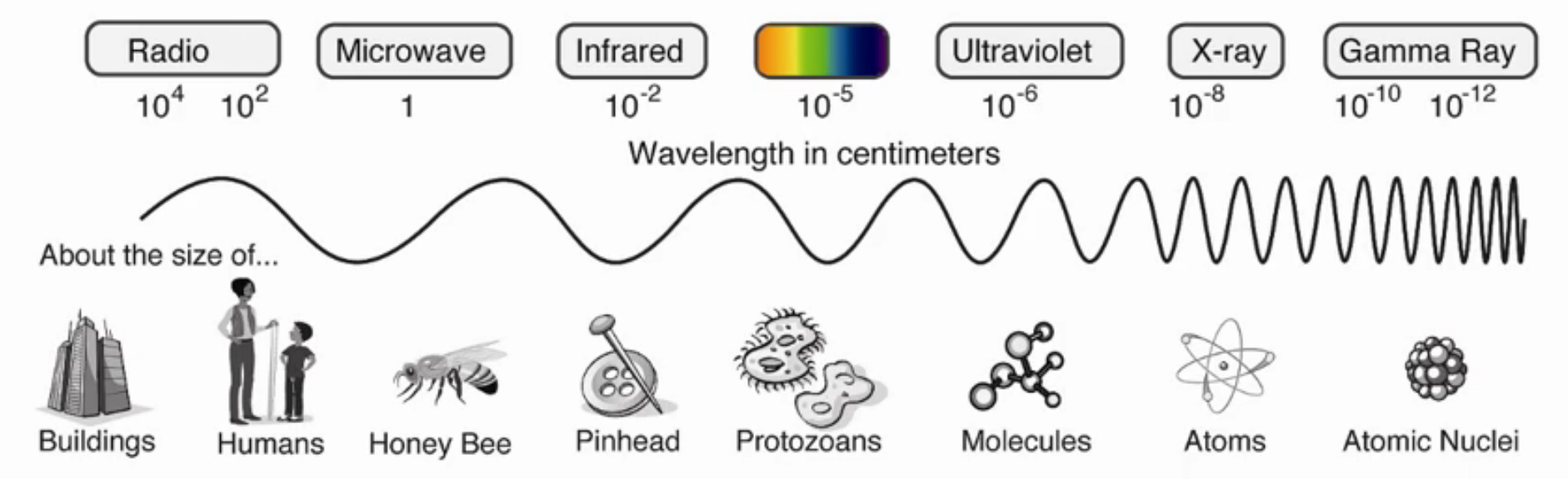
- Medical Imaging:
  - A technique and process used to **create images** of the **human body** (or parts and function thereof) for **clinical purposes**
  - A technical processing **to analyze/manipulate and operate** on medical images for clinical and research uses
  - Medical imaging is ontologically catalogued as a subfield of data or signal processing, an engineering discipline, rather than data management

Some definitions

- Medical Imaging Modalities:
  - Defined as a broad spectrum of medical devices and technologies which produces biomedical images
  - Modalities are used to observe and obtain information about human's internal structures for enhancing clinical diagnosis, aiding medical treatments, and support biomedical research
  - There are many classifications of medical imaging modalities:
    - According to the energy of the radiation source
    - According to the location of the radiation source
    - …

Medical Imaging: classification

- According to the energy of the radiation source

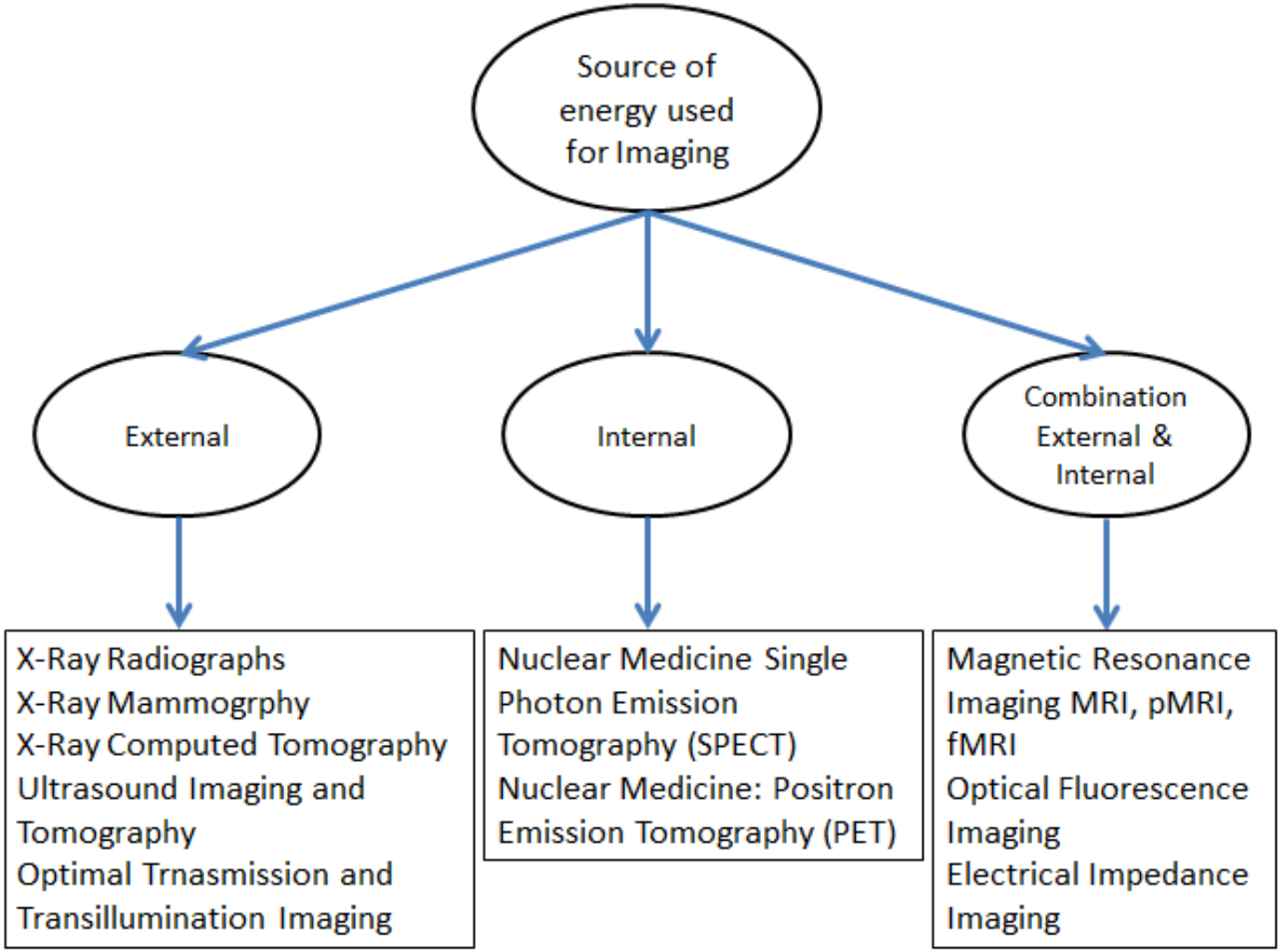


Medical Imaging: classification

- According to the wavelength being mapped
  - Optical
    - Fluoroscopy, Computed Tomography, Mammography, Tomosynthesis, Colonoscopy, Microscopy, Nuclear Medicine, …
  - Sounds (not electromagnetic!)
    - Ultrasound
  - Radiofrequency (RF) pulse
    - MRI
  - Thermal energy
    - Thermography, microwave, …

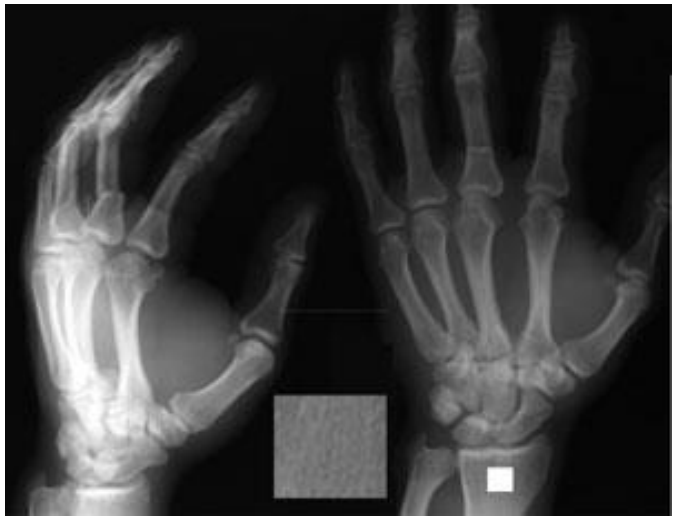
Medical Imaging: classification

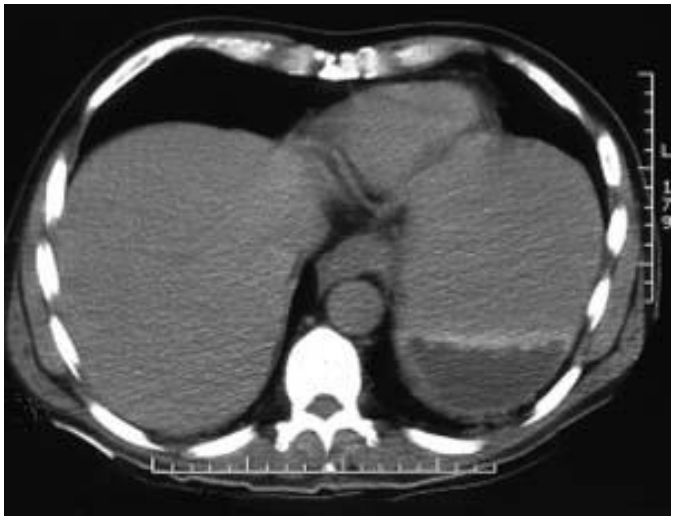
- According to the location of the radiation source

