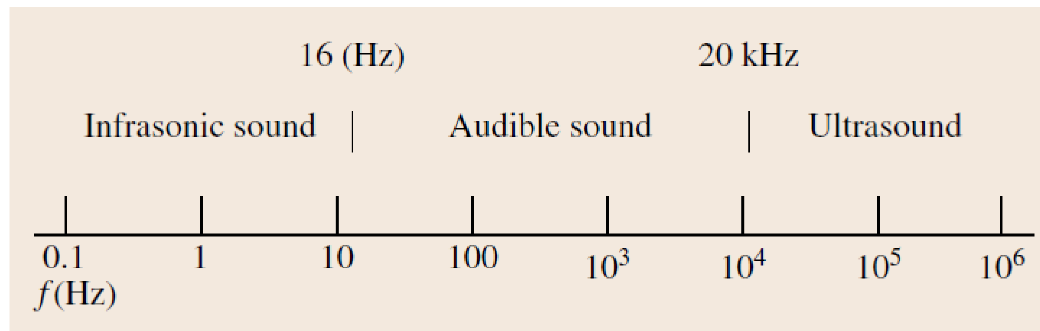
MEDICAL IMAGING SYSTEMS

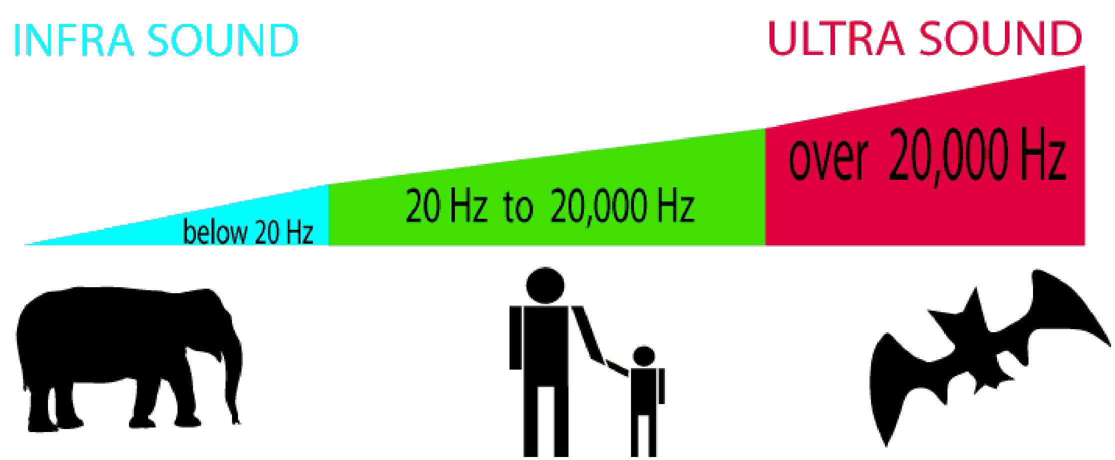
EE 370 – 2015

Prof. Yasser Mostafa Kadah – www.k-space.org

Nature of Ultrasound

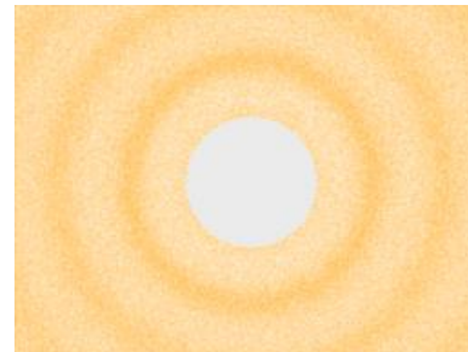
- Same Nature as sound waves but at higher frequencies
  - Cannot be heard by human ear





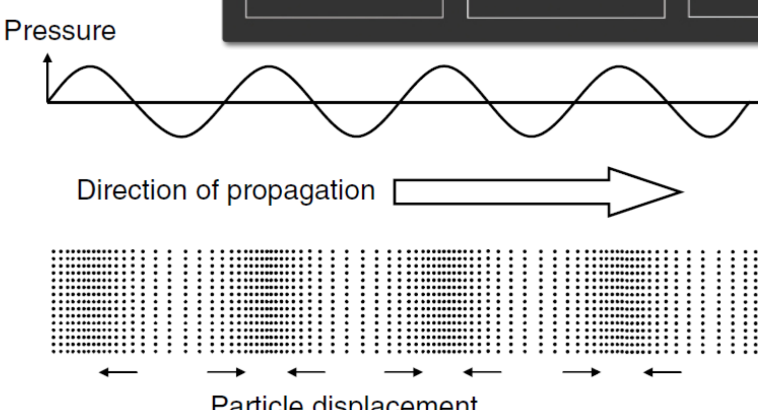
Propagation of Ultrasound Waves

- Mechanical waves in nature
  - Cannot travel in vacuum
- No permanent relocation of atoms
  - Only vibrations around same position



$$c = f\lambda$$

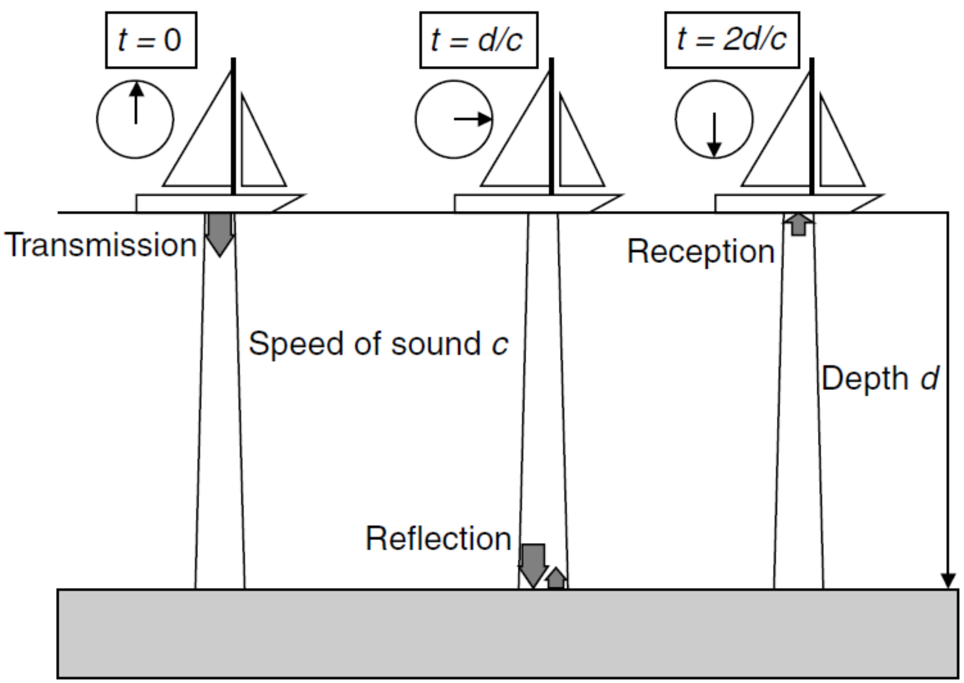
$$\text{Speed of sound } c = \sqrt{k/\rho}$$

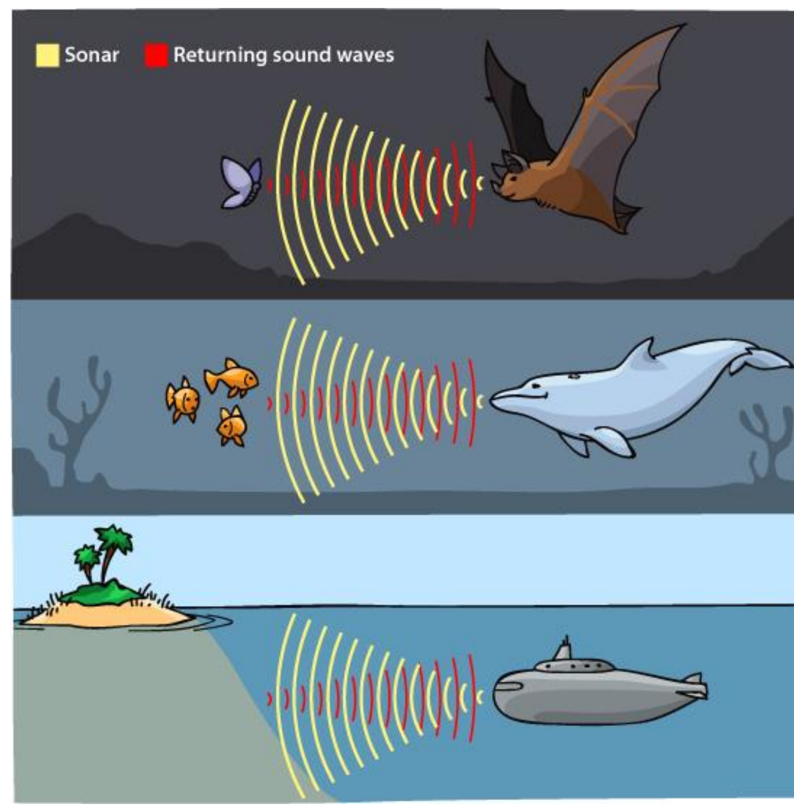


Material	c ($\mathrm{m\,s^{-1}}$)
Liver	1578
Kidney	1560
Amniotic fluid	1534
Fat	1430
Average tissue	1540
Water	1480
Bone	3190–3406
Air	333

Ultrasound Imaging Basic Idea

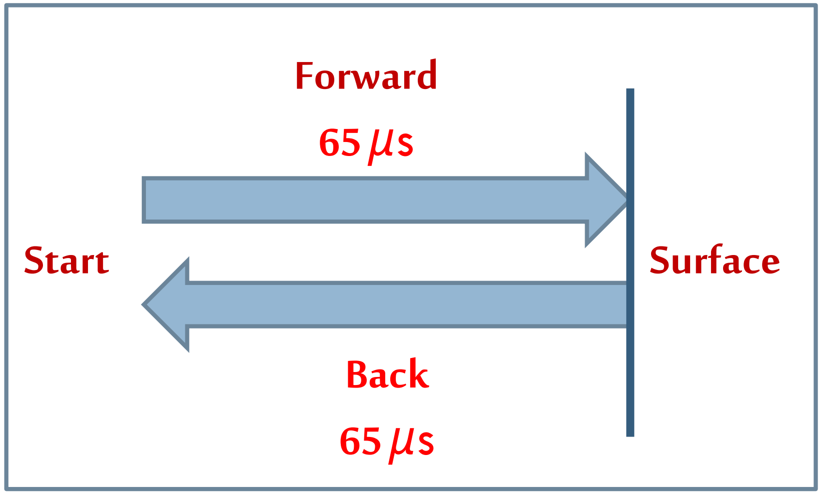
- Echo Ranging
  - Sending waves and measuring time when reflected echo is received to determine location of reflecting surface
  - Used by bat and dolphin in nature
  - Military applications in Sonar

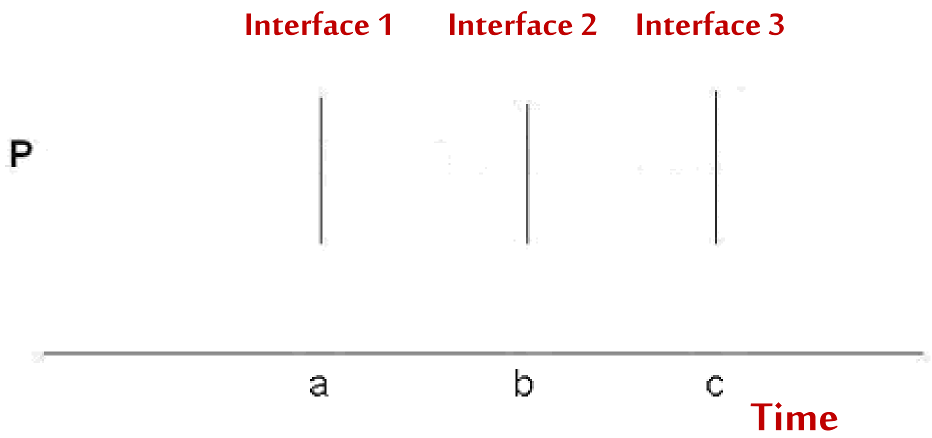




Example for Echo Ranging

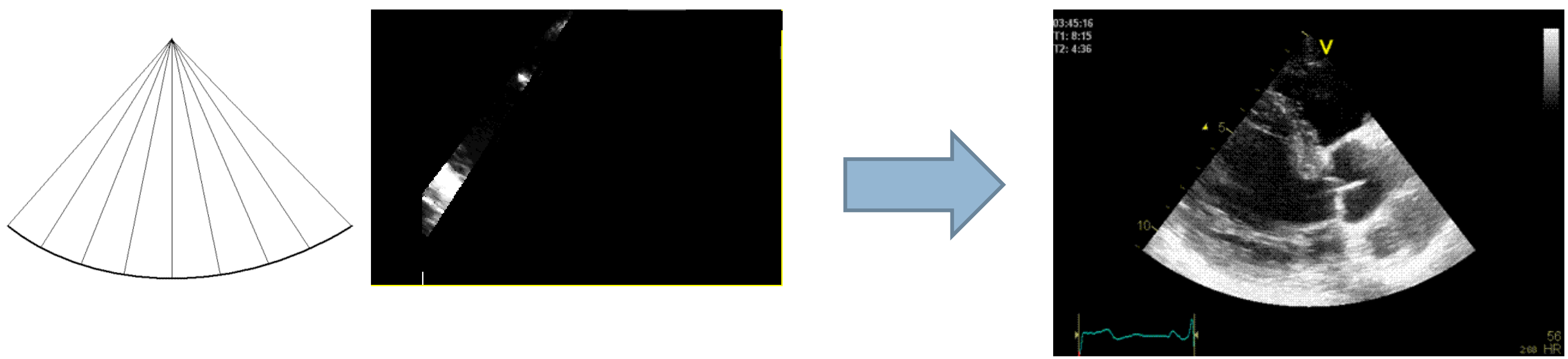
- Given that the average speed of ultrasound in tissues is 1540 m/s, if an echo returns after 130 μs from its transmission, compute the distance to the reflection surface.
  - Distance = speed x (echo time/2) = 0.1 m





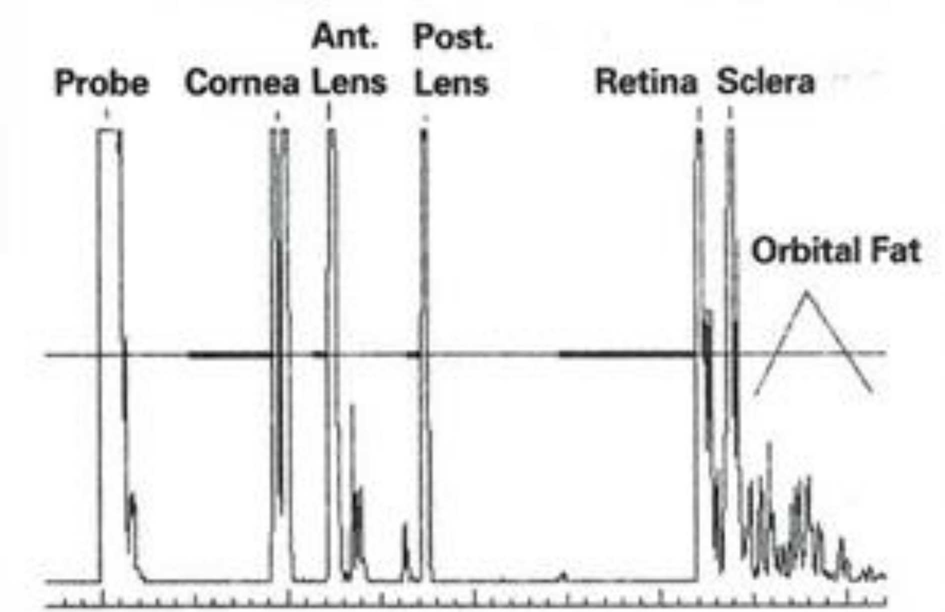
Ultrasound Image Formation

- Ultrasound waves are transmitted to a particular direction and reflected echoes are received and their time is recorded
- Compute distance of each echo based echo ranging to form a line
- Transmission in different directions are done to acquire multiple lines to form an image