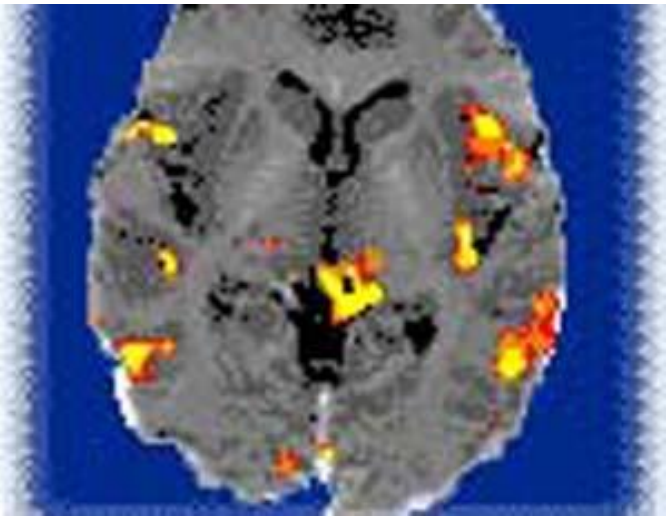


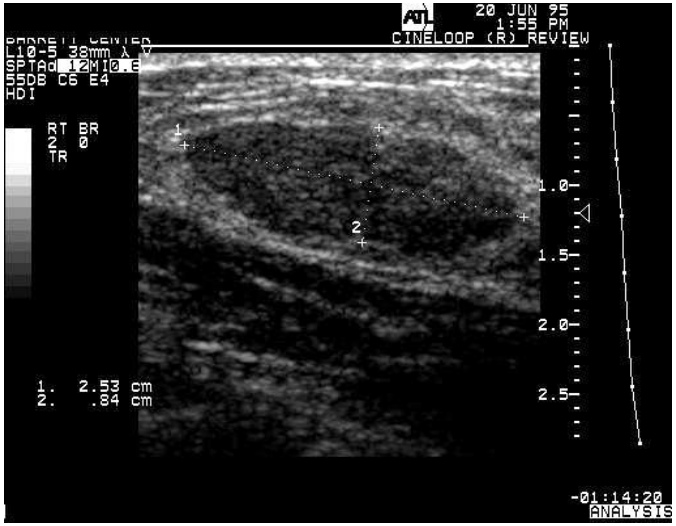
Medical Imaging: examples

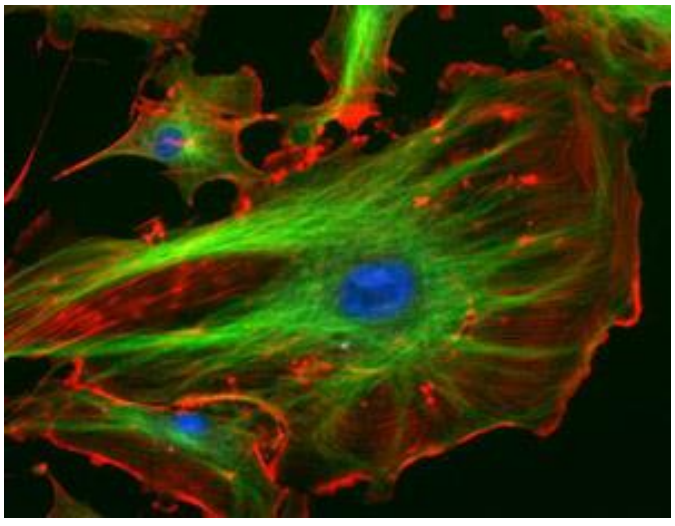
- Examples of medical images

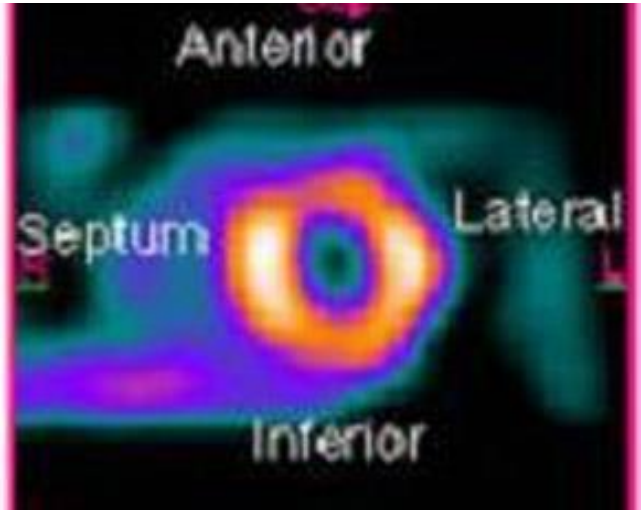












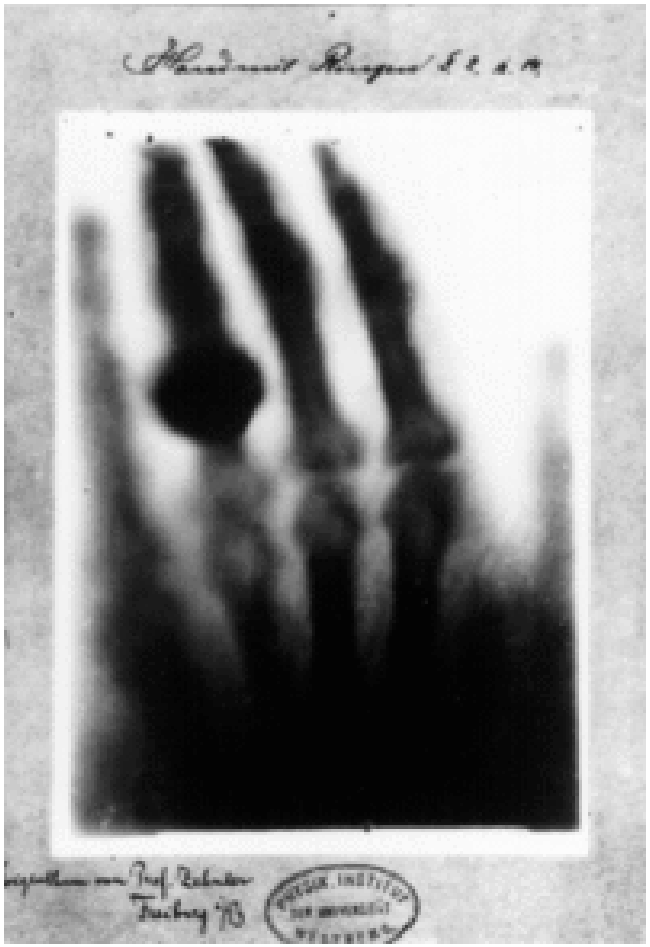
Medical Imaging: modalities

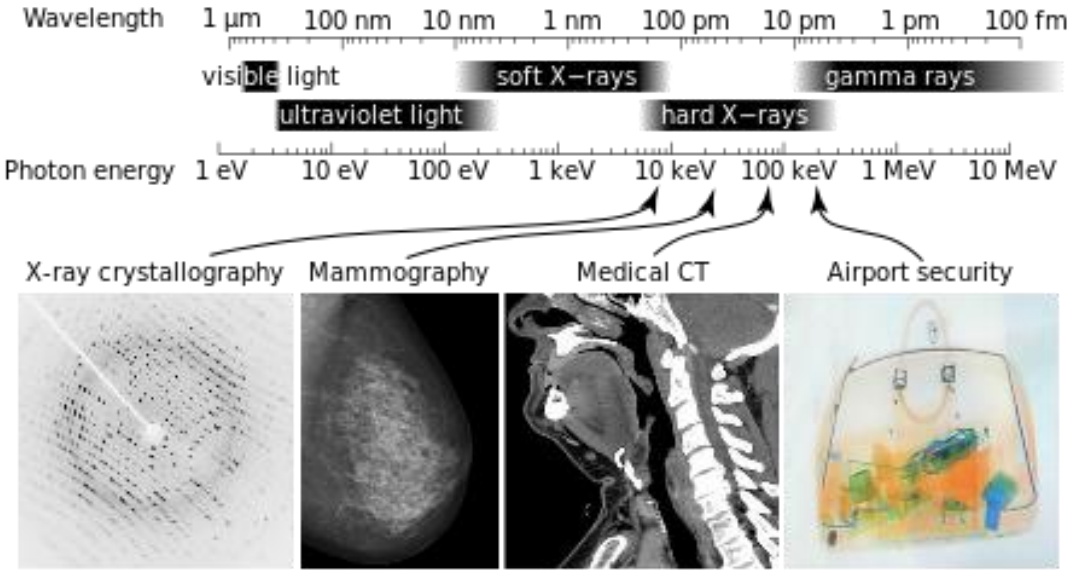
- Modalities:
  - X-Ray Imaging and Computed Tomography
  - Magnetic Resonance Imaging
  - Ultrasonic Imaging
  - Others (PET, SPECT, Fluorescence Microscope)

- General Image Characteristics:
  - Spatial Resolution
  - Signal-to-Noise Ratio
  - Contrast-to-Noise Ratio
  - Image Filtering
  - The Receiver Operating Curve

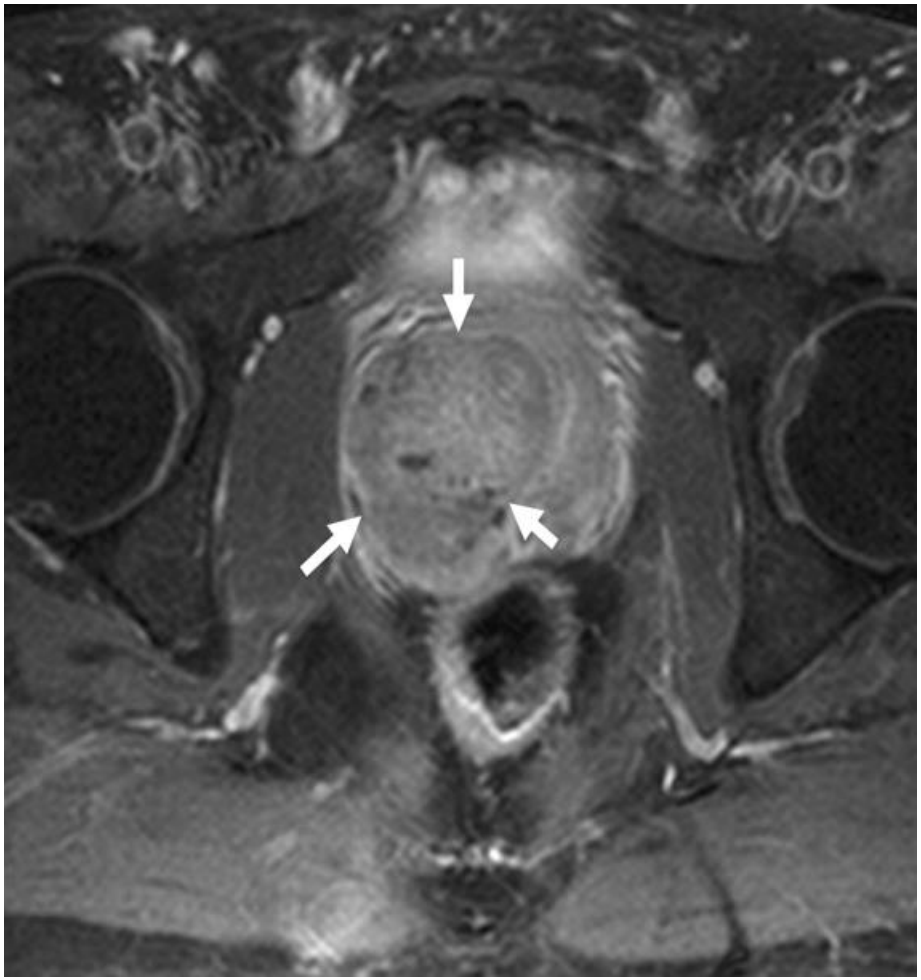
X-Ray Imaging

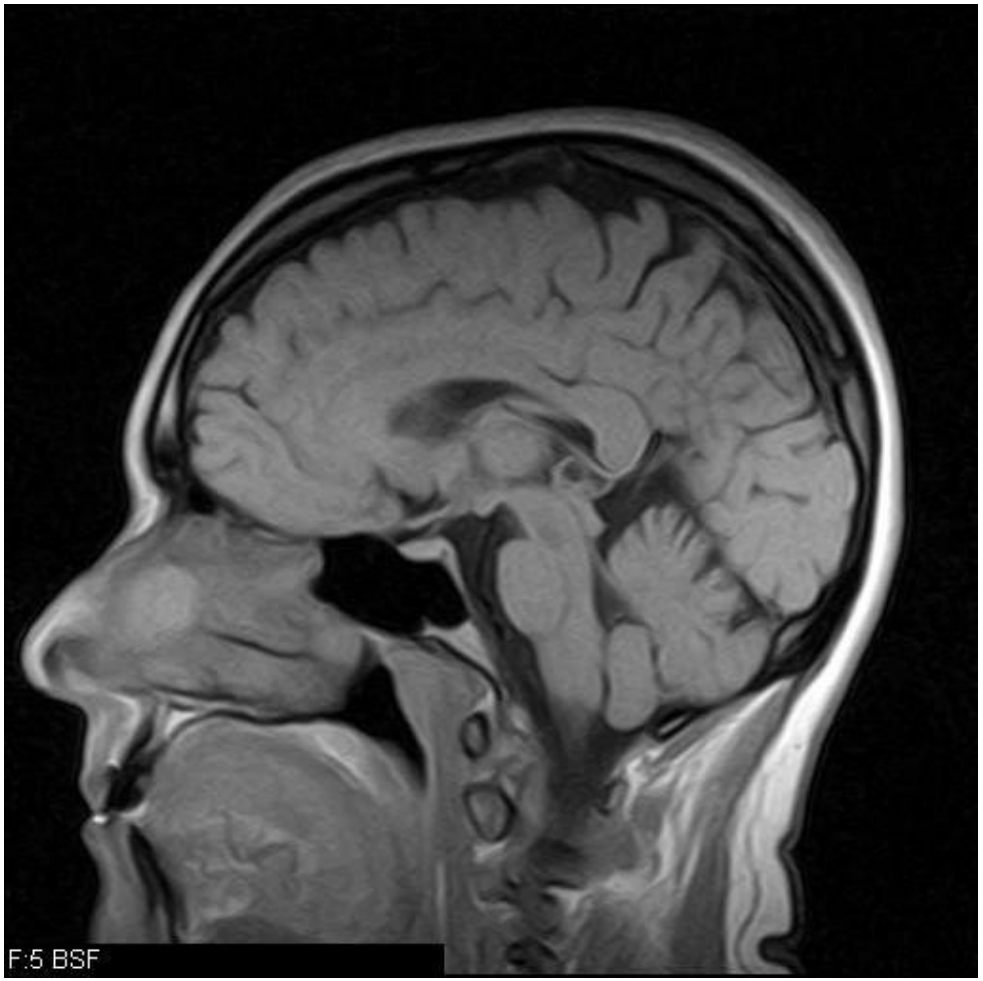
- "Discovered" by Röntgen in late 1800s





Magnetic Resonance Imaging (MRI)

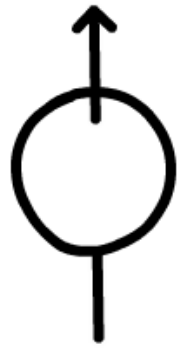




Magnetic Resonance Imaging (MRI)

- Basic concepts
- NMR (Nuclear Magnetic Ressonace)
  - Electromagnetism, magnetic field

  - Hydrogen: Single proton and electron.
    - Focus on the proton (Nuclear!)
    - Spin.



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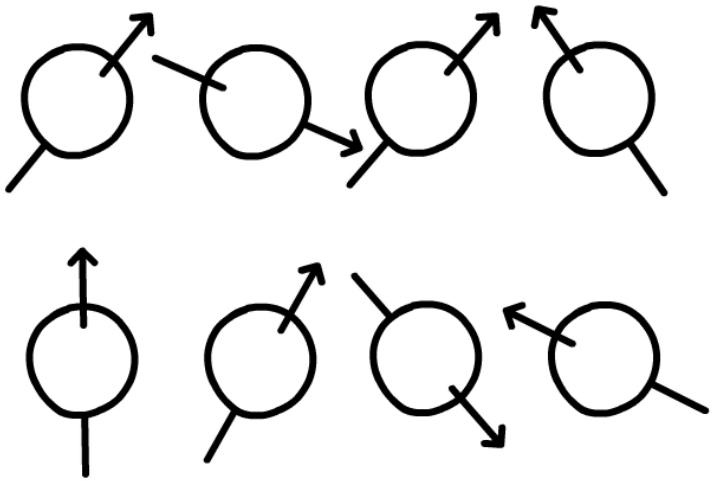
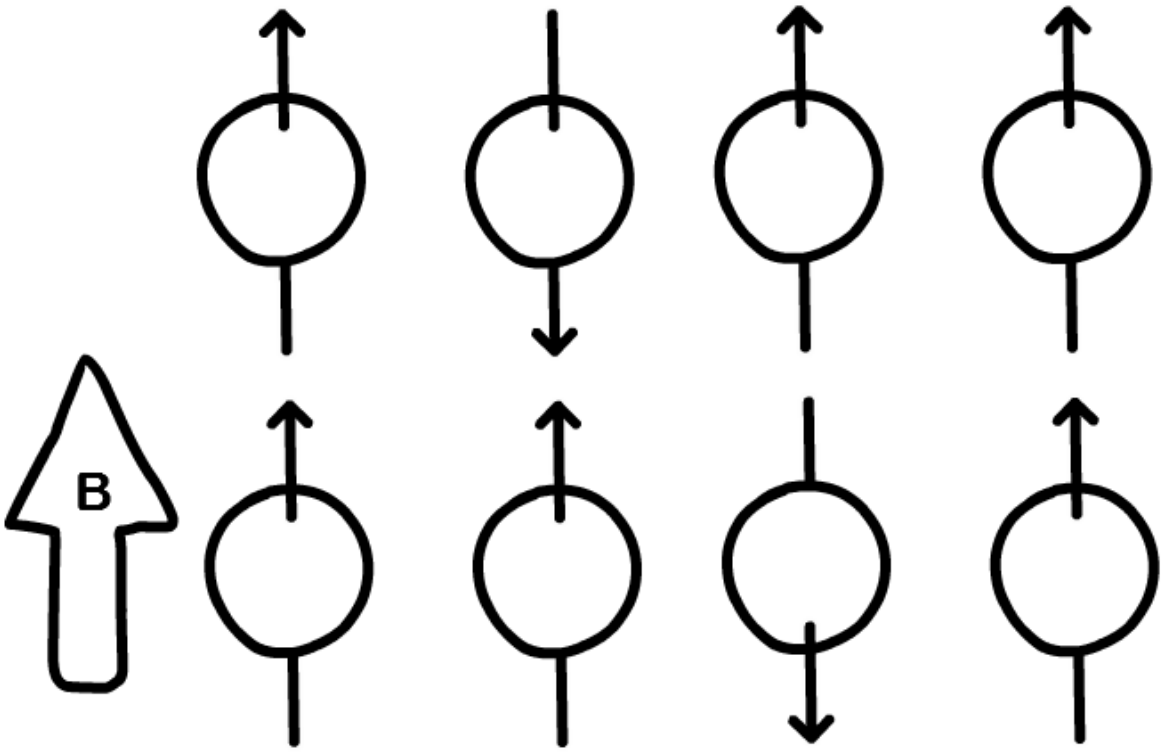


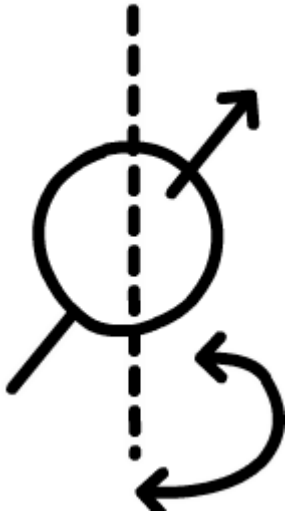
Magnetic Resonance Imaging (MRI)

- Under a strong magnetic field.
  - Align into low (within B) and high energies (against B)



Magnetic Resonance Imaging (MRI)

- In fact they precess (not completely aligned)
- Larmor Frequency



$$f = \gamma \times B_0$$

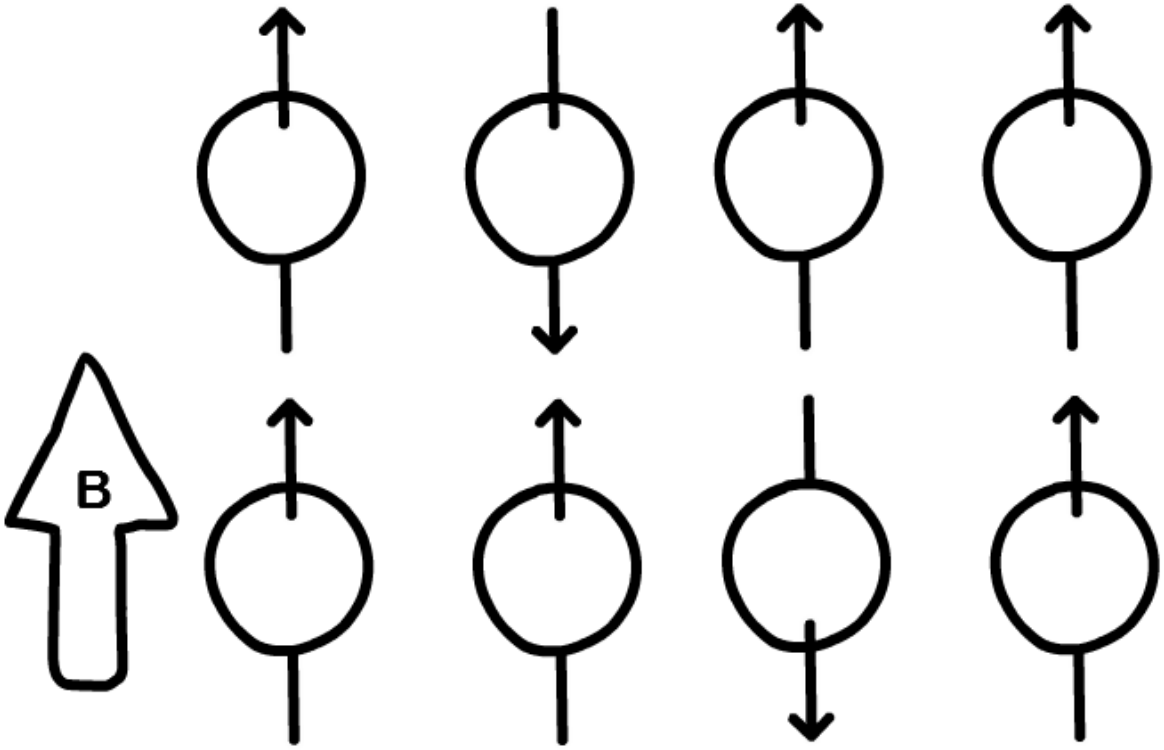
f = Precession frequency γ = Gyromagnetic Ratio

B_0 = Magnetic field Strength

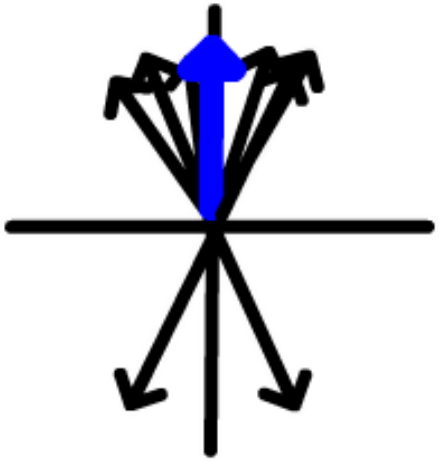
- 1 T = 42.58 MHz 2T = 85.15 MHz

Magnetic Resonance Imaging (MRI)

- Representing the Net Magnetization (adding up all vectors of the protons).

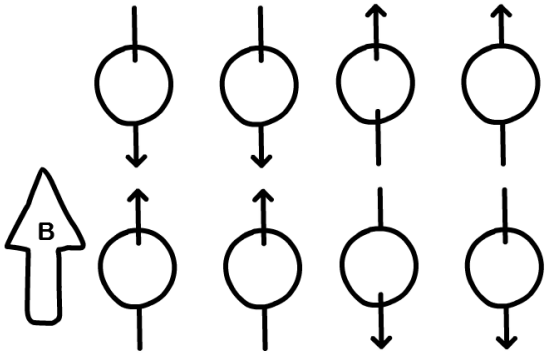


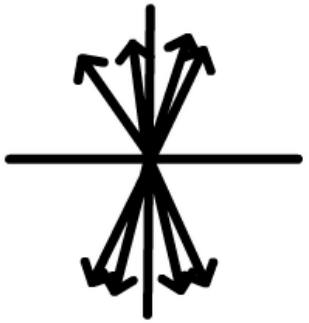
Longitudinal Magnetization



Magnetic Resonance Imaging (MRI)

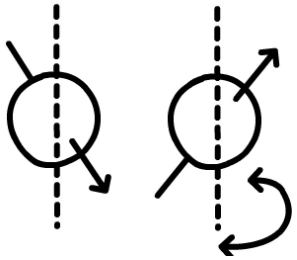
- A RF signal sinusoidal at 42.58 MHz (assuming 1T)
  - Protons move to high energy state (0 Longitudinal mag)

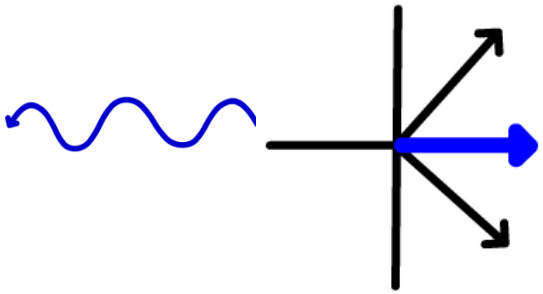




0 Longitudinal Magnetization

  - Protons "spin together" with the RF, signal (Resonance!)
    - Generates a RF signal as protons spin in resonance.

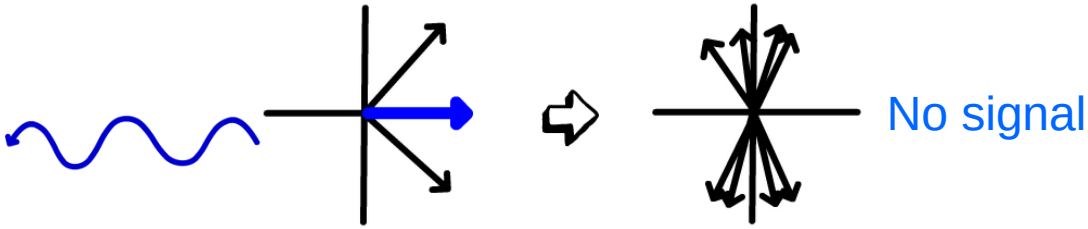




Transverse Magnetization

Magnetic Resonance Imaging (MRI)

- Removing the RF signal and… relax!
  - T2 relaxation (Spin-spin): Protons are not in ressonance any more.
    - Protons spread a part (they are all +).
    - Transverse magn. is removed (RF signal is gradually eliminated).
    - No energy transfer occurs.



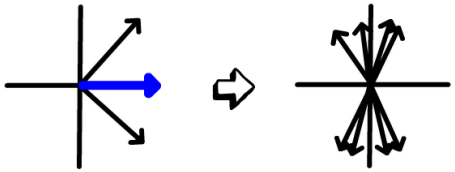
  - T1 relaxation (Spin-lattice): Protons move from high energy state to low energy.
    - Transfer of energy (heat to the lattice)
    - Longitudinal magnetisation is restored.