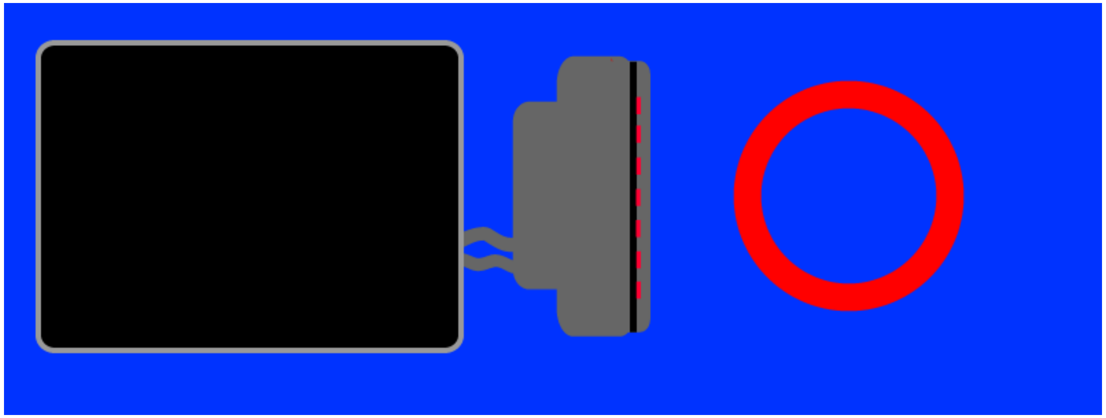
A-Mode (Amplitude)

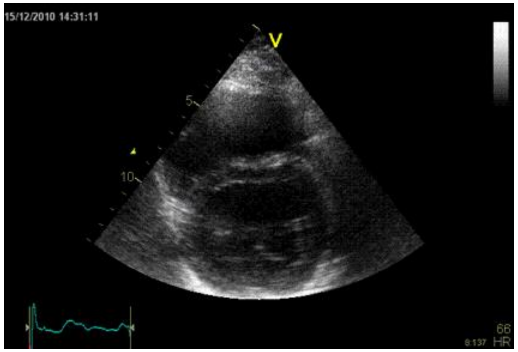
- Sends ultrasound pulse and presents received echo as 1D plot
  - Applications: opthalmology

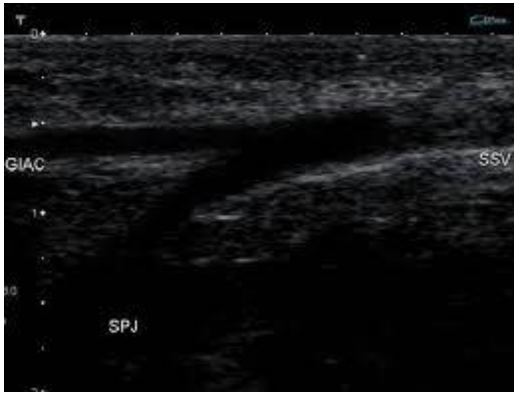


B-Mode (Brightness)

- Sends and receives echo from a particular line (direction)
  - Received echo is represented as intensity of line in image
- Scans sufficient consecutive lines to form an image
- Repeat scanning to get multiple images to show image in real-time

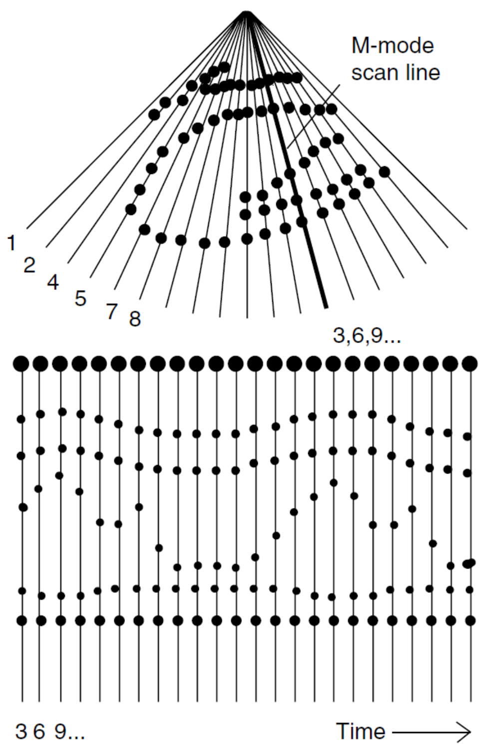


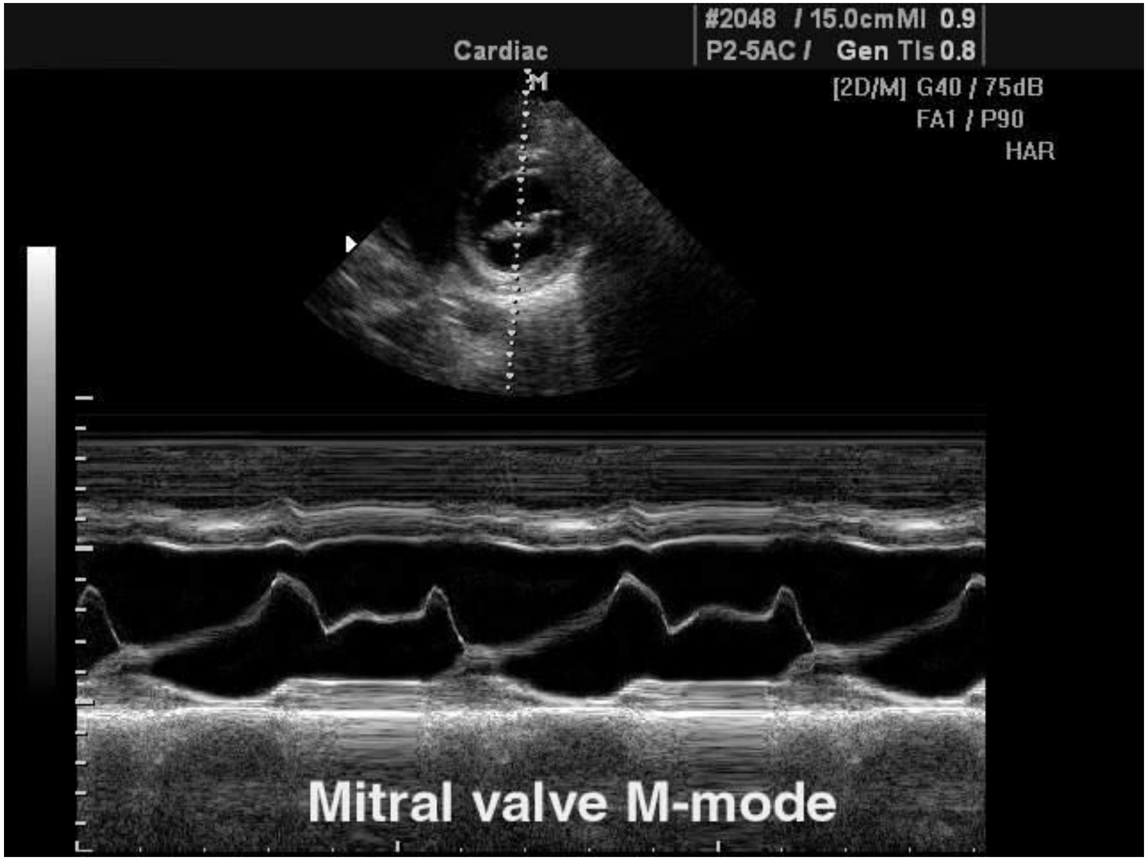




M-Mode (Motion)

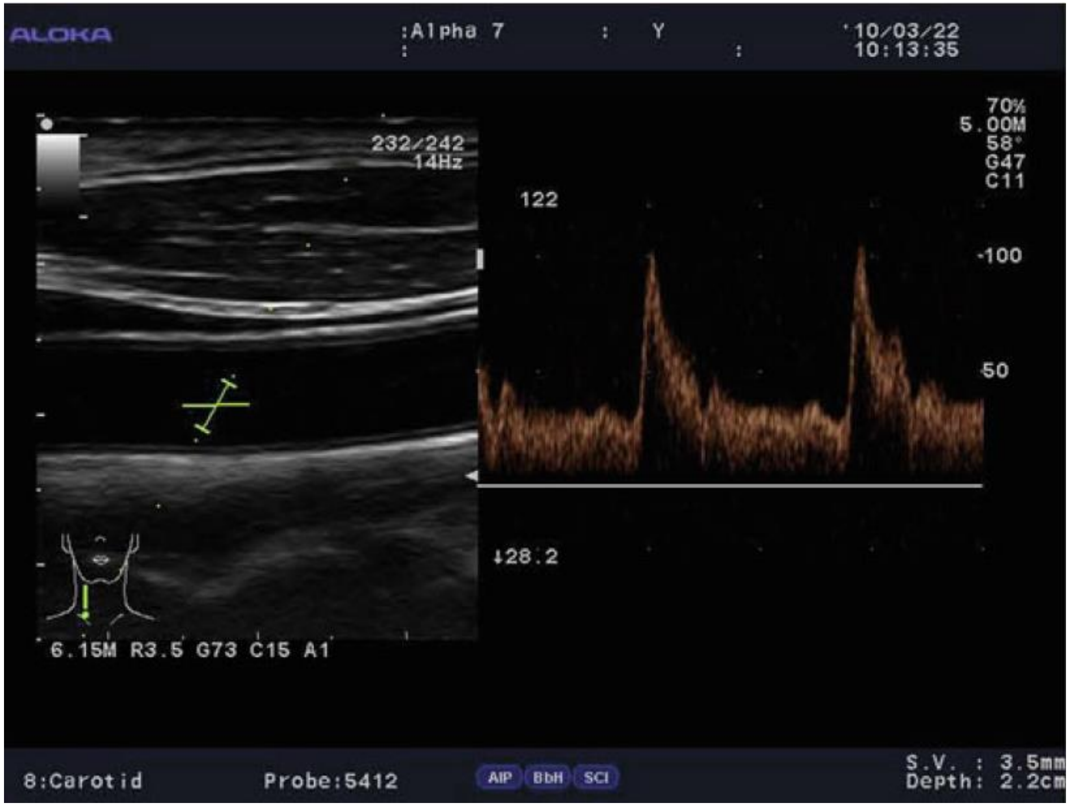
- One line in B-mode image is selected by doctor and scanned repeatedly with time – output is displayed as moving line trace
  - Application: study of heart valves





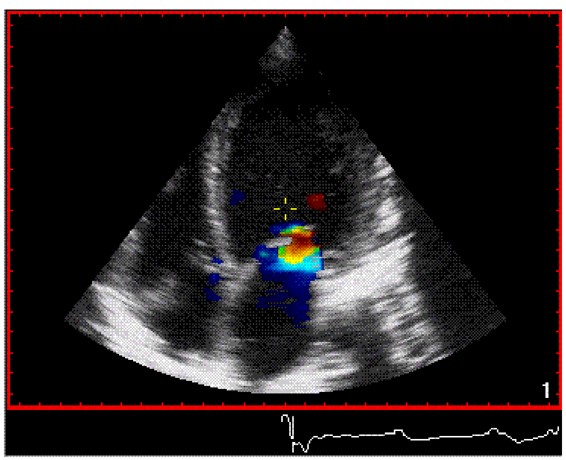
Spectral Doppler Mode

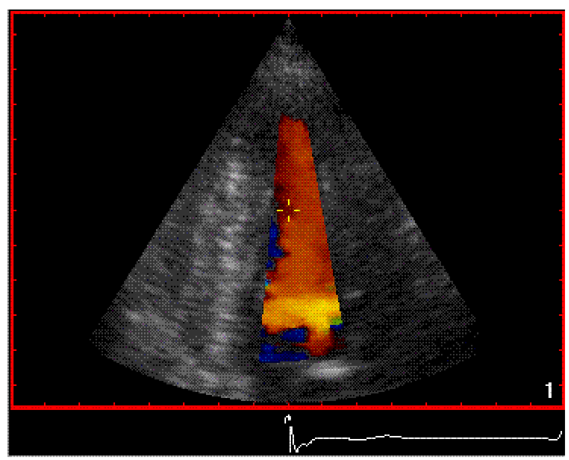
- Sample volume is selected in B-mode image to analyze its blood flow
  - Blood flow velocity profile within sample is displayed with time
  - Application: diagnosis of vascular disease (e.g., stenosis or aneurysm)

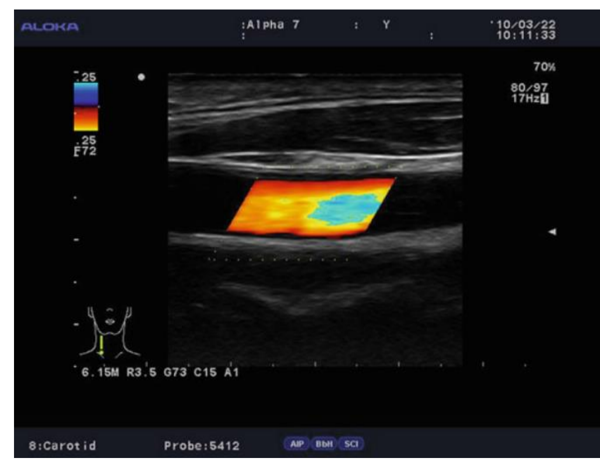


Color Doppler Mode (Color Flow Mapping)

- Instead of single sample volume, blood velocity maps within large area are estimated and displayed in color-code based on direction
  - Red: toward probe – blue: away from probe
  - Velocity mapping is done in real-time

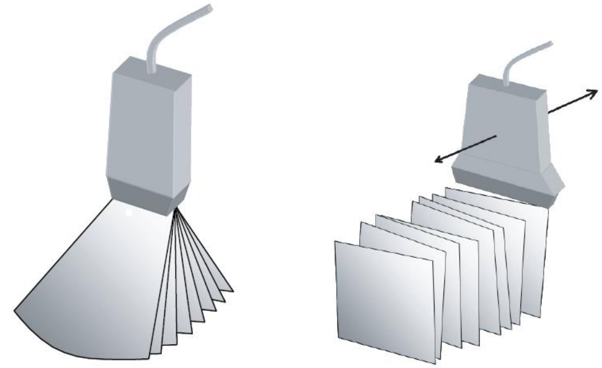






3D and 4D Imaging Modes

- Volume (multiple 2D) Scanning
  - Freehand or mechanical scanning



2D Imaging

Real-Time Slice

3D Imaging

Static Volume

4D Imaging

Real-Time Volume

Reflection of Ultrasound Waves

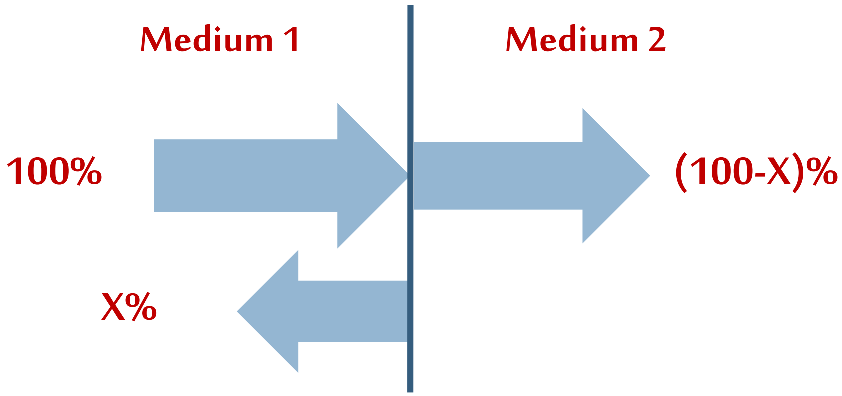
- Ultrasound waves are reflected when there is a mismatch in acoustic impedance defines as:

$$z = \sqrt{\rho k} = \rho c$$

- Reflected wave depends on difference in acoustic impedance as:

$$R_A = \frac{p_r}{p_i} = \frac{z_2 - z_1}{z_2 + z_1} \qquad \frac{I_r}{I_i} = R_i = R_A^2$$