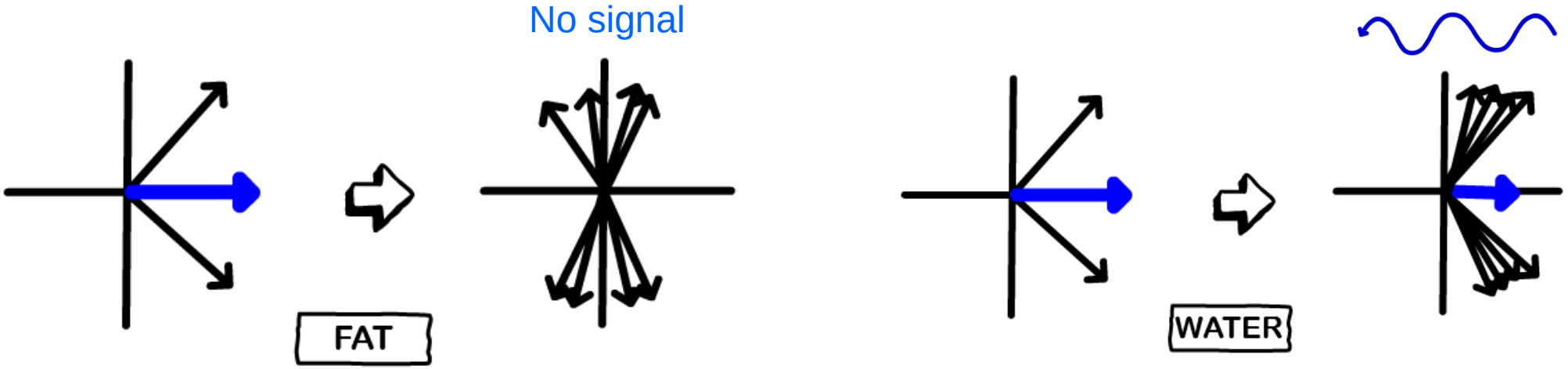
Magnetic Resonance Imaging (MRI)

- Pulse sequence
  - Repetition time (TR): how quickly we put the RF signal
  - Echo Time (TE): how quickly we measure the transverse relaxation.
- Different tissues will react differently (different relaxation) due to the Hydrogen (proton) concentration and structure or bounding (fat vs water).
- Typical sequences:
  - T1W
  - T2W
  - Proton density (PD), FLAIR

Magnetic Resonance Imaging (MRI)

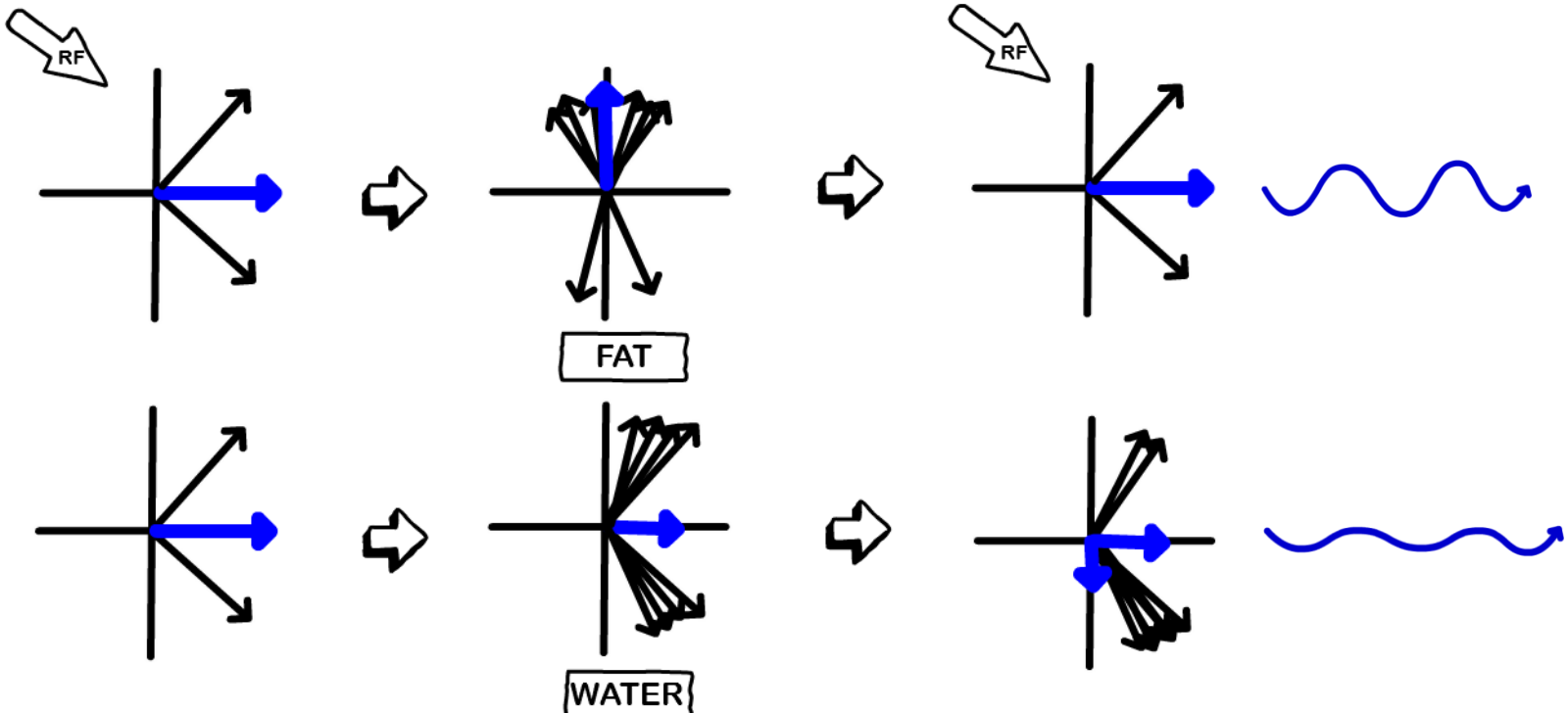
- To accentuate differences on T2 (spin-spin).
  - Wait a long time for TR
  - Wait a long time for TE
  - In water after a long TE transverse magnetizaton still exists (voxel: white), while in fat is removed (voxel: grey/black).





Magnetic Resonance Imaging (MRI)

- To accentuate differences on T1 (spin-lattice).
  - Regrowing longitudinal magnetisation.
  - Fat (bounded protons) recover quickly than water (lower signal). Fat would appear lighter than water.
  - Short TR AND Short TE.



Magnetic Resonance Imaging (MRI)

- Example: brain imaging, several sequences.

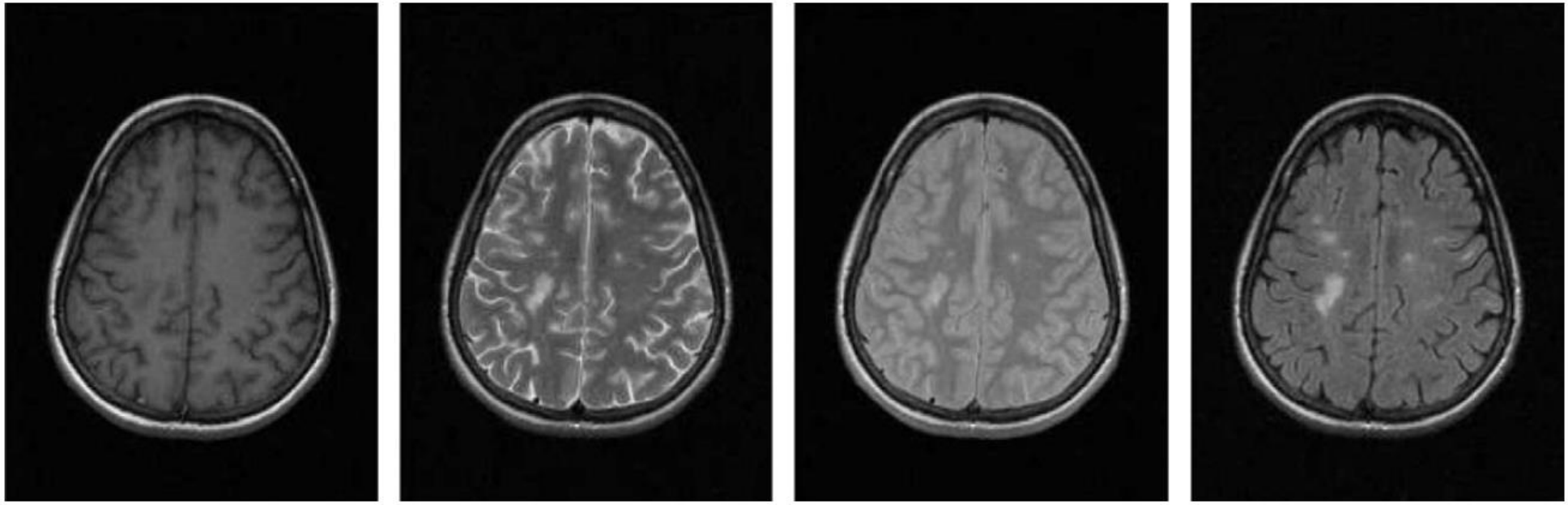


Fig. 1. MR images of a brain slice with MS lesions: (a) T1-w, (b) T2-w, (c) PD-w, and (d) FLAIR, respectively. Note that soft tissues are more distinguishable in the T1-w image, while lesions are usually better appreciated in the FLAIR one.

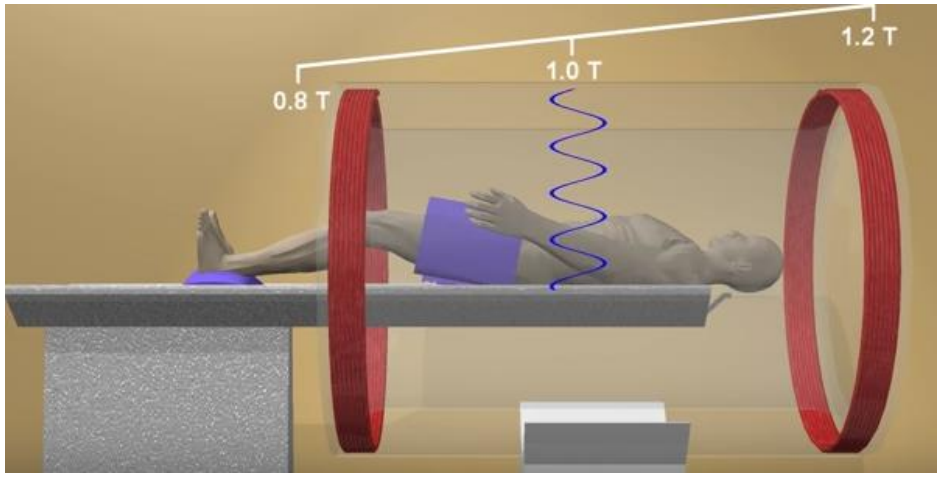
Magnetic Resonance Imaging (MRI)

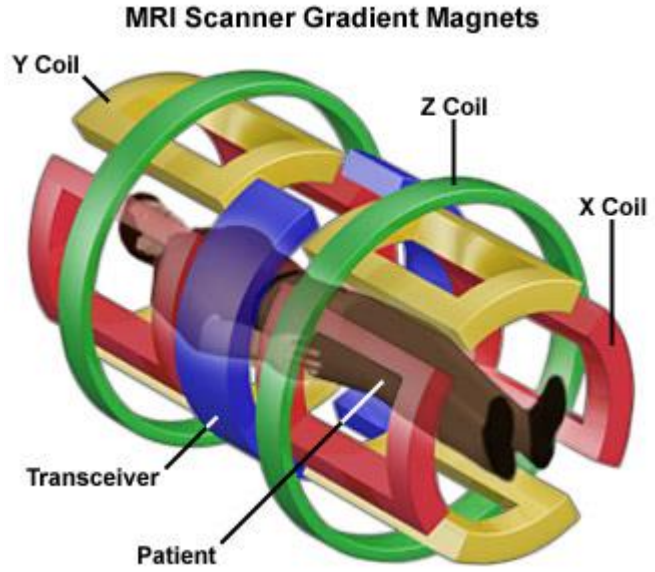
- Relaxation times

Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5
Proteins	250	0.1- 1.0
Ice	5000	0.001

Magnetic Resonance Imaging (MRI)

- For a single pixel, what about a 3D volume?
  - 3D localization using gradient magnets (x,y,z)
  - Slightly modify the magnetic field.
  - Recall that resonance depends on magnetic field, hence it changes the phase of the spins (unique localization).



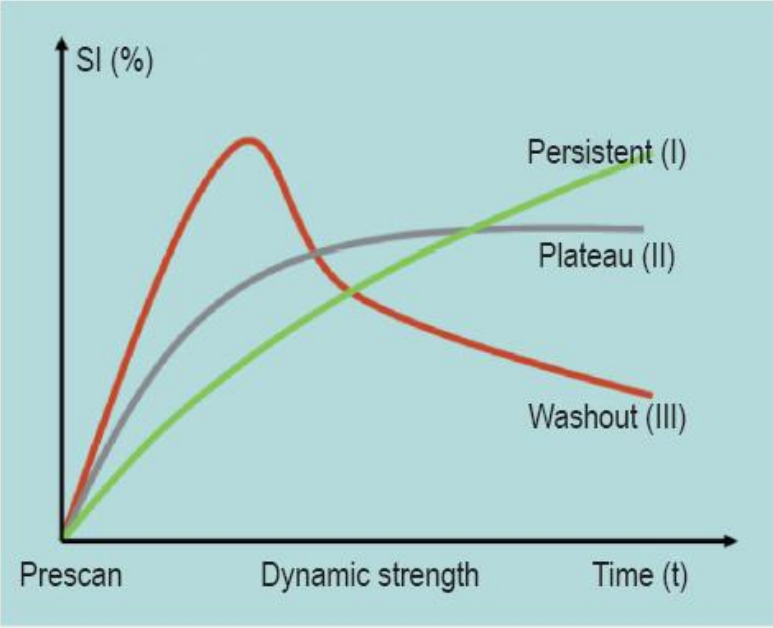


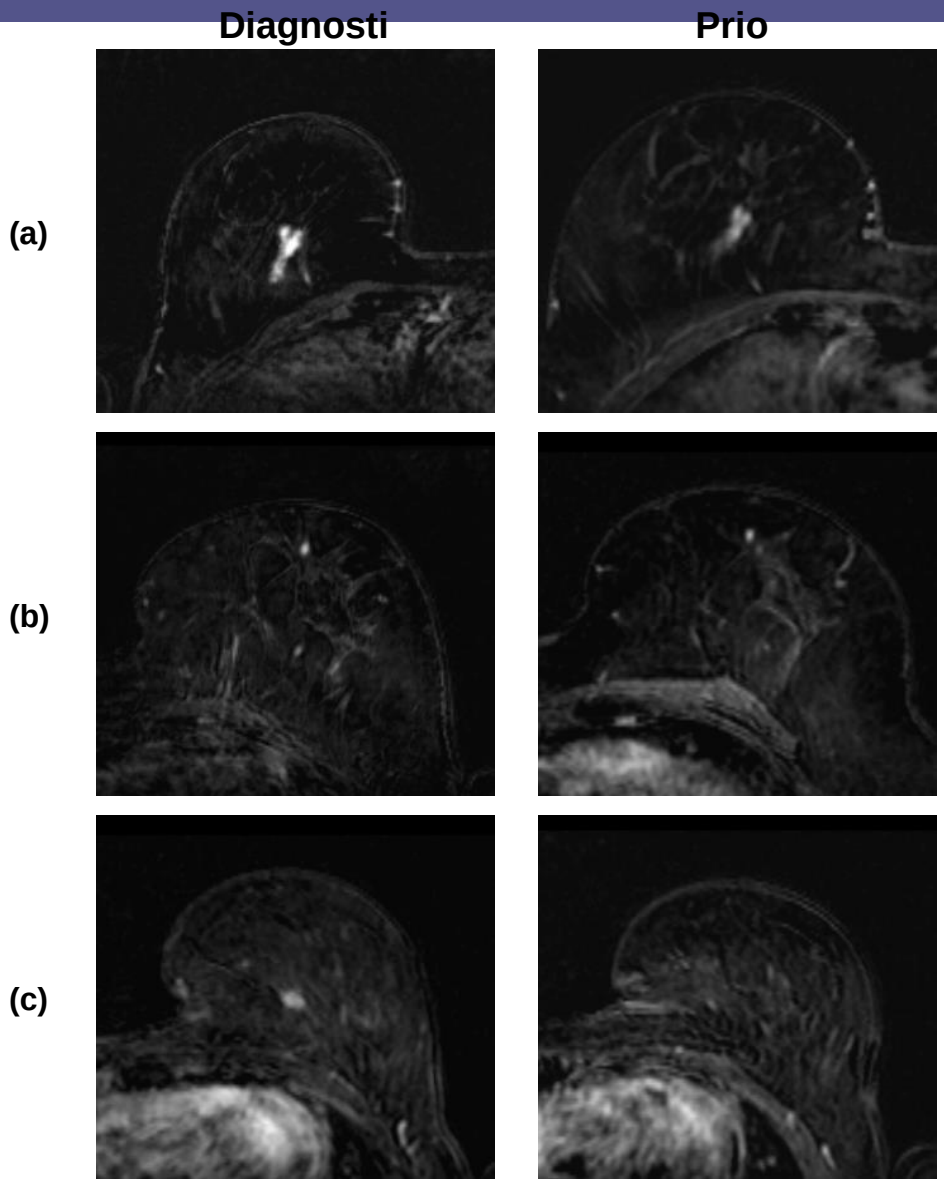
Magnetic Resonance Imaging (MRI)

- Contrast agents.
  - Dynamic Contrast Enhanced (DCE) MRI
  - Injection of a constrast agent (Gadolinium based) which causes the relaxation time to decrease (in T1W). So provides a higher signal.
  - Acquisition is done at different time intervals and enhancement is estimated.

Magnetic Resonance Imaging (MRI)

- DCE MRI
  - 4D data
  - Kinetic and morphological features

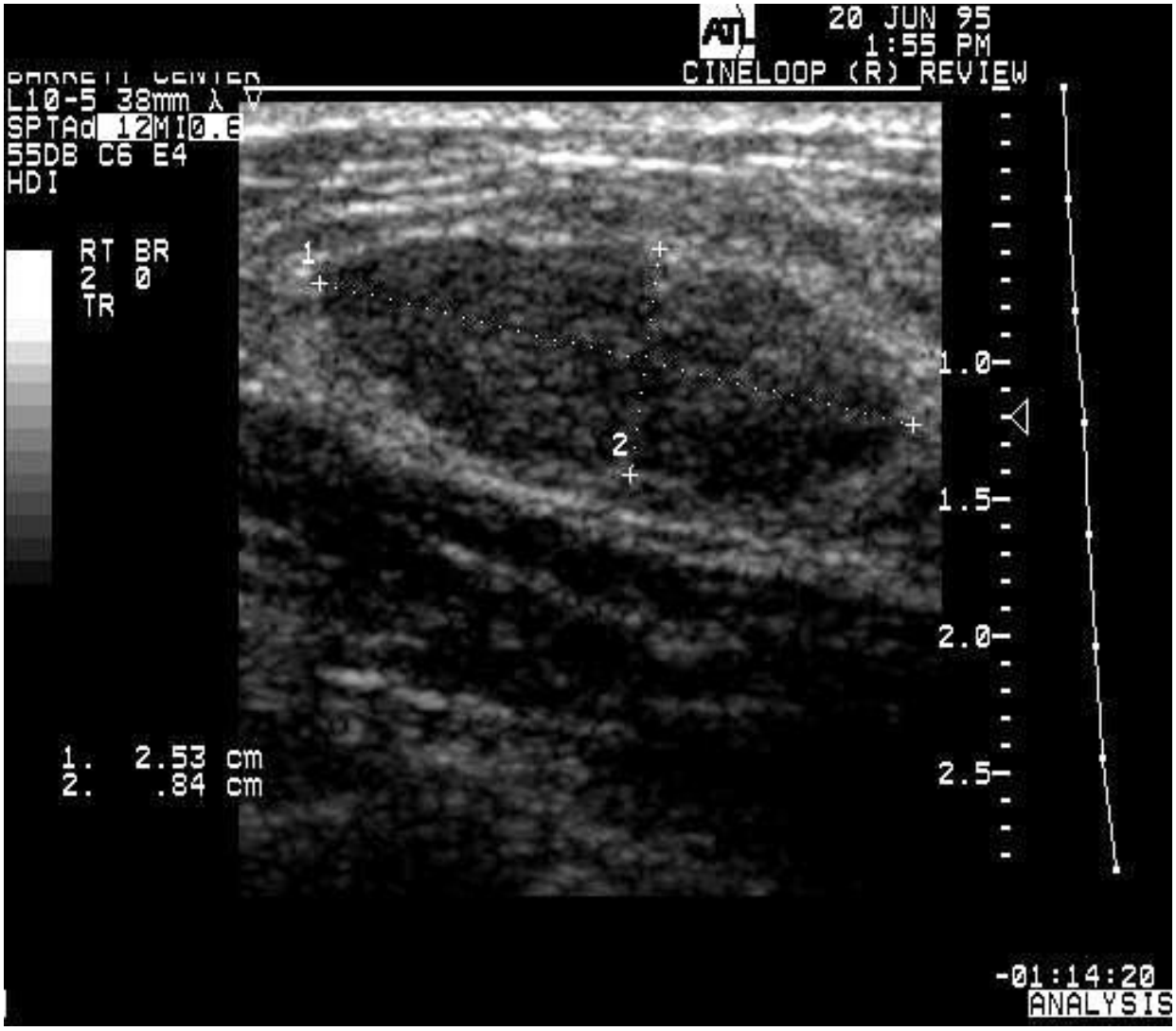




Magnetic Resonance Imaging (MRI)

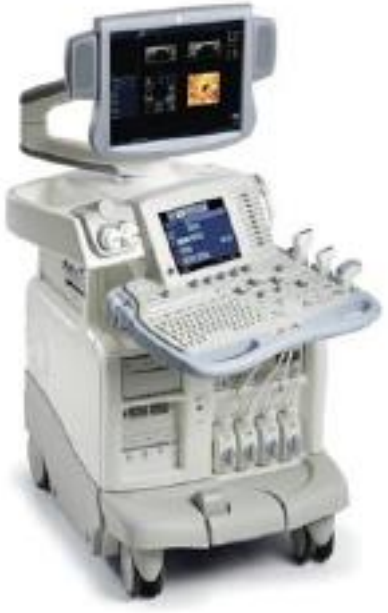
- Advantages:
  - Non-ionizing radiation
  - Obtains images in any plane
  - Has excellent soft tissue contrast detail
  - Particularly useful in neurological, cardiovascular, musculoskeletal, and oncologic imaging
- Disadvantges:
  - High purchase and operating costs
  - Lengthy scan time
  - Difficult for some patients to tolerate
  - Not suitable for patients with pacemakers or metallic parts

Ultrasound Imaging (US)



Ultrasound Imaging (US)

- Characteristics
  - A diagnostic medical imaging technique used to visualize many internal organs, to capture their size, structure and any pathological lesions with real time images
  - One of the most widely used diagnostic tools in modern medicine



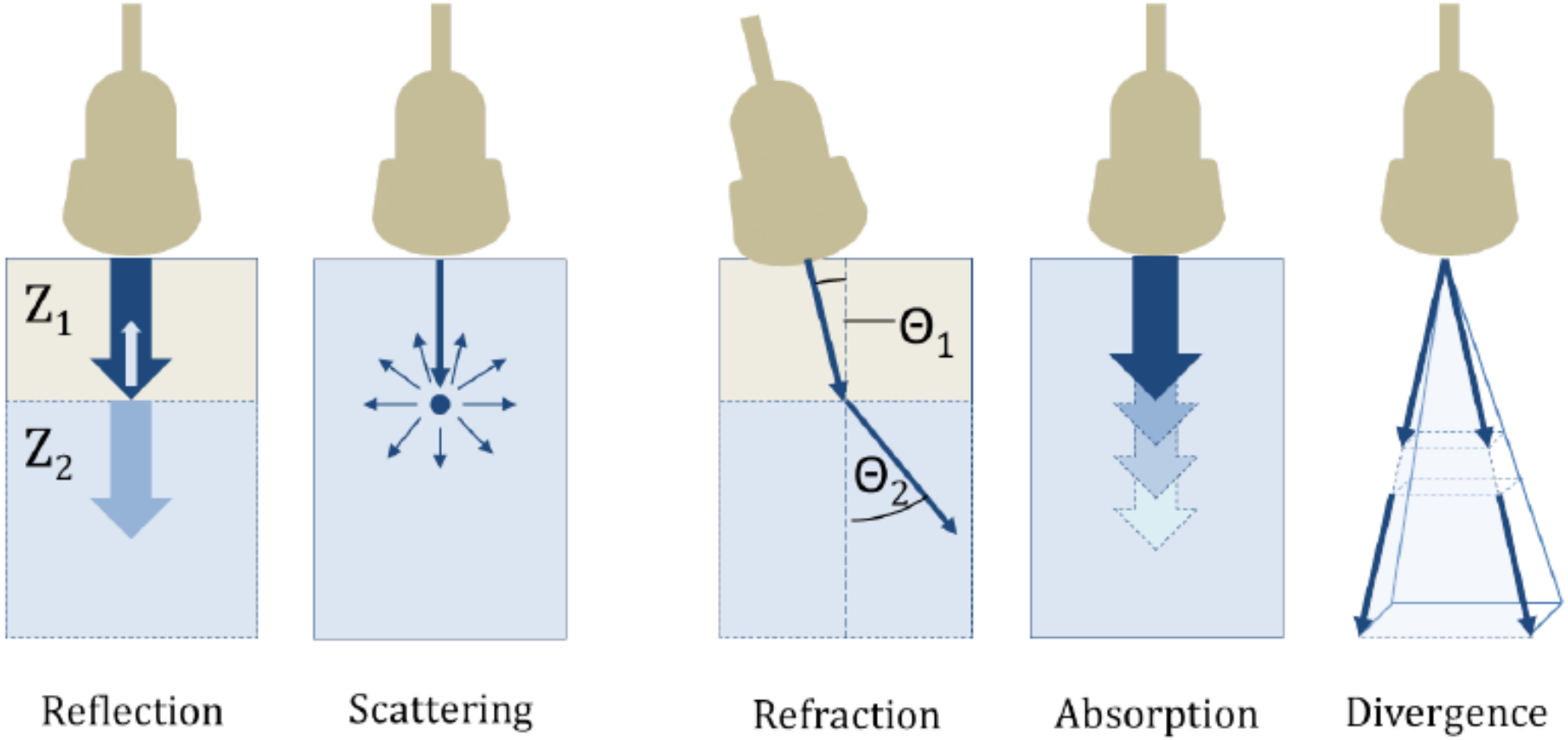
Ultrasound Imaging (US)

- Basics
  - Capture de reflection and backscattering of acoustic waves
  - At transition between matters (i.e muscle and fat) ultrasound waves are partly reflected and partly transmitted.
  - The **echo runtime** indicates the distance between transducer and tissue border.
  - The **echo amplitude** is related to the tissue properties
    - Acoustic impedance (density and speed of sound in the material)

$$Z = c_s \cdot \rho$$

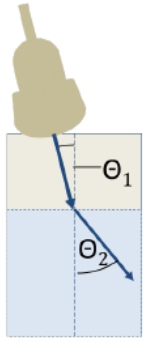
Ultrasound Imaging (US)

- Acoustic attenuation
  - Image is reconstructed from reflected and scattered signals



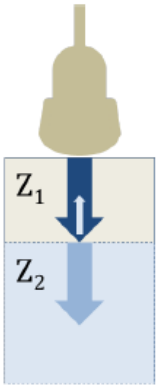
Ultrasound Imaging (US)

- Acoustic waves refraction and reflection
  - Refraction angle (Snells law) $\sin\theta_2 = \sin\theta_1 \frac{c_2}{c_1}$
  - Reflected amplitude $r(\theta_1, \theta_2) = \frac{A_R}{A_0} = \frac{Z_2 \cos\theta_1 - Z_1 \cos\theta_2}{Z_2 \cos\theta_1 + Z_1 \cos\theta_2}$



Refraction

when is perpendicular $r(0,0) = \frac{Z_2 - Z_1}{Z_2 + Z_1}$



Reflection

If $Z_2 = Z_1$ reflection is 0

Ultrasound Imaging (US)

- Typical values

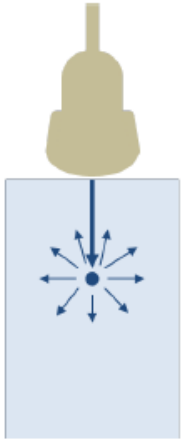
Table 1.1: Speed of sound in different tissues. The acoustic impedance $Z = c_s \cdot \rho$ is computed from density ρ and speed of sound c_s. All numbers refer to body temperature of 37 °C (Numbers from Deserno (2011)).