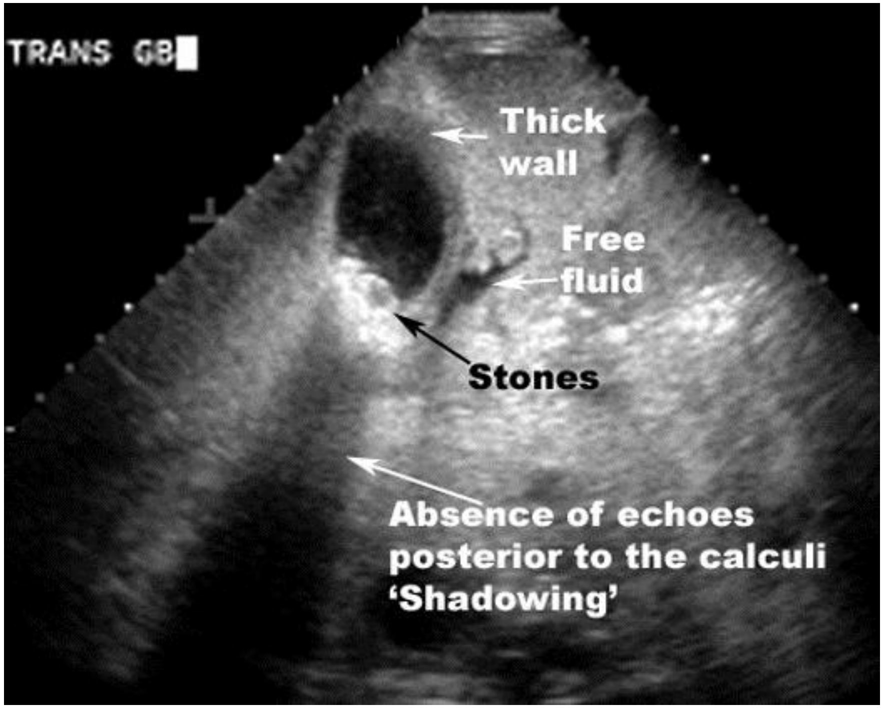
  - Important to be small enough to allow reaching sufficient depth

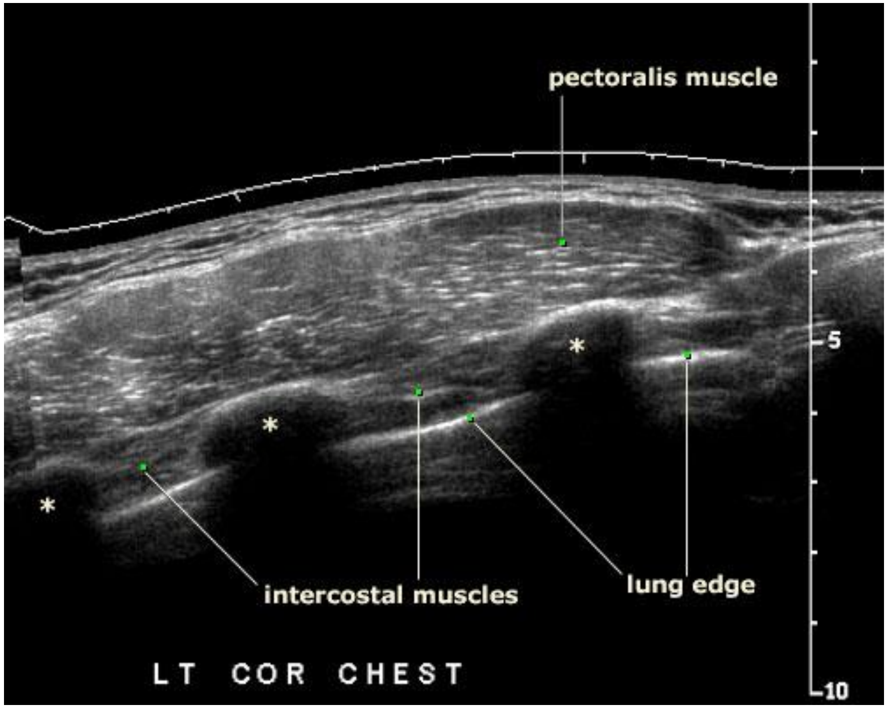


Interface	R_A
Liver–kidney	0.006
Kidney–spleen	0.003
Blood–kidney	0.009
Liver–fat	0.11
Liver–bone	0.59
Liver–air	0.9995

Example for Ultrasound Reflection

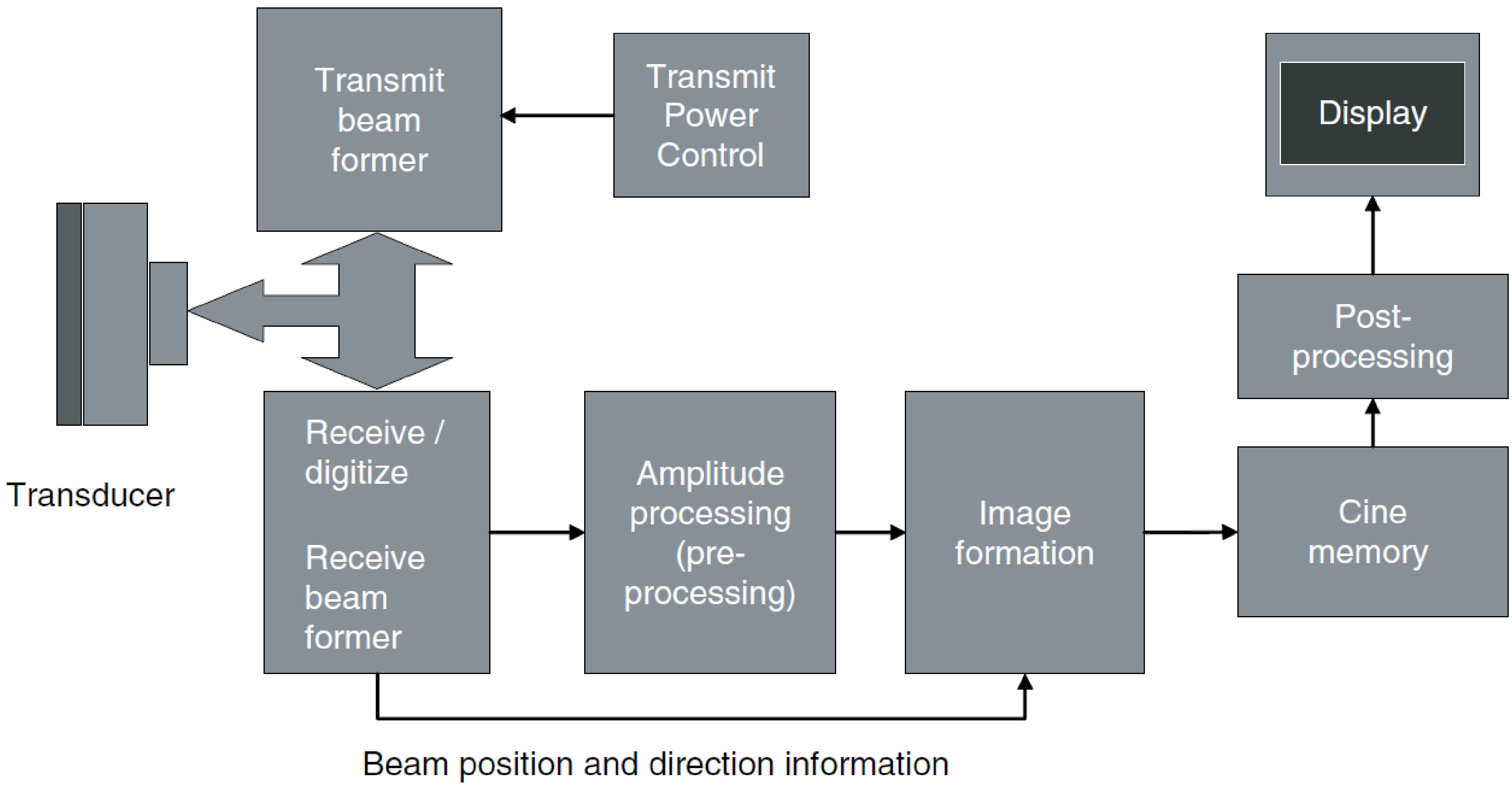
- Shadowing phenomenon
  - Evidence of presence of bone, air or stones





B-Mode Instrumentation

- Processing block diagram



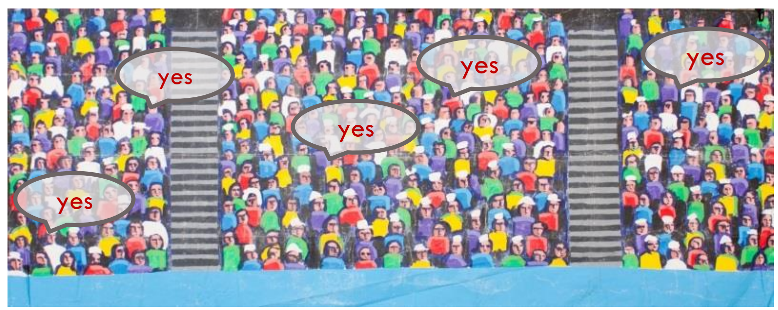
أجهزة التصوير بالموجات فوق الصوتية

Ultrasound Safety

- Ultrasound waves deposit energy in human tissues
  - Mechanical effects (e.g., cavitation)
  - Thermal effects (e.g., heating of tissues)
- To date, no clear evidence that ultrasound imaging cause harm
  - Only imaging modality allowed to scan fetus
- A fundamental approach to the safe use of diagnostic ultrasound is to use the lowest output power and the shortest scan time consistent with acquiring the required diagnostic information
  - "ALARA" principle (i.e. as low as reasonably achievable)

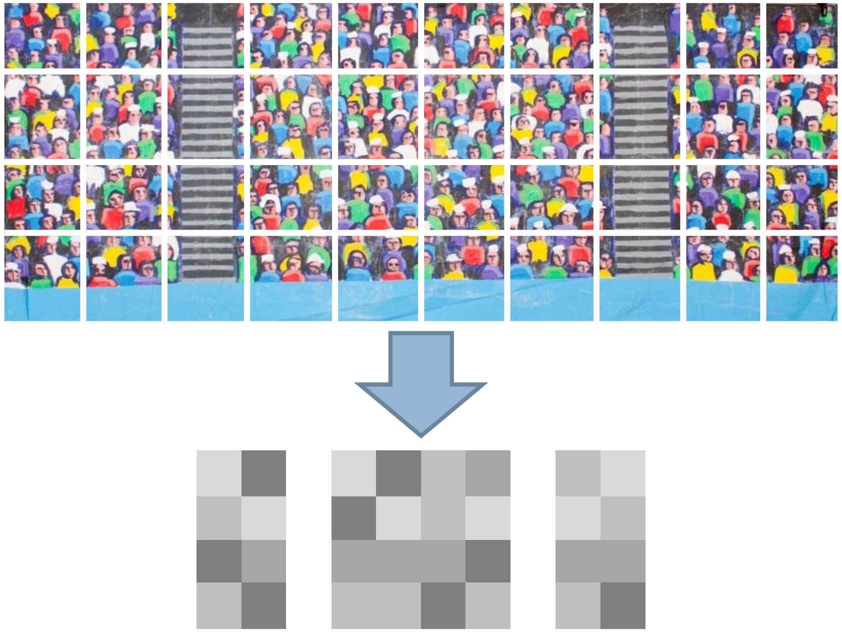
MRI: Introductory Example 1

- Question: How could we determine the number of people with name "Farid" in a population?
  - Use a calling device heard by every one to call on "Farid"
  - Wait to hear from all those who reply with "yes"
  - Measure the strength of reply received relative to that of 1 person.



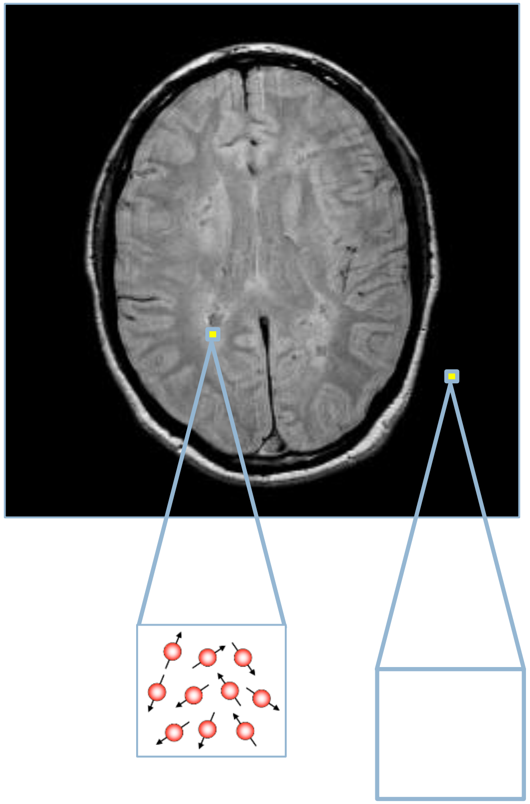
MRI: Introductory Example 2

- Question: How could we map the distribution of the people with name "Farid" in a population?
  - Divided the population into blocks
  - Call on "Farid" as before but now measure the reply within each block
  - Draw a map of the response strength in each block



Magnetic Resonance Imaging Basic Idea

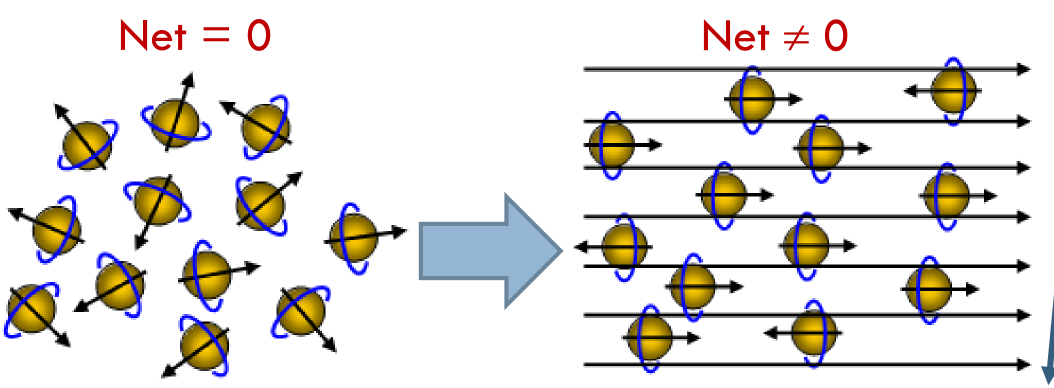
- Draw a map of the distribution of Hydrogen in human tissues
- Similar to introductory examples:
  - Population: all atoms in human tissues
  - “Farid”: Hydrogen atom
  - Map: distribution of Hydrogen atom



Nuclear Magnetic Resonance

- Physical phenomenon described by Bloch and Purcell in 1946
  - Nuclei of some atoms act as tiny bar magnets (odd number of protons or neutrons) that are aligned randomly with a net magnetization of zero
  - With applied external magnetic field, magnets tend to align with magnet and hence a nonzero net magnetization results
  - Communication with such nuclei is possible at their resonance frequency or Larmor Frequency:

$$\omega = \gamma B_0$$



No Magnetic Field

Applied Magnetic Field B0

Nucleus	Spin Quantum Number (S)	Gyromagnetic Ratio* (MHz/T)
^{1}H	1/2	42.6
^{19}F	1/2	40.0
^{23}Na	3/2	11.3
^{13}C	1/2	10.7
^{17}O	5/2	5.8