Material	c_s *in* $\mathrm{m\,s^{-1}}$	ρ *in* $10^3\,\mathrm{kg\,m^{-3}}$	Z *in* $10^6\,\mathrm{kg\,m^{-2}\,s^{-1}}$
Bone	3600	1.70	6.12
Marrow	1700	0.97	1.65
Blood	1570	1.02	1.61
Muscle	1568	1.04	1.63
Water	1540	0.99	1.53
Fat	1400	0.97	1.36
Air	340	1.20×10^{-3}	4.08×10^{-4}

- What happens with Air? And Bone?

Ultrasound Imaging (US)

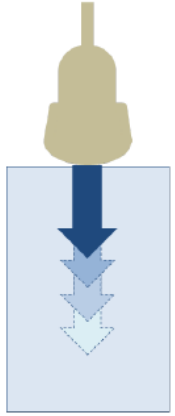
- Scattering
  - Major structures have a **specular** reflection but for small structures scattering of the signal happens (and is related to the tissue strucutre).
  - Typical noise on ultrasound related to the diffuse reflection and the size relative to the wave length.



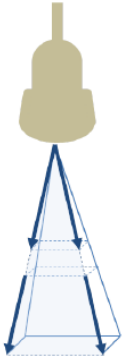
Scattering

- Attenuation of the signal:
  - Absorption. Transform of the energy of the wave into heat (exponential decay)
  - Divergence. Related to the spread of the beam

Being r the distance to the source. $I \propto 1/r^2$



Absorption



Ultrasound Imaging (US)

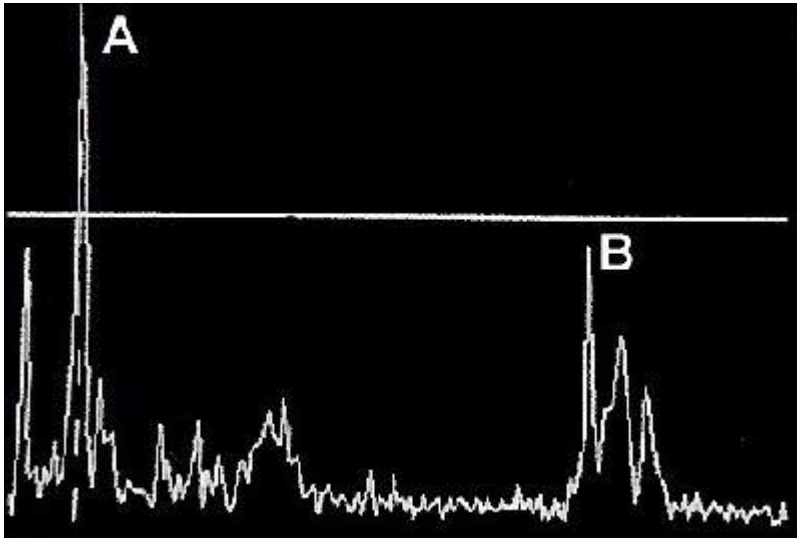
- Imaging
  - Attenuation is proportional to frequency
  - Ressolution is proportional to frequency
    - Axial
    - Lateral

Table 1.2: Penetration depth, spatial resolution of different ultrasound frequencies as well as typical organs that are imaged at (approximately) these frequencies. (Table similar to a table in Postema & Attenborough (2011, p. 157))

Frequency in MHz	*Wavelength in* mm	*Penetration depth in* cm	*Lateral resolution in* mm	*Axial resolution in* mm	*Clinical application*
2	0.78	25	3.0	0.80	Liver, Fetus, Heart
3.5	0.44	14	1.7	0.50	Kidney
5.0	0.31	10	1.2	0.35	Brain
7.5	0.21	6.7	0.8	0.25	Thyroid, Superficial Vessels
10.0	0.16	5.0	0.6	0.20	Prostate, Breast
15.0	0.10	3.3	0.4	0.15	Breast
21.0	0.09	1.1	0.36	0.13	Eye, Skin

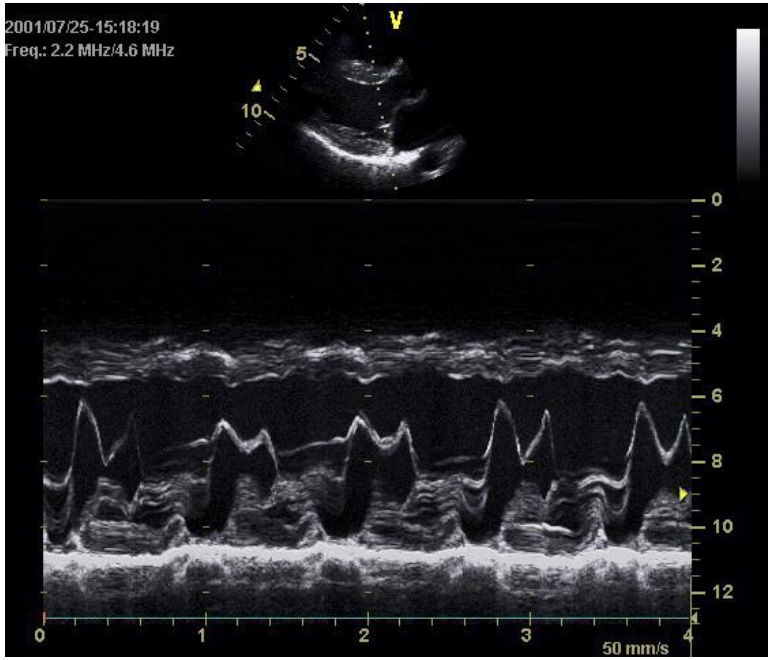
Ultrasound Imaging (US)

- A-mode Ultrasound (A=Amplitude)
  - Now obsolete in medical imaging. Wave spikes are represented when a single beam passes through objects of different consistency and hardness. The distance between these spikes (e.g. A and B) can be measured accurately by dividing the speed of sound in tissue (1540 m/sec) by half the sound travel time



Ultrasound Imaging (US)

- M-mode Ultrasound (M=Motion)
  - A single beam can be used to produce an M-mode picture where movement of a structure such as a heart valve can be depicted in a wave-like manner due to its high sampling frequency (up to 1000 pulses per second)

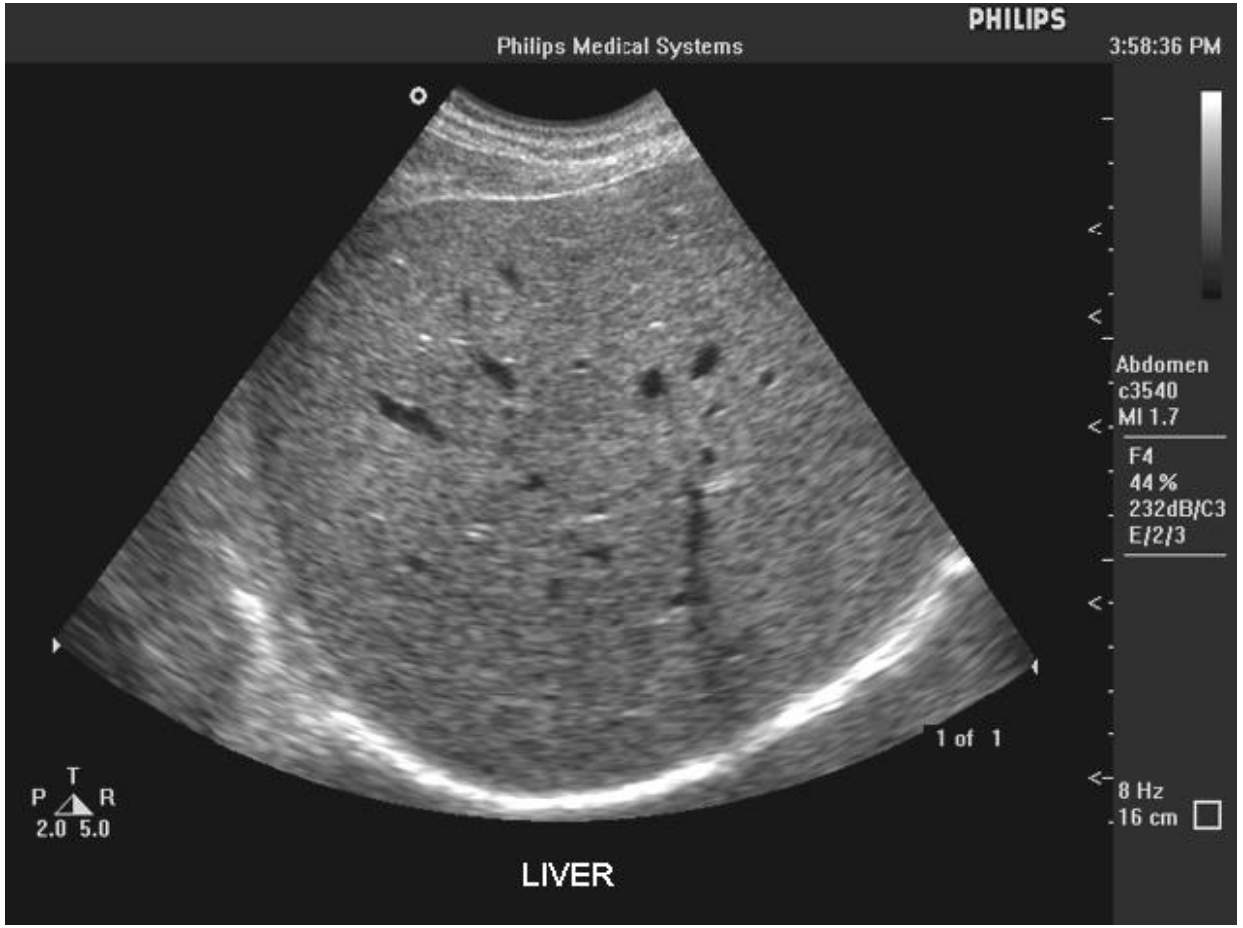


Ultrasound Imaging (US)

- B-mode Ultrasound (B=Brightness)
  - Same as A-mode, but one dimensional graphical display with brightness corresponding to amplitude of reflected sound
  - Most modern ultrasound devices are real-time 2D imaging systems. Multiple crystals (linear, curved or phased-array) or moving crystal
  - Sequential B-mode pulses sweeping across a plane to display the image in either a linear or 'sector' format
  - Displayed as real time imaging with up to 100 images per second

Ultrasound Imaging (US)

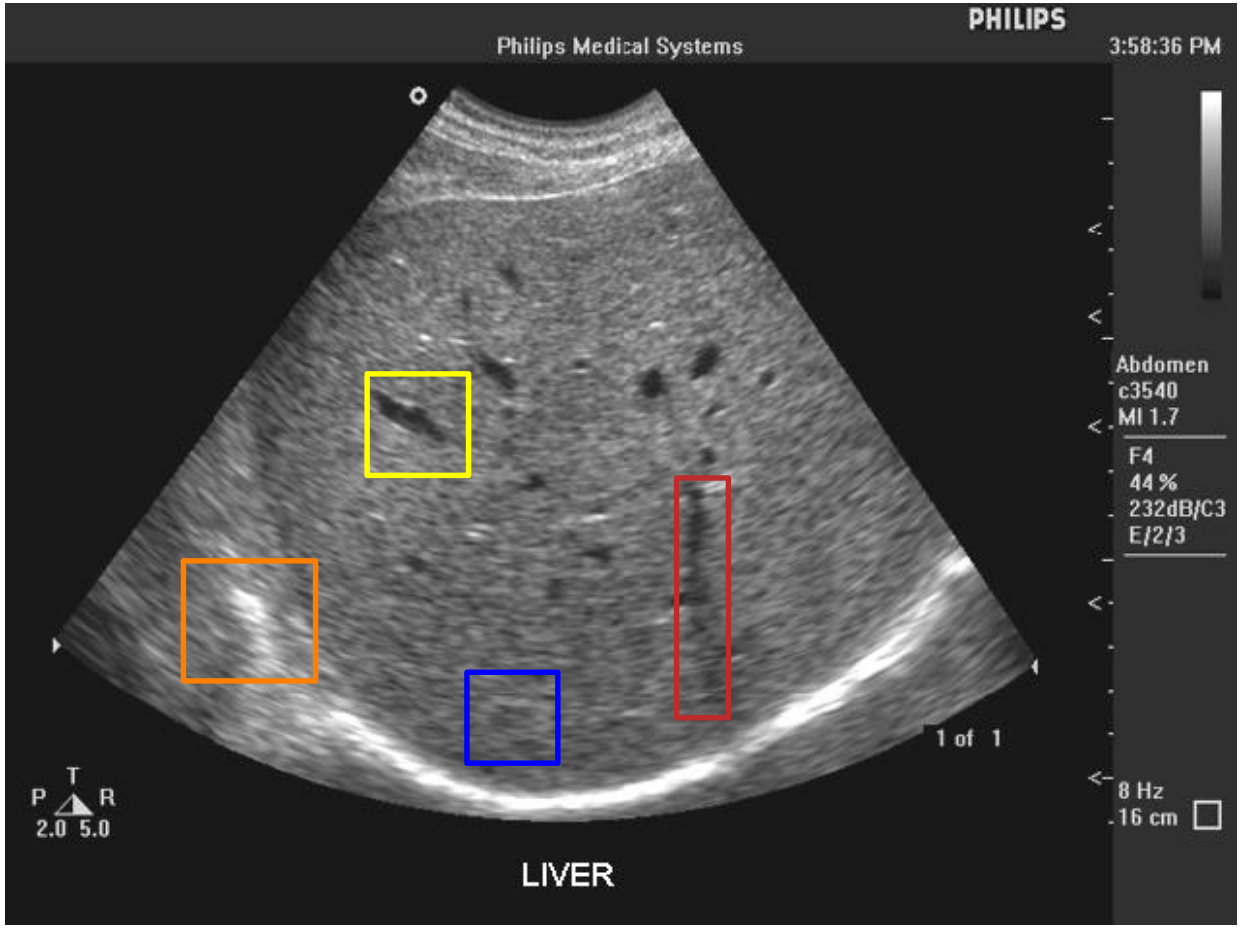
- B-mode Ultrasound (B=Brightness)



Ultrasound Imaging (US)

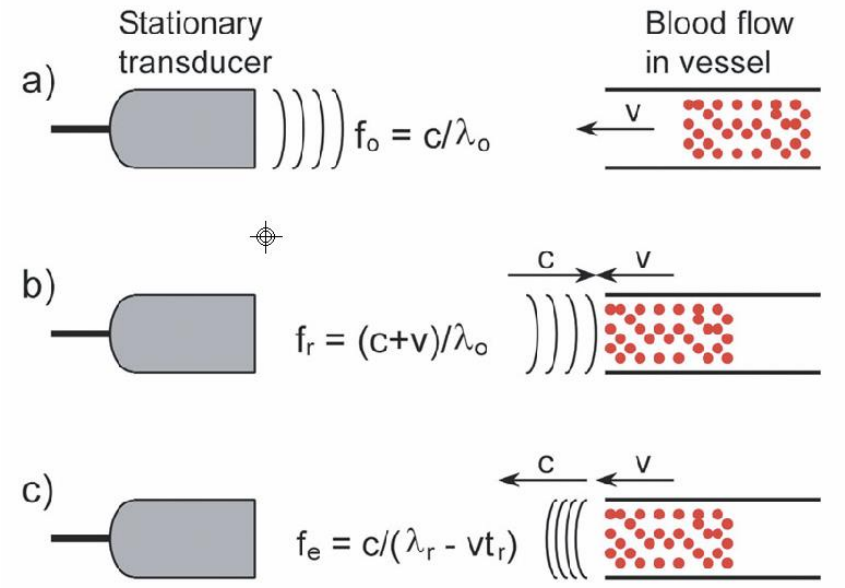
- B-mode Ultrasound (B=Brightness)

- Speckle echo-pattern
- Hypo-echoic or echo-free regions
- Shadows
- Refraction & Multiple pahtways



Ultrasound Imaging (US)

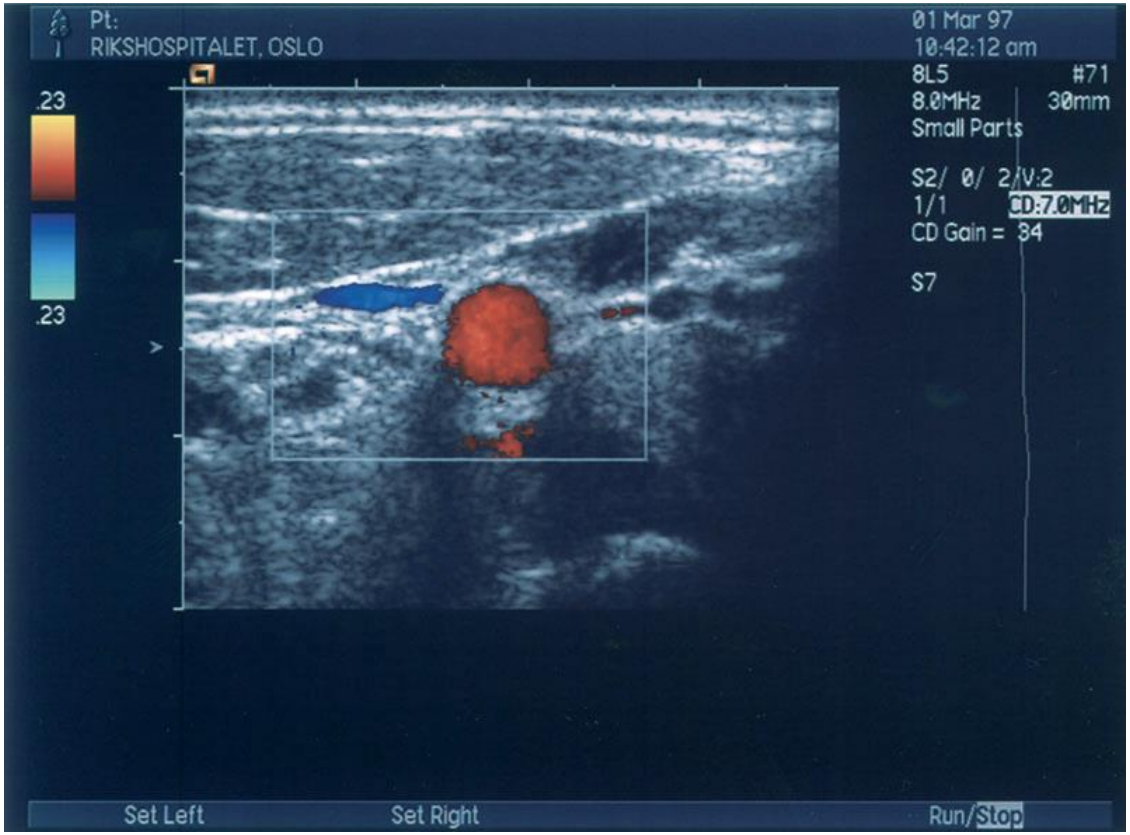
- Doppler Ultrasound
  - Measures the Doppler frequency shift between the transducer and the red blood cells
    - Higher frequency = blood towards transducer
    - Lower frequency = blood away from transducer



$$f_D = f_e - f_0 = 2 f_0 \frac{v \cdot \cos\alpha}{c}$$

Ultrasound Imaging (US)

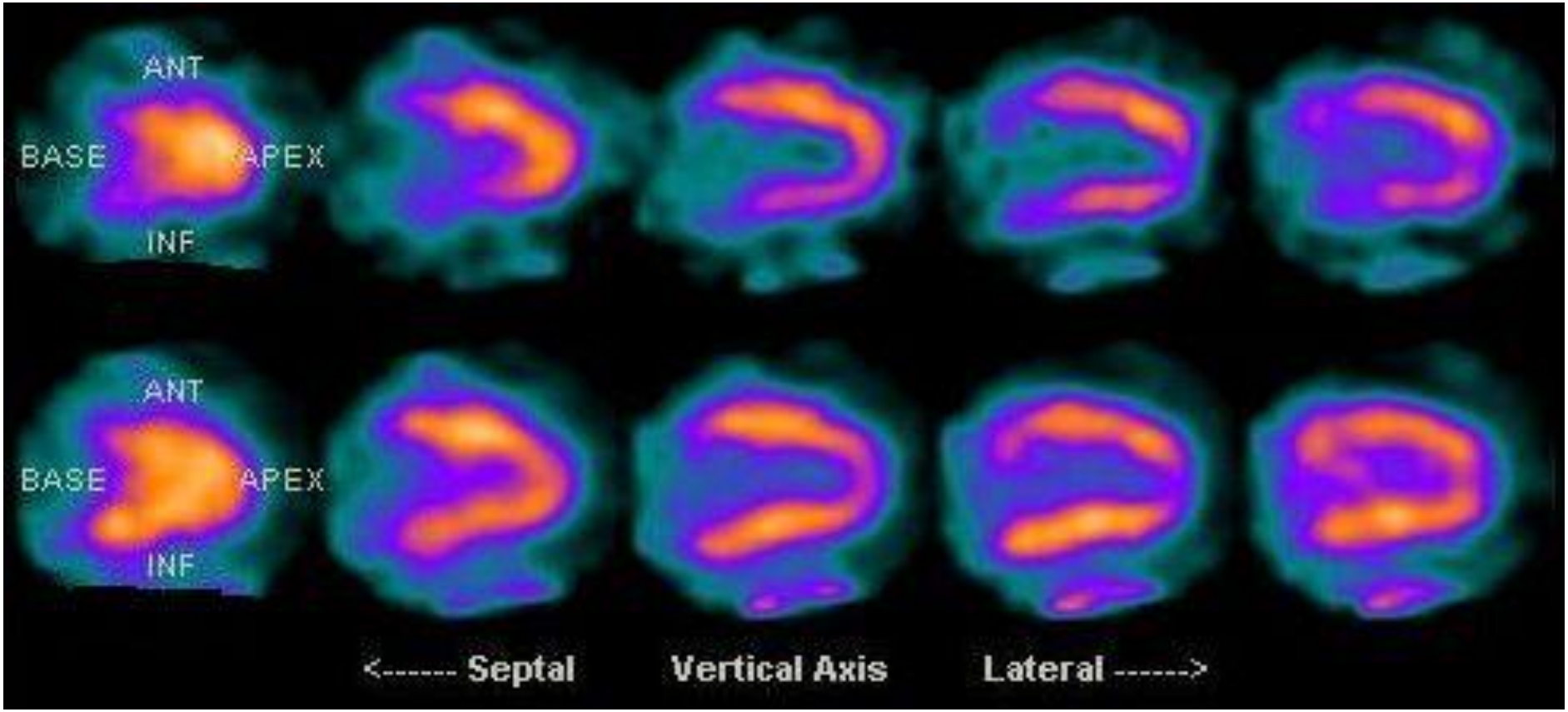
- Doppler Ultrasound
  - Measures the Doppler frequency shift between the transducer and the red blood cells



Ultrasound Imaging (US)

- Advantages:
  - Relatively low cost
  - Non-ionizing energy source and safe
  - Can scan in any plane
  - Portable equipment
  - Used in many areas: Obstetrics and Gynecology, Mammography, Adbominal, Ophtalmology, …
- Disadvantges:
  - Operator-dependent
  - Poor visualization of structures underlying bone or air
  - Scattering of sound through fat yields to poor images