Net Magnetization Magnitude

- Follow Boltzmann distribution $e^{-(U/k_B T)} = e^{\gamma m \hbar B/k_B T}$

$$\langle \mu_z \rangle = \frac{\gamma \hbar \sum_{m=-I}^{I} m\, e^{\gamma m \hbar B/k_B T}}{\sum_{m=-I}^{I} e^{\gamma m \hbar B/k_B T}}.$$

- At room temperature, $\gamma I \hbar B/k_B T \ll 1$

$$M_z = N \langle \mu_z \rangle = \frac{N \gamma^2 \hbar^2 I(I+1)}{3 k_B T} B.$$

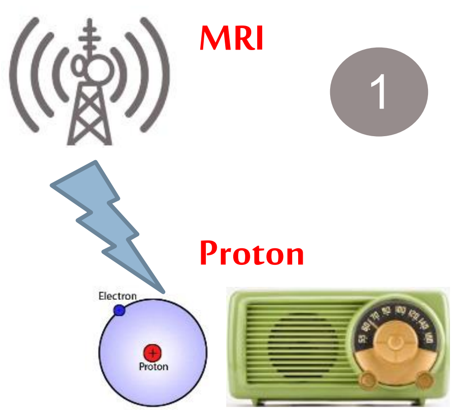
⇨ M_z is proportional to the applied field B0

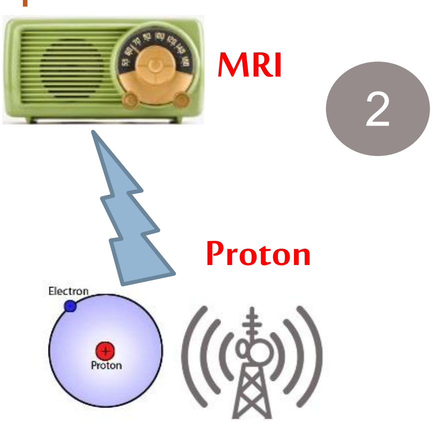
Communication with Nuclei: Introductory Example

- Radio station transmission
  - Station transmits its programs on a particular frequency
  - Each station has a unique frequency
  - Listener can pick up the station on his radio by tuning to its frequency

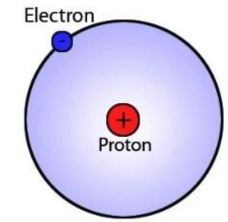
Communication with Nuclei: Proton

- Step #1: Send radiofrequency pulse at Larmor frequency of proton
  - Protons act as a radio tuned to Larmor frequency
  - Protons only can listen to this frequency – other nuclei are not tuned to it
  - Energy in RF pulse is absorbed by protons raising their energy level
- Step #2: Protons with high energy level return to their ground state
  - Protons act as radio station sending radiofrequency at Larmor frequency
  - All received RF energy at this Larmor frequency come only from protons
  - By measuring received energy, count of protons can be estimated





Why Protons?



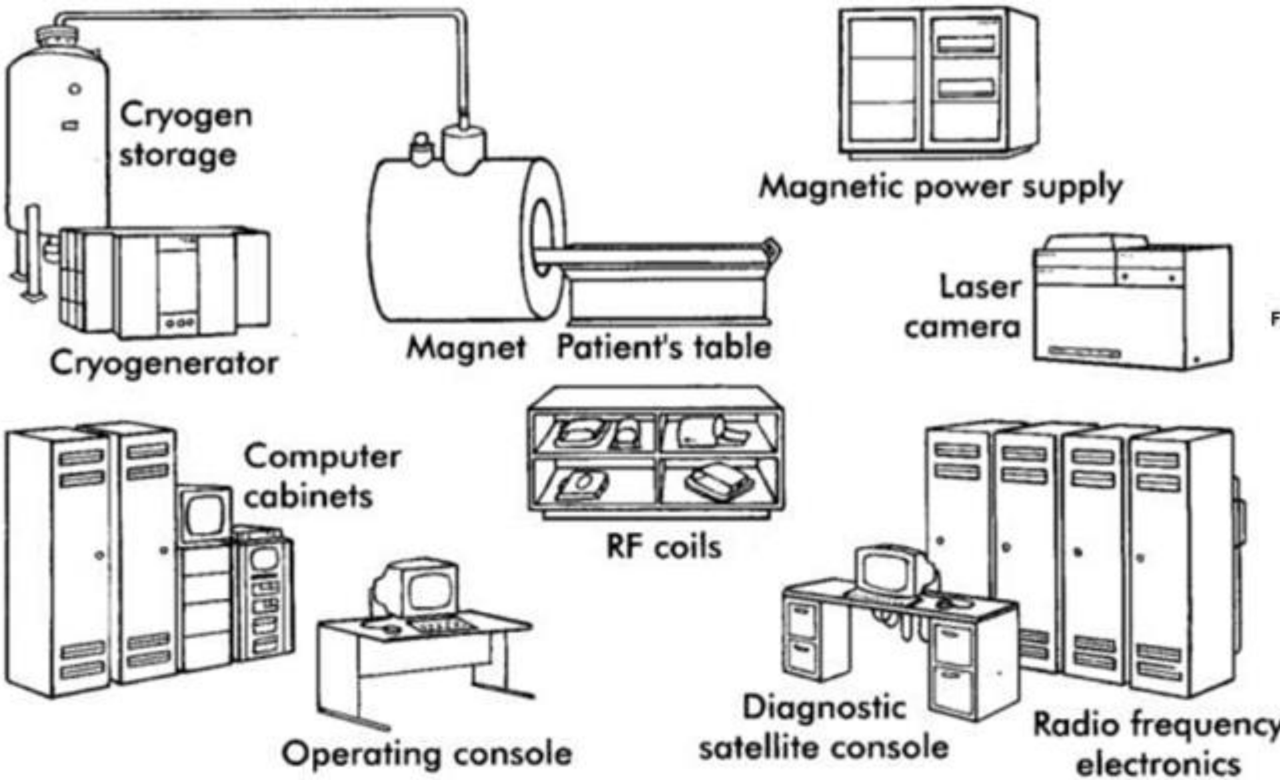
- Natural abundance and tissue abundance
- Essential part of all organic compounds
  - Variations unique to different tissue types

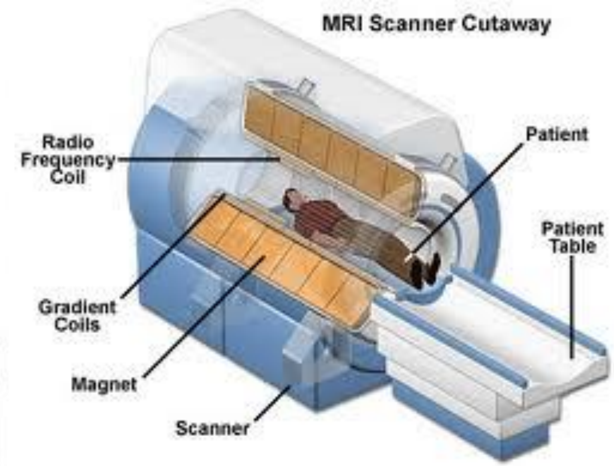
Element	Symbol	Natural Abundance
Hydrogen	^{1}H	99.985
	^{2}H	0.015
Carbon	^{13}C	1.11
Nitrogen	^{14}N	99.63
	^{15}N	0.37
Sodium	^{23}Na	100
Phosphorus	^{31}P	100

Element	Biological Abundance
Hydrogen (H)	0.63
Sodium (Na)	0.00041
Phosphorus (P)	0.0024
Carbon (C)	0.094
Oxygen (O)	0.26
Calcium (Ca)	0.0022
Nitrogen (N)	0.015

Distribution of elements in the body (by weight)		
element	**atomic number**	**percentage**
oxygen	8	65.0
carbon	6	18.5
hydrogen	1	9.5
nitrogen	7	3.3
calcium	20	1.5
phosphorus	15	1.0

MRI Components



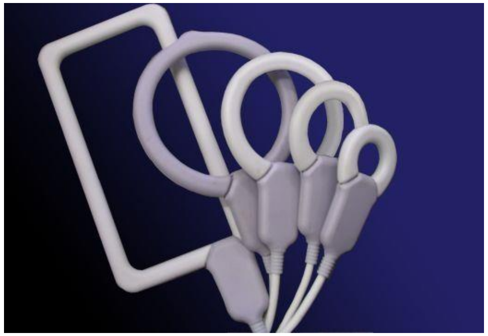


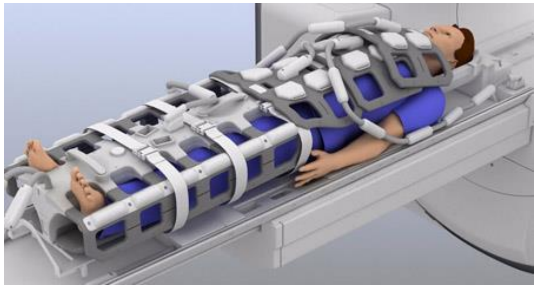
RF Coils for MRI

- The tighter they cover the imaged region, the better the quality
  - Various shapes and sizes for different applications









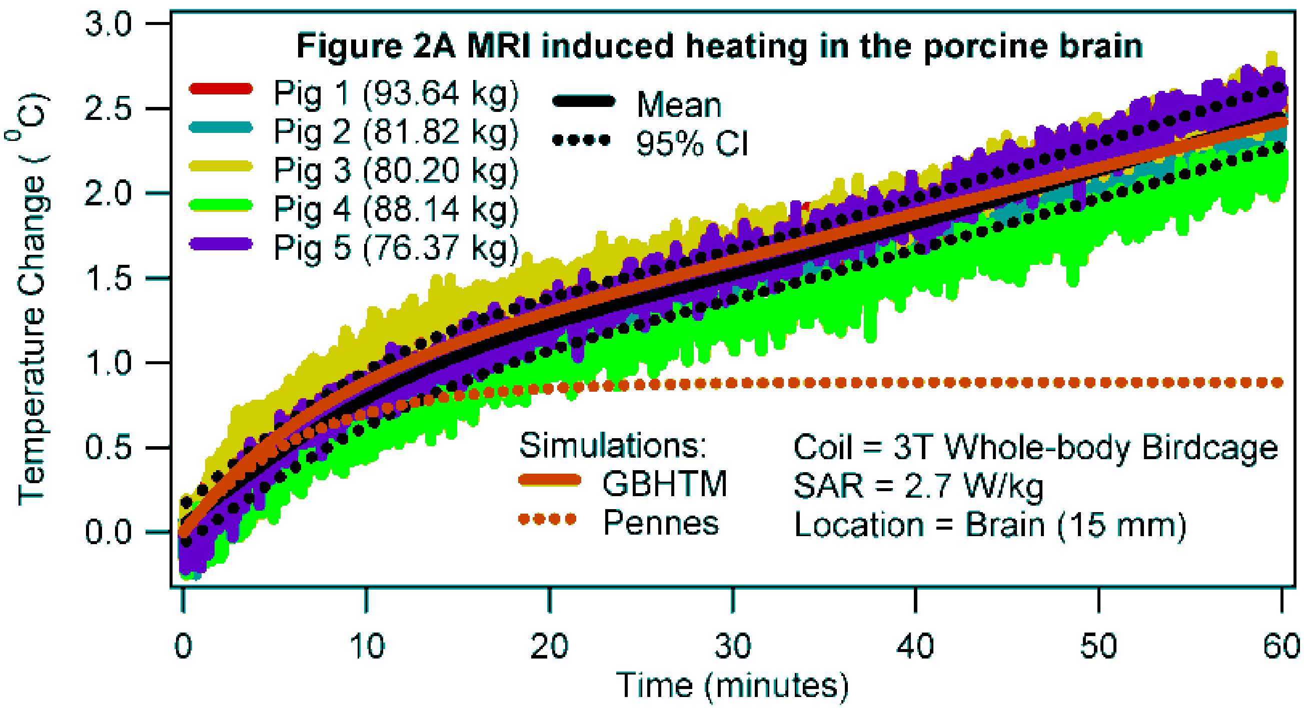
Practical MRI System Design

Open Design

Closed Design

Bioeffects of RF Energy

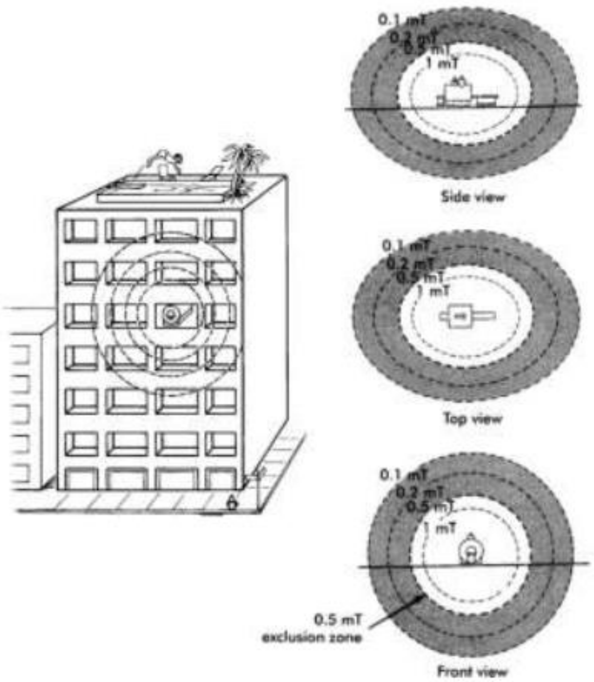
- Heat deposition
  - Strict control of such energy by MRI system safety that prevents patient exposure to unacceptable heating levels

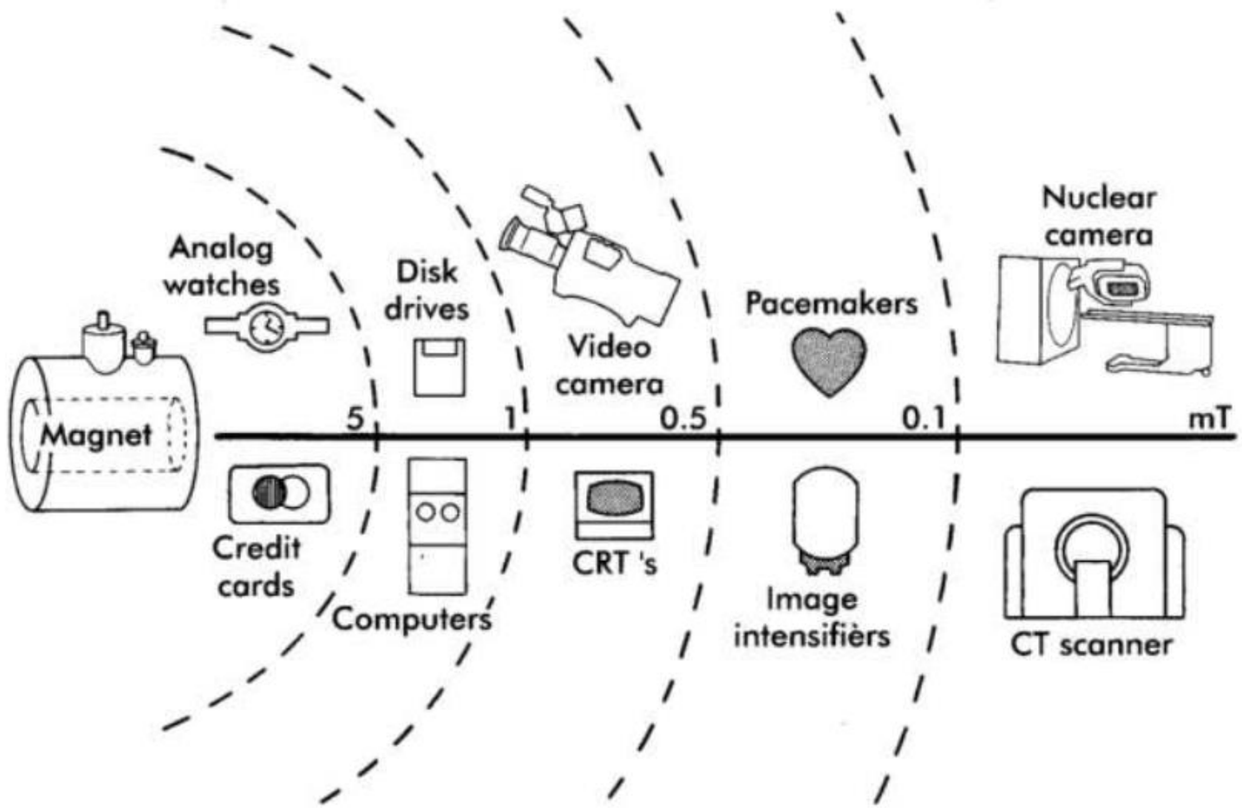


Noise During MRI Scanning

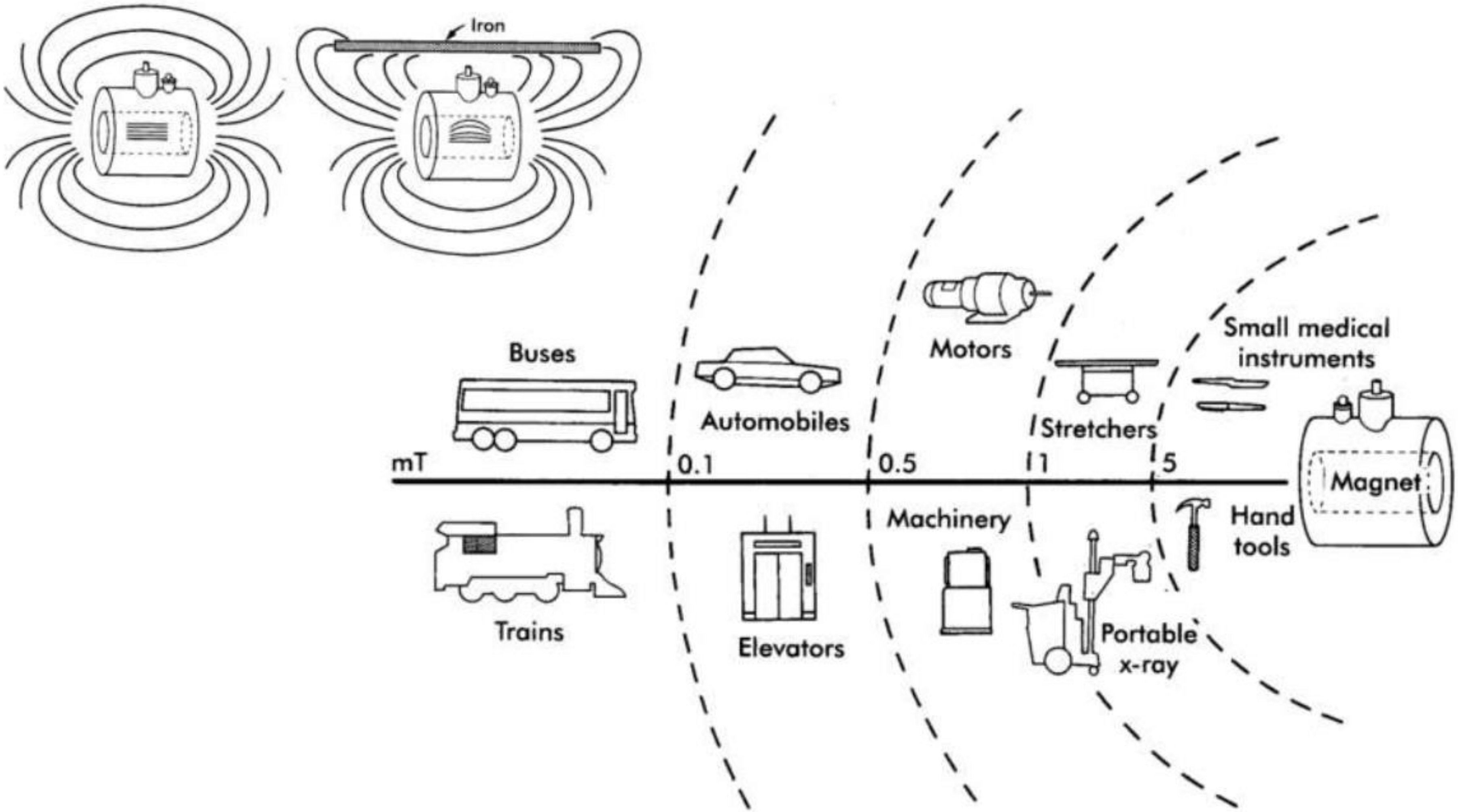
- RF pulses cause vibration of the coils and/or their packaging that result in very loud noise that could be harmful to human ears
- Patients should wear protective ear plugs or earphones during scan

MRI Effects on Environment



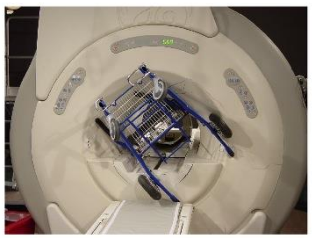


Environment Effects on MRI

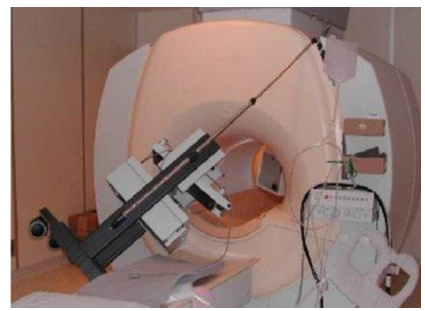


MRI Safety Incidents

- Must always keep in mind how strong the magnetic field used is and never use any ferromagnetic tools/accessories near magnet

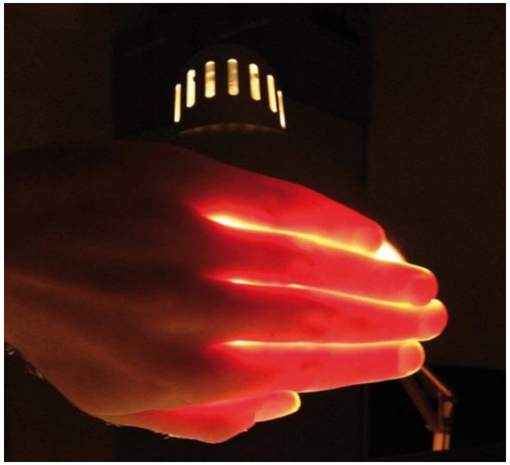






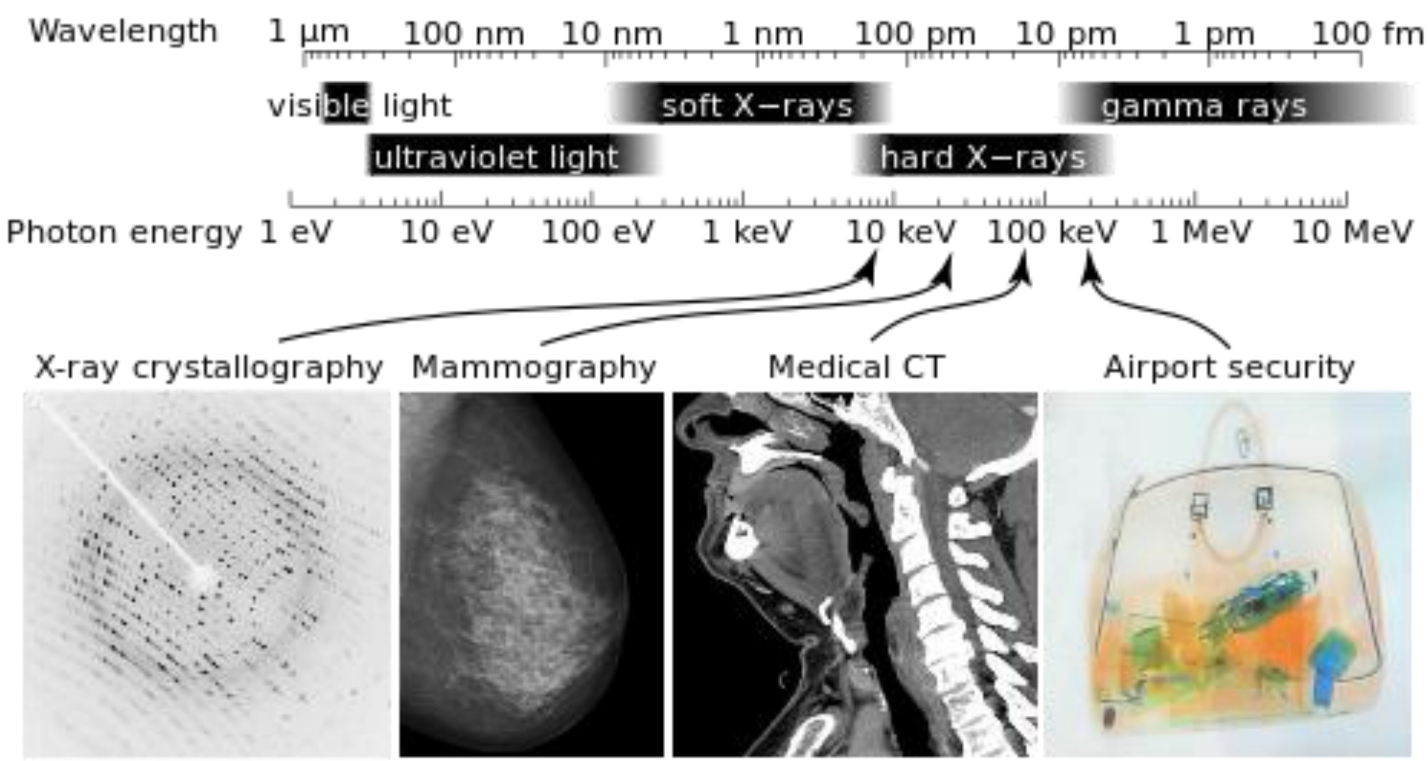

X-Ray Imaging: Introductory Example

- What happens when you put your hand in front of a flashlight?
  - Part of hand appears red while other part appears totally opaque
  - Red part: part that allowed light to pass (small thickness)
  - Opaque part: part that absorbed all light (large thickness)
- Ability of visible light to penetrate human body is very limited
  - Cannot be practically used for imaging except in very few applications
  - Can penetrate shallow soft tissues but not bone



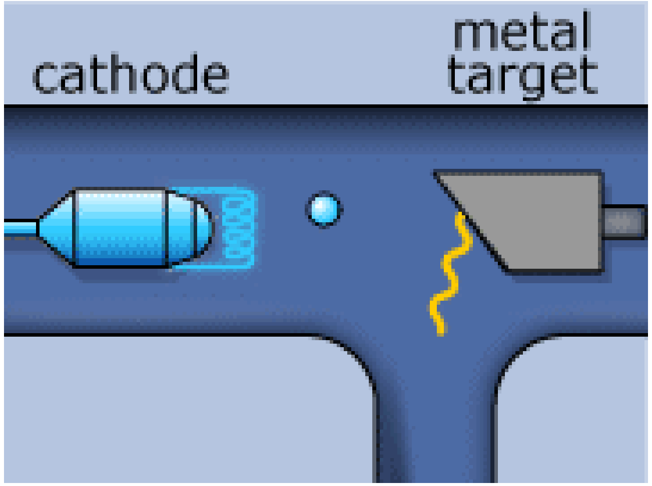
X-Ray Nature

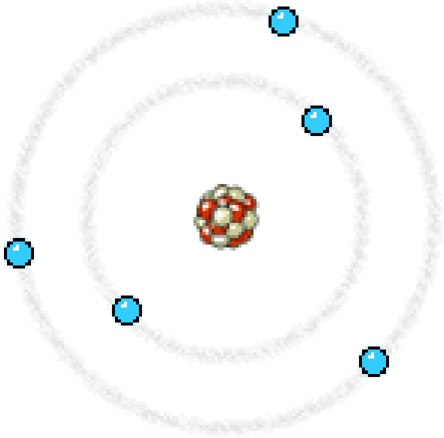
- X-Ray has same electromagnetic wave nature as light but with much higher energy
  - Allows much higher penetration and makes it useful to image human body

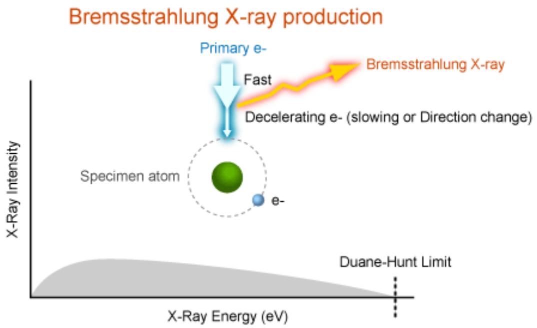


X-Ray Generation

- Heavy metal (Tungsten) target is bombarded by high speed electrons
- When electron enter electric field inside an atom, it decelerates until coming to a complete stop giving off its energy as photon
  - Process called "Bremsstrahlung"
  - Resultant X-Ray beam depends on count and speed of electrons

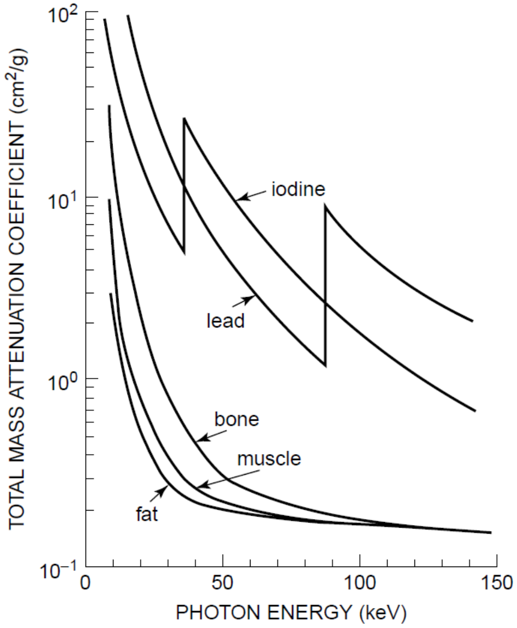






X-Ray Attenuation inside Body

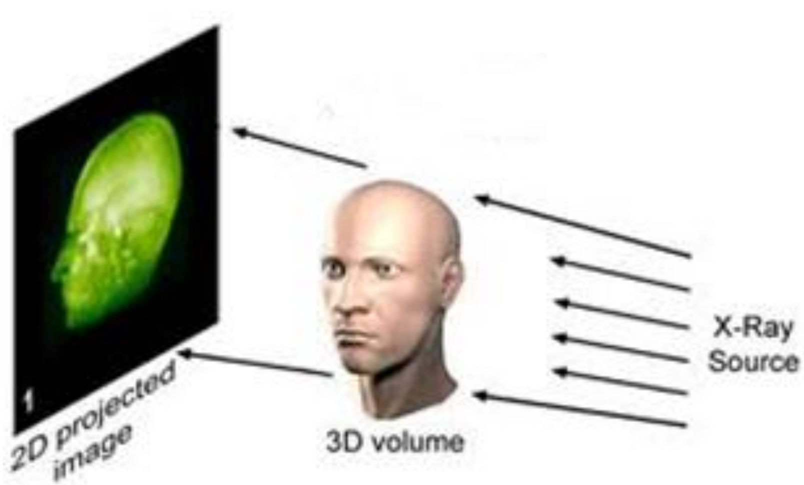
- Contrast mechanism in X-Ray images
  - X-Ray image is just a map of absorption in different parts of the body