Nuclear Medicine, PET, and SPECT

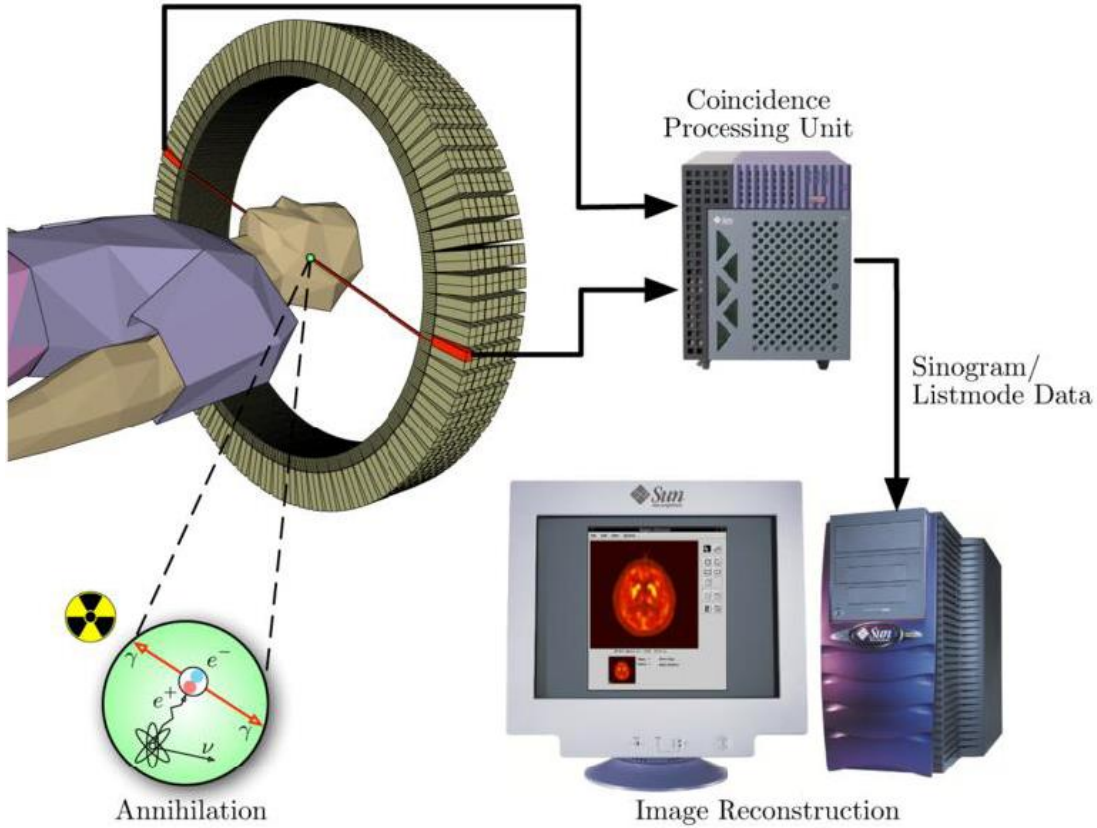


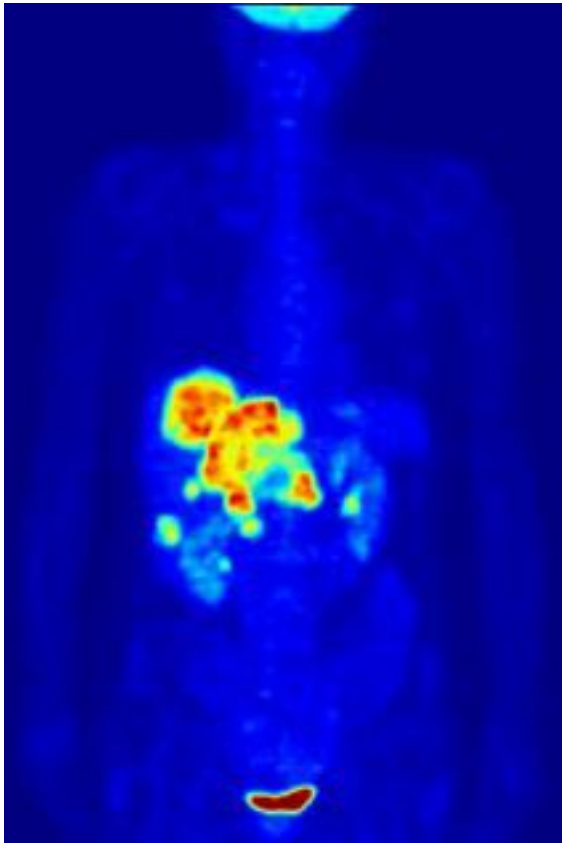
Nuclear Medicine, PET, and SPECT

- Characteristics
  - Uses radionuclides with other chemical compounds (pharmaceuticals) to form radiopharmaceuticals
  - Relies on the process of radioactive decay in the diagnosis and treatment of disease
  - Different modalities:
    - PET (Positron Emission Tomography)
    - SPECT (Single-Photon Emission Computed Tomography)
    - Scintigraphy ('scint')

Nuclear Medicine, PET, and SPECT

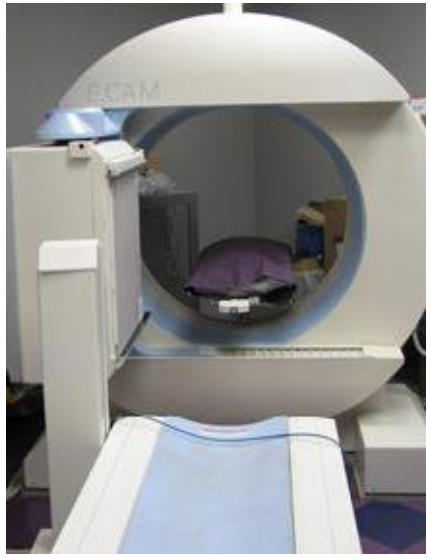
- How it works
  - Positron Emission Tomography (PET) uses coincidence detection to image functional processes





Nuclear Medicine, PET, and SPECT

- How it works
  - PET detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the biologically active molecule
  - Images of tracer concentration in 3D or 4D space (with time) within the body are then reconstructed by computer analysis
  - Reconstructions in CT and PET are similar

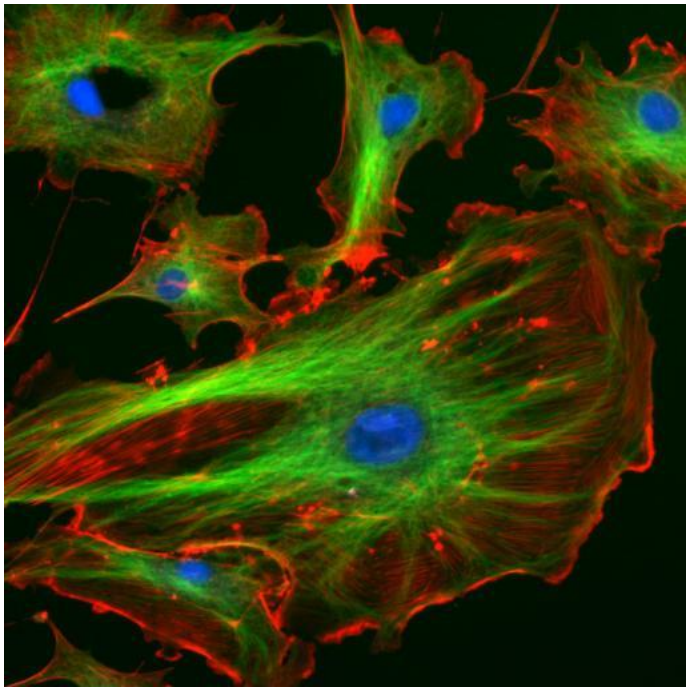


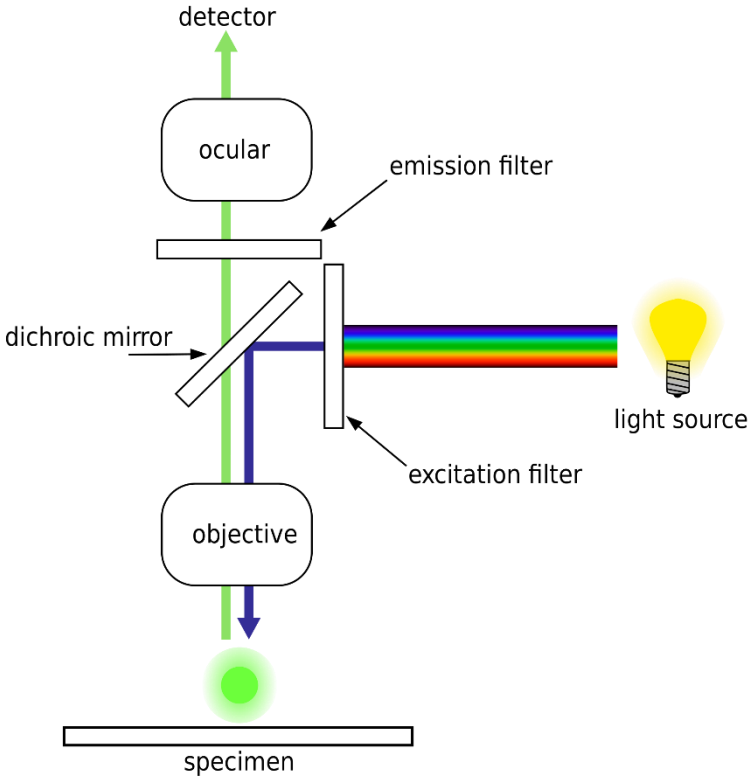
Nuclear Medicine, PET, and SPECT

- Advantages:
  - Measure targeted specific chemical-functional tissue function
  - Valuable diagnostic tool particularly in imaging cardiovascular system and oncologic assessment
- Disadvantges:
  - High cost
  - PET isotopes require a cyclotron for production

Fluorescence Microscopy

- Detection of the emitting wavelength of the specimen (longer wavelength than light source)
- Tissue needs to be prepared (stain with fluorophore)



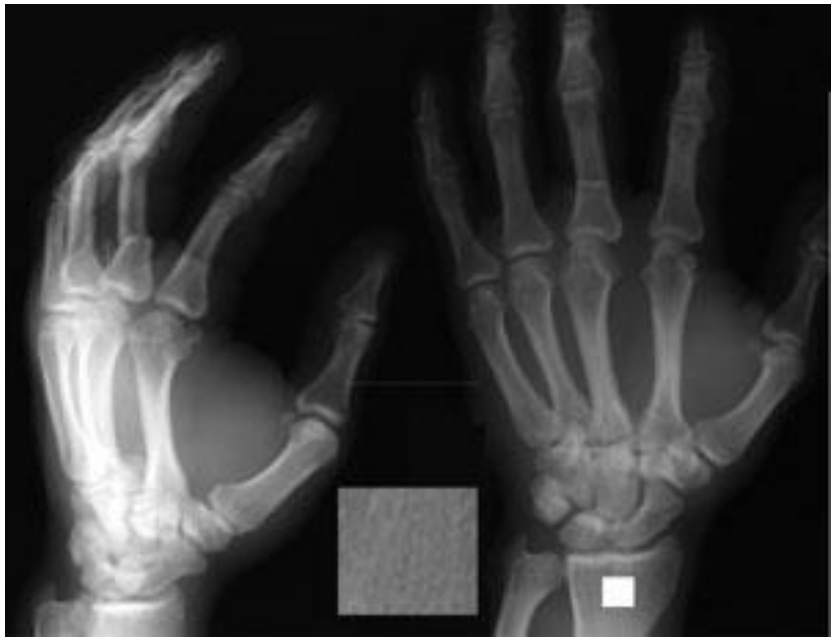


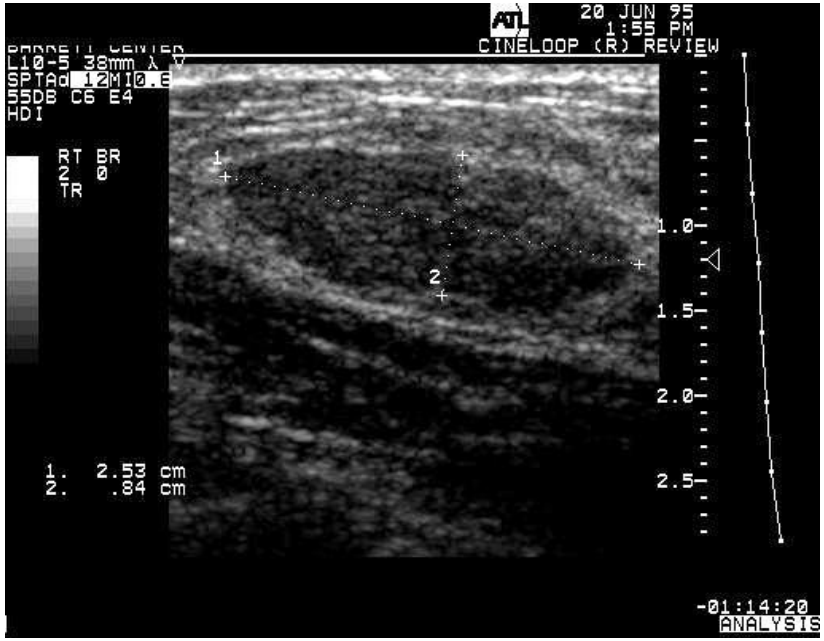
Modality Comparison

Modality	Strength	Weakness	Safety
X-Ray	Simple, versatile	Only Air-Tissue-Bone	Ionizing
CT	Sectional Images	Low Resolution	Ionizing
MRI	Can see many properties	Slow	Safe
Ultrasound	Real time	Only abdomen, limbs	Safe
Isotope	Functional	Slow, low resolution	Ionizing
Fluorescence	Can see many properties	Low penetration	Not applicable

Thoughts on Imaging

- Three entities in imaging
  - Object
  - Image
  - Observer





Conclusions

"Your x-ray showed a broken rib,
but we fixed it with Photoshop."

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MIA – Medical Image Modalities

Questions?