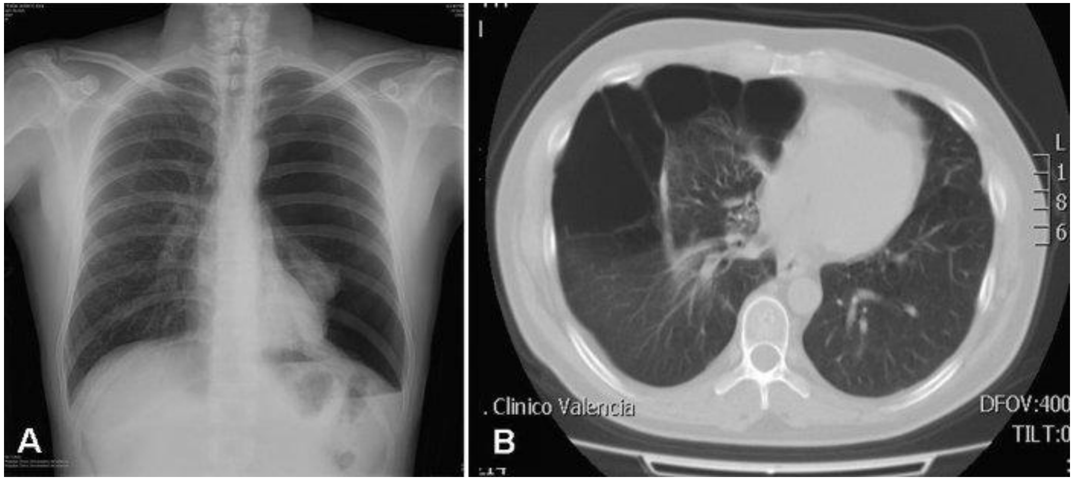


Tissue	Attenuation Coefficient At 60 keV
Bone	0.528
Blood	0.208
Fat	0.185
Soft tissues	0.213
Water	0.206
Air	0.0004

X-Ray Imaging Basics

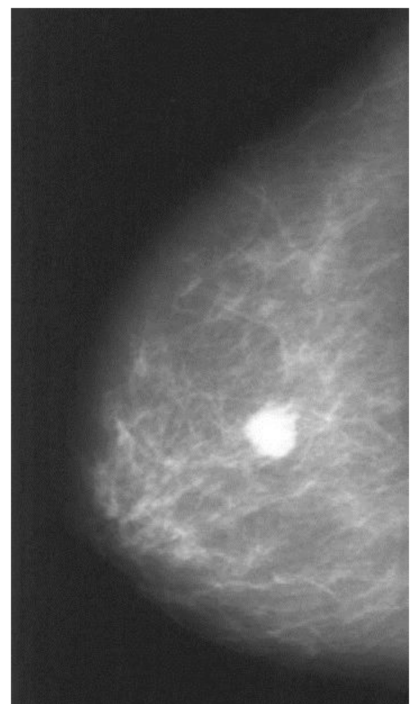
- Projection imaging
  - Internal organs (3D) overlap in the resultant 2D image
  - Every point in the image comes from all tissues in the path of the X-Ray

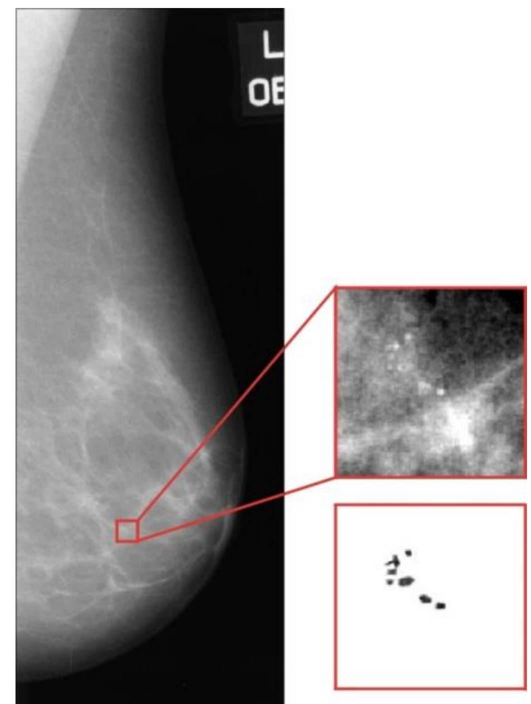




Mammography

- Imaging using low-energy X-Rays
- Considered as the standard method for screening due to its high resolution and sensitivity





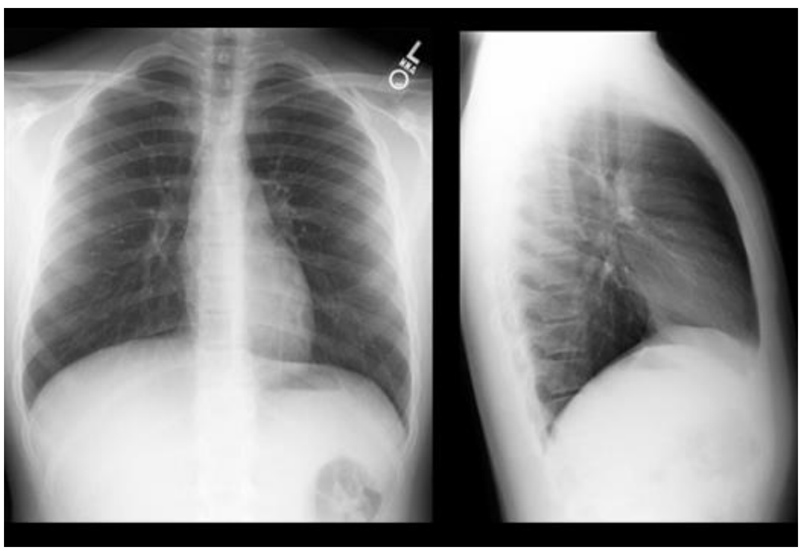
Plain X-Ray Imaging of Bone

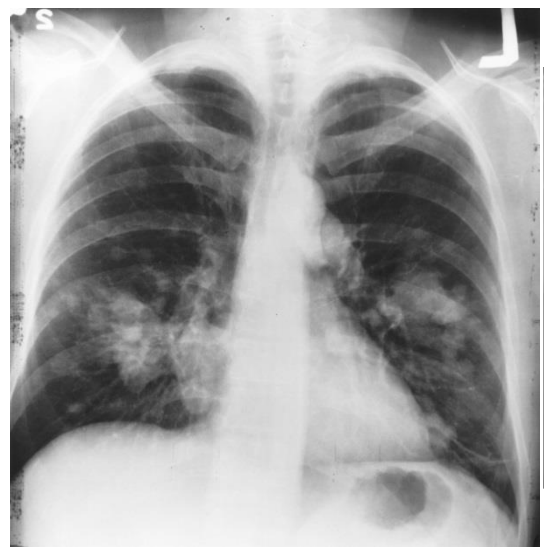
- Imaging using high-energy X-Rays
- Allows viewing of bones, joints and artificial implants



Plain X-Ray Imaging of Chest

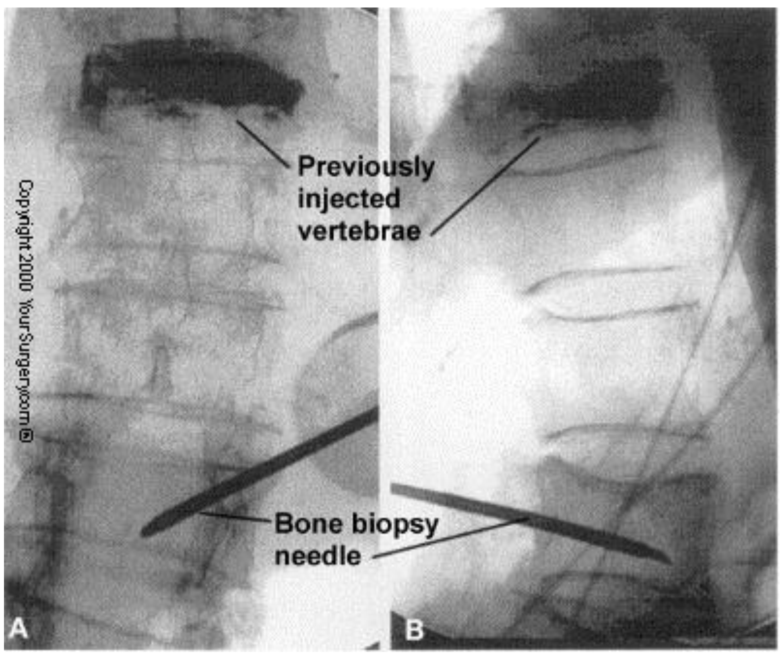
- Imaging using medium-energy X-Rays
- Allows accurate diagnosis of any pathological changes in lungs





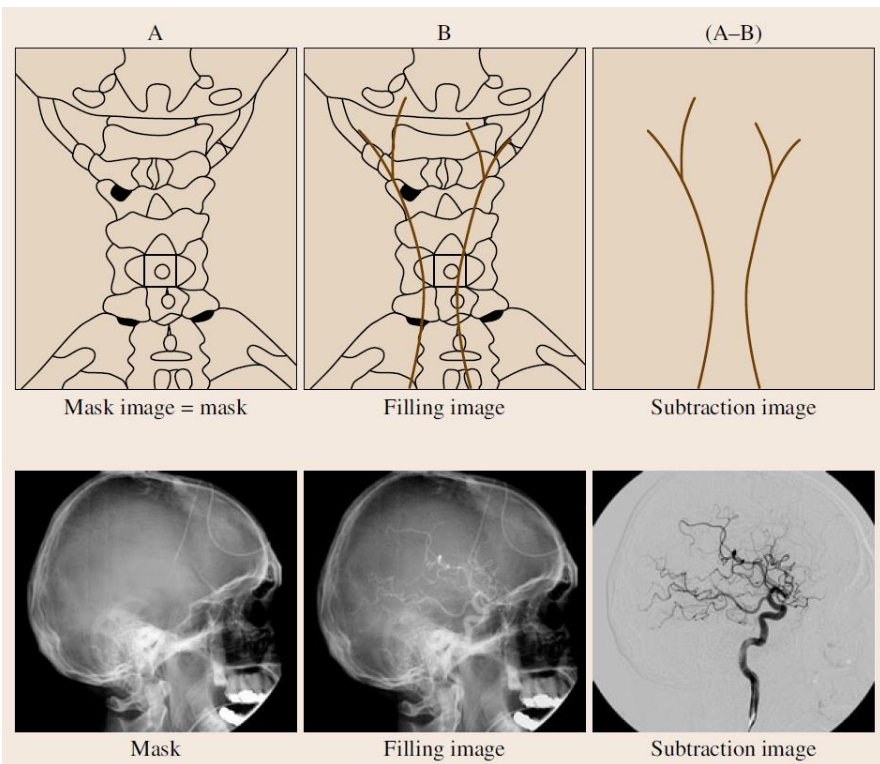
Continuous X-Ray Imaging (Fluoroscopy)

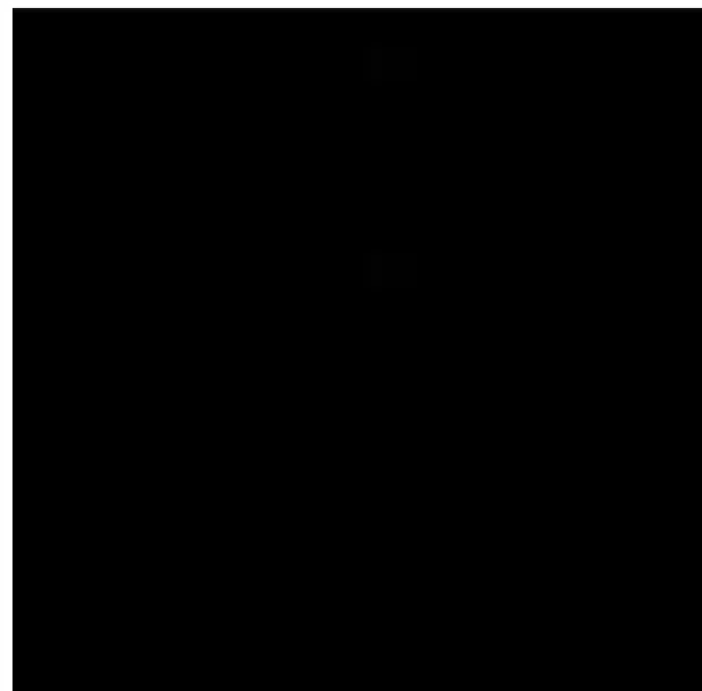
- Surgeon can inject contrast material to view vessels
- Follow up of needles or catheters during surgical procedure



Digital Subtraction Angiography

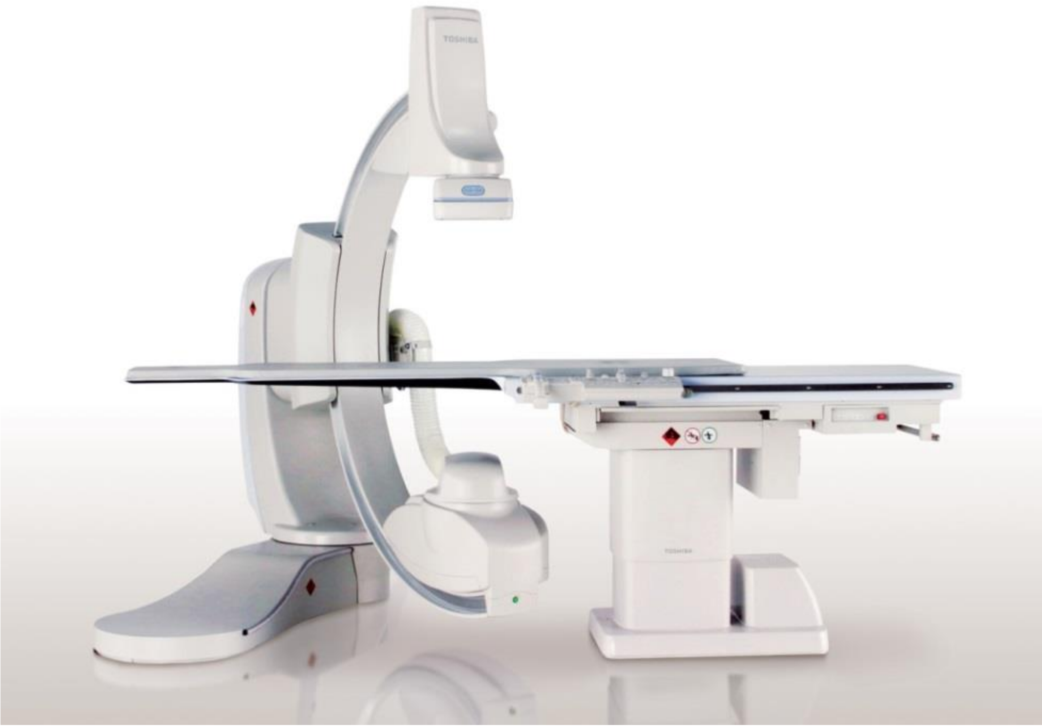
- Allows cleaner viewing of vessels by subtracting X-Ray images before and after injection of contrast agent





Plain X-Ray Imaging System

- Film-based (old) or Digital (new)
  - Digital x-ray systems eliminate problems in film and processing and are more environment-friendly



Difference Between Analog and Digital Systems

Analog (Film)

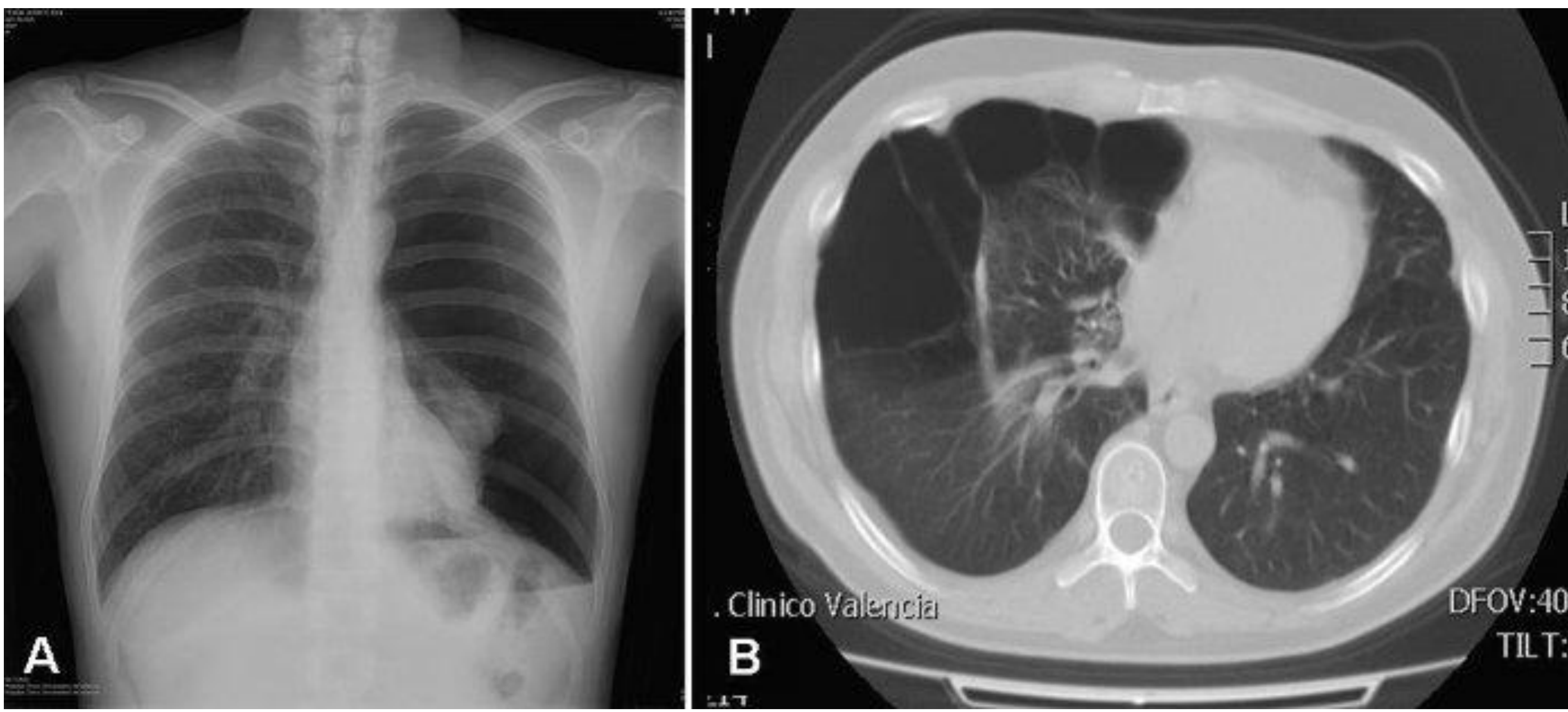
Digital (Filmless)

Film vs. Digital Images

- Contrast enhancement in digital systems allows much better viewing

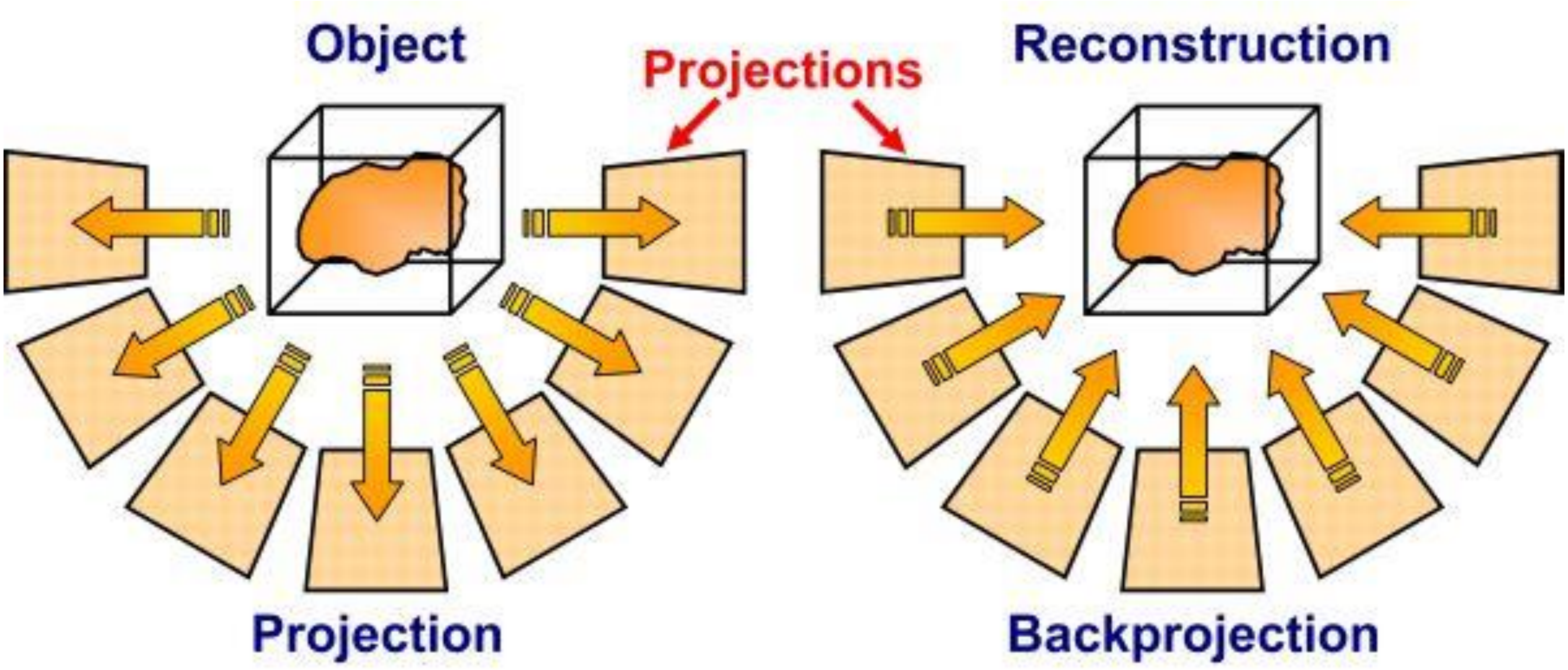
Computed Tomography (CT)

- Tomography aims to image slice of the body
  - Eliminate overlap problem in projection imaging
  - Each point in the image represents a single point in reality not an accumulation of many points as in projection imaging

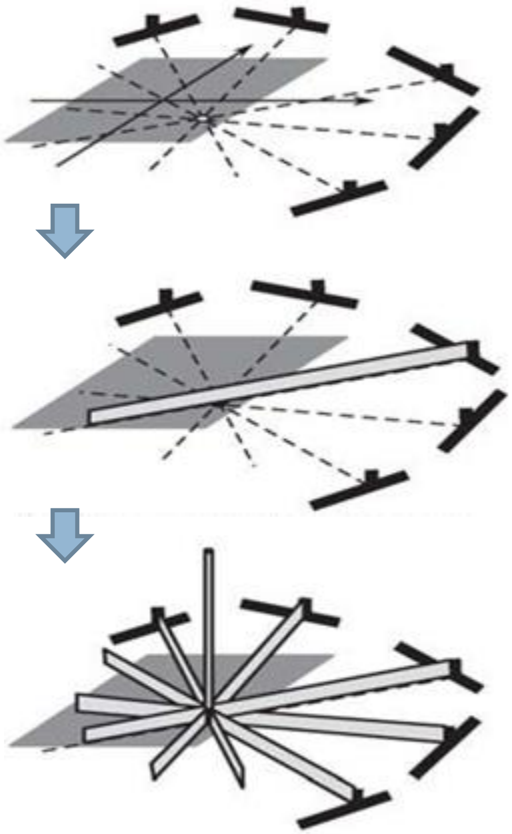


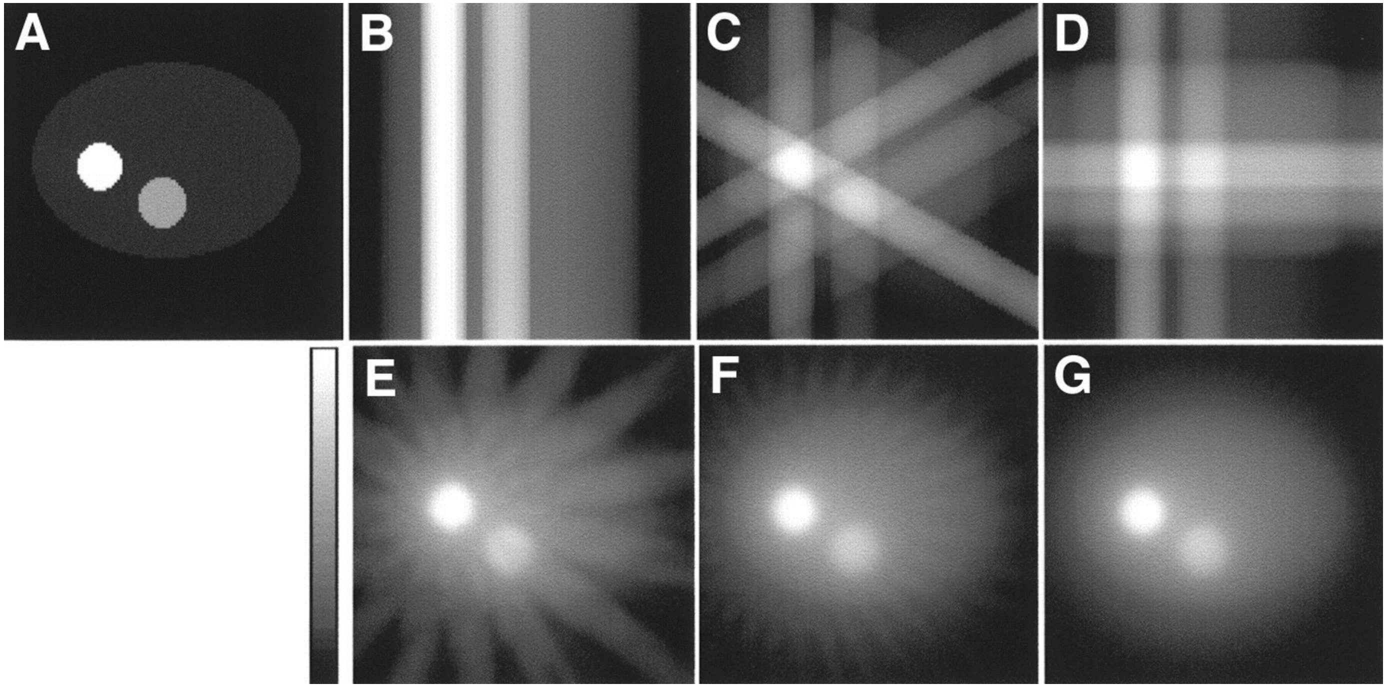
Acquisition and Reconstruction: Backprojection

- Collect projections of the object from different angles
- Distribute each projection equally among all points in its path

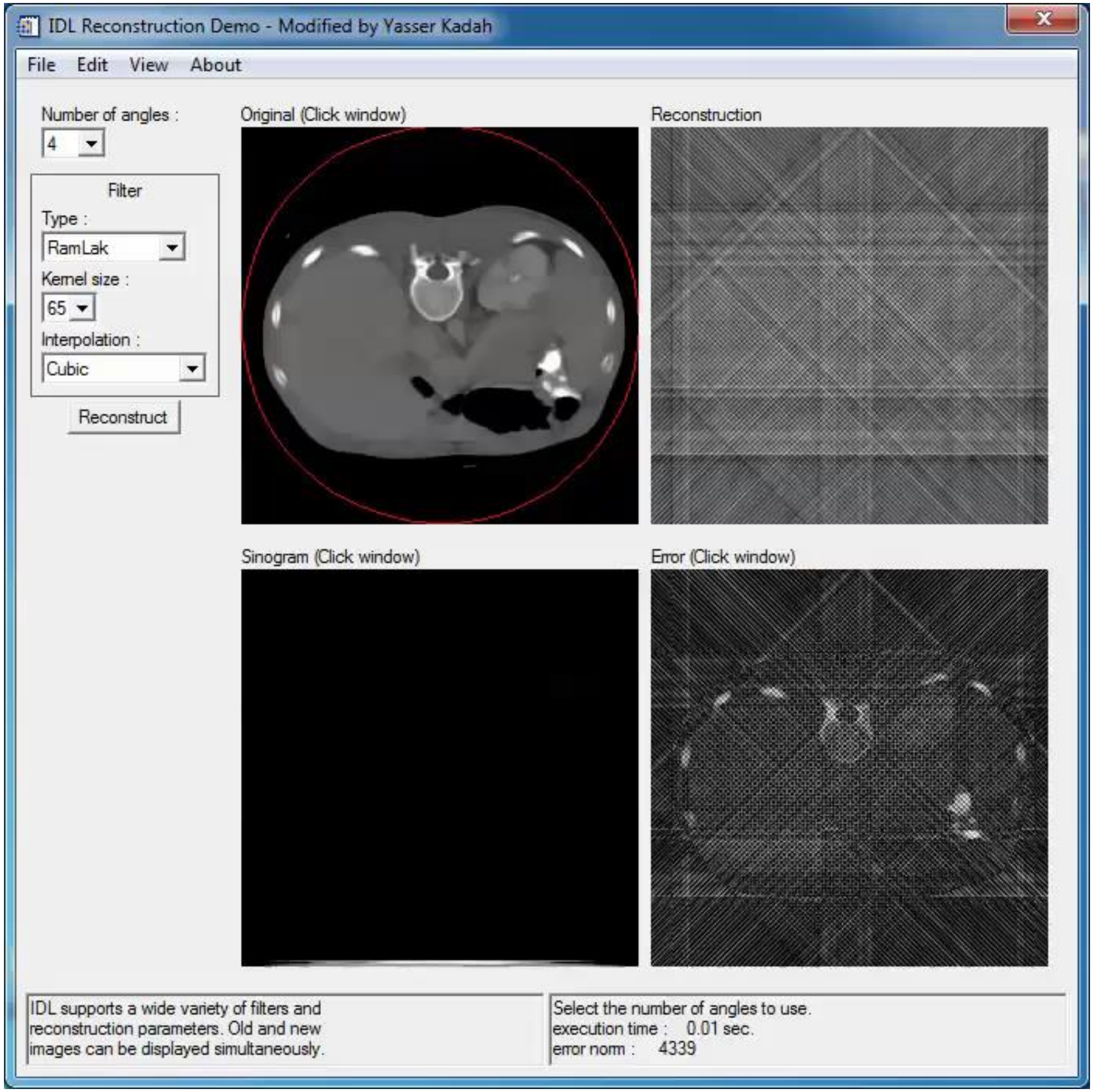


Example for Backprojection

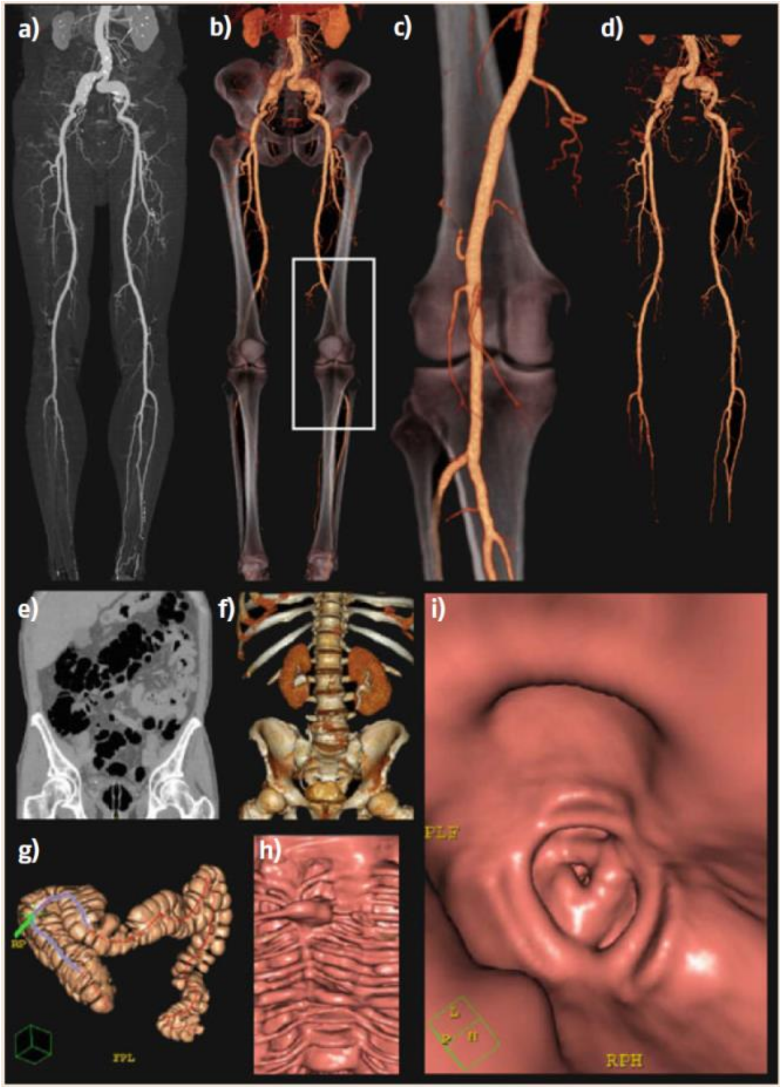


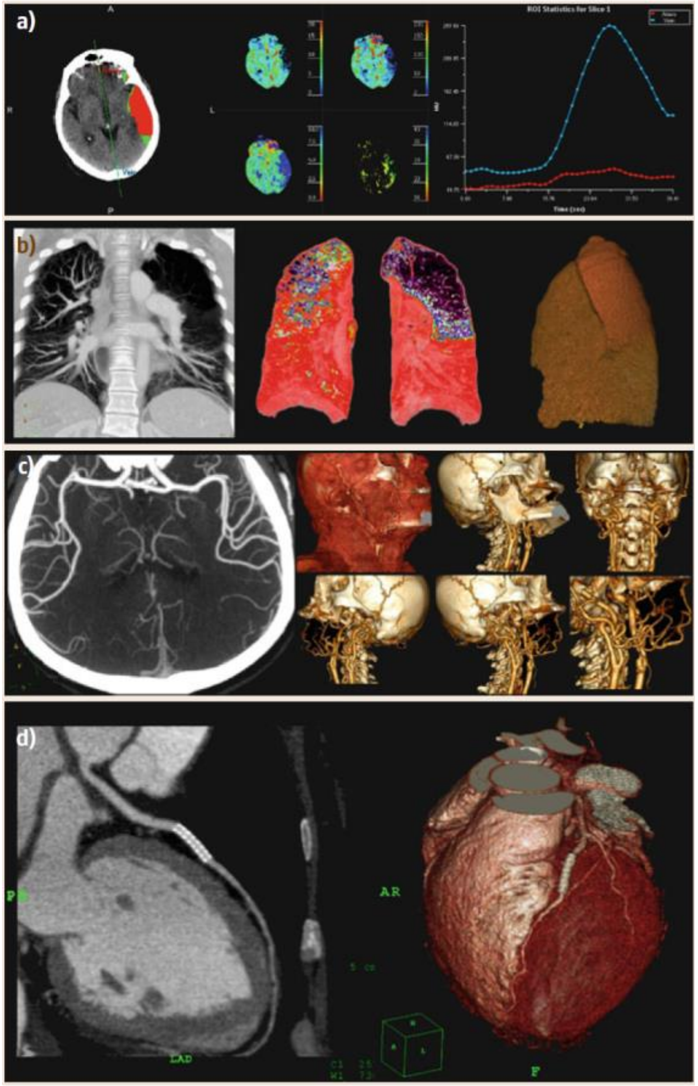


Demo of Actual Image Reconstruction

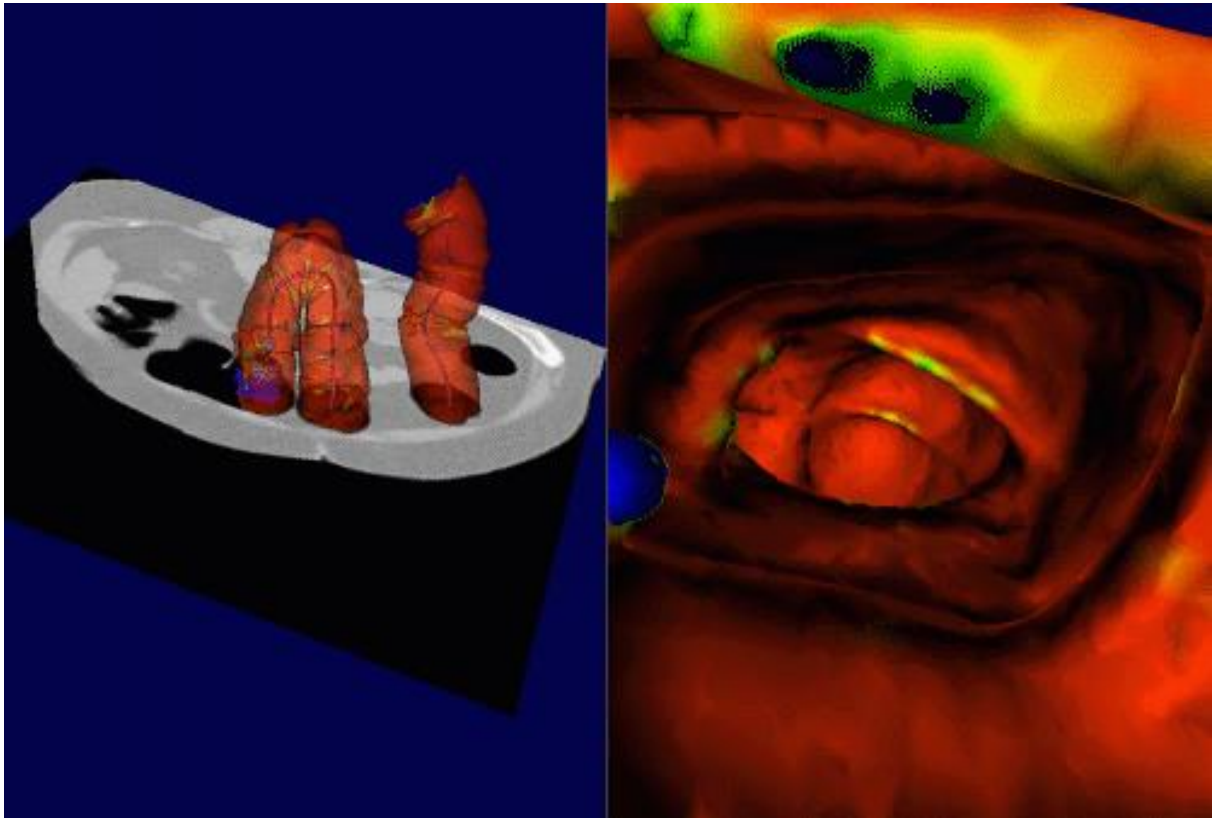


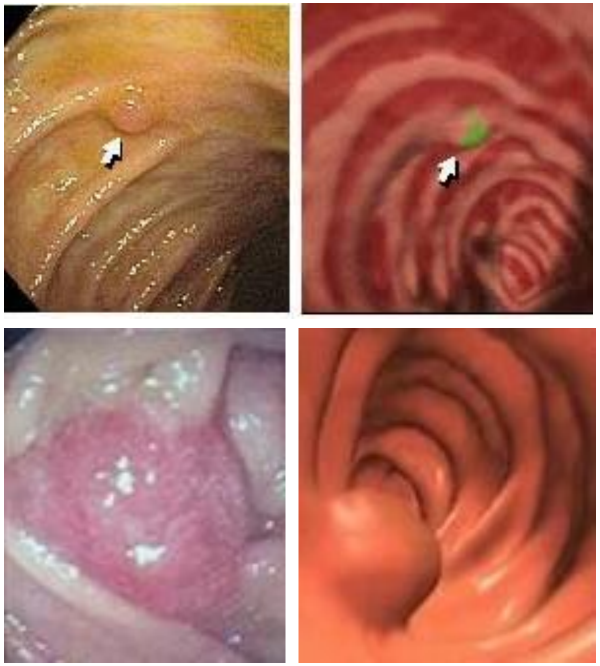
CT Imaging Applications





Virtual Colonoscopy



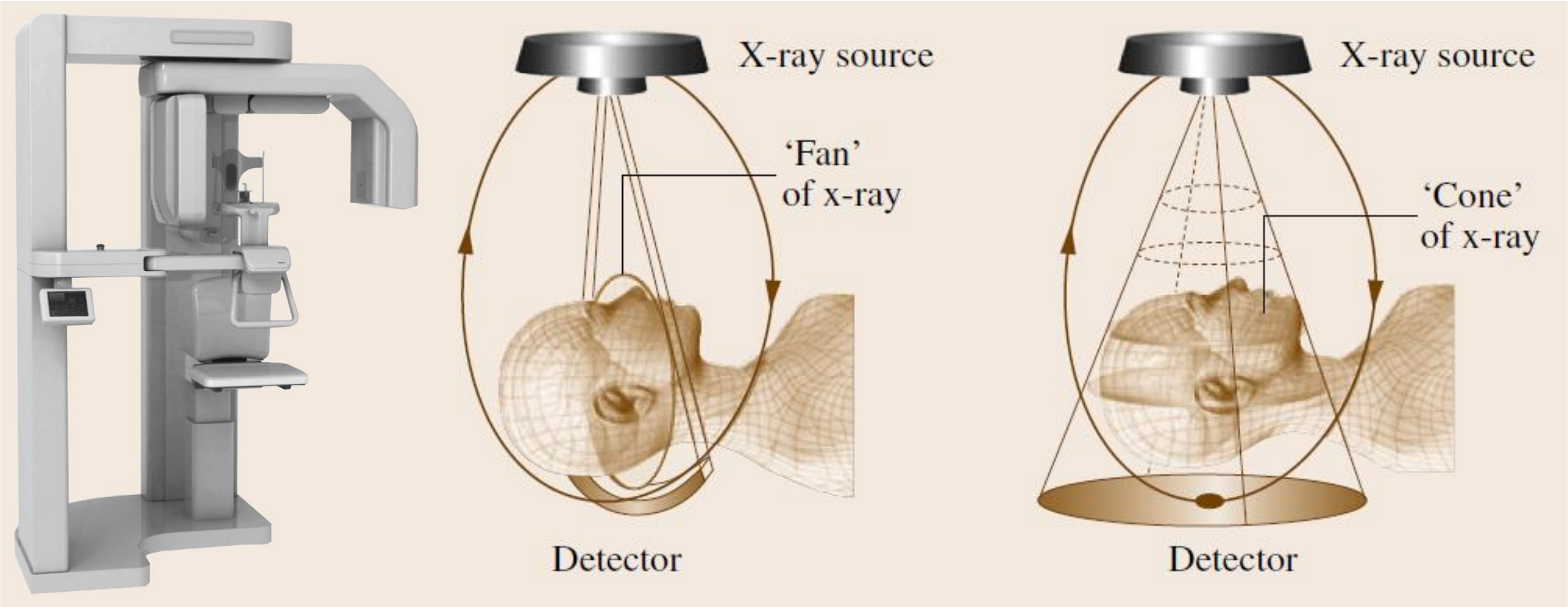


Modern CT Systems

- Multislice CT
  - The more the slices, the faster the system

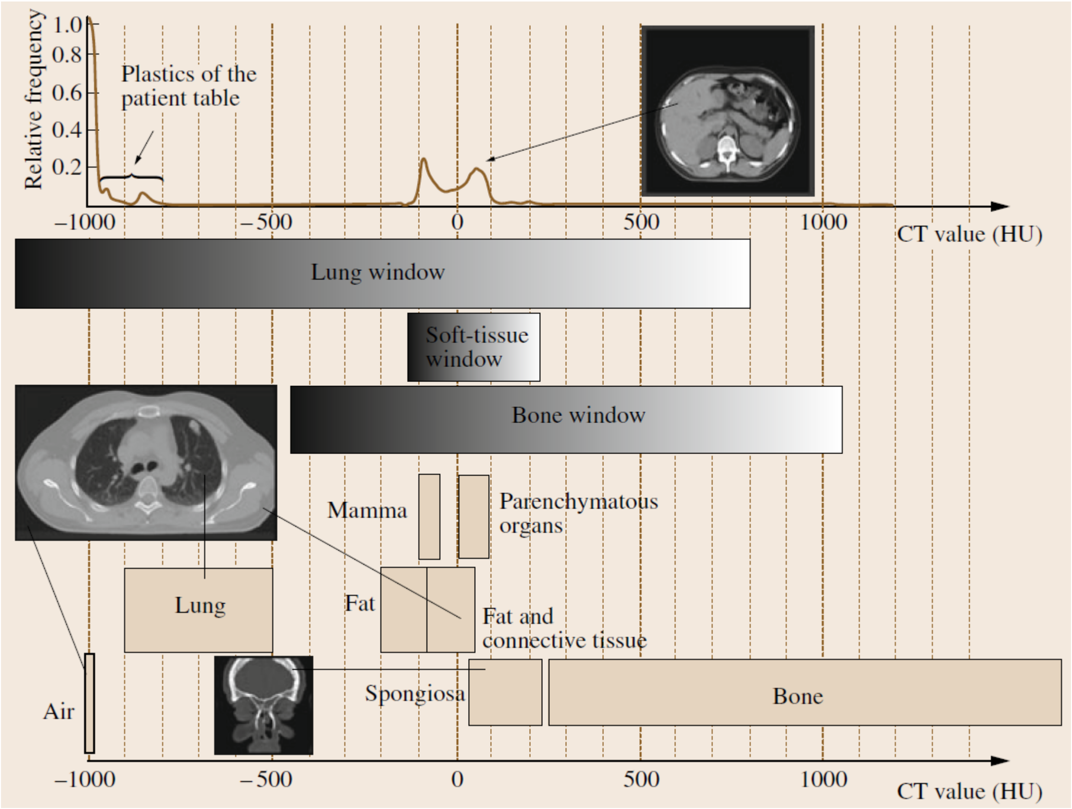
Cone Beam CT

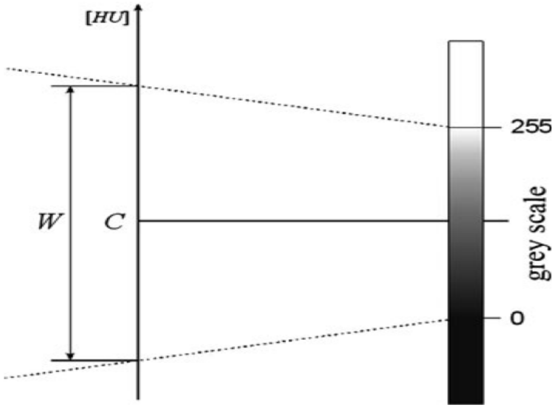
- Mainly used for dental application now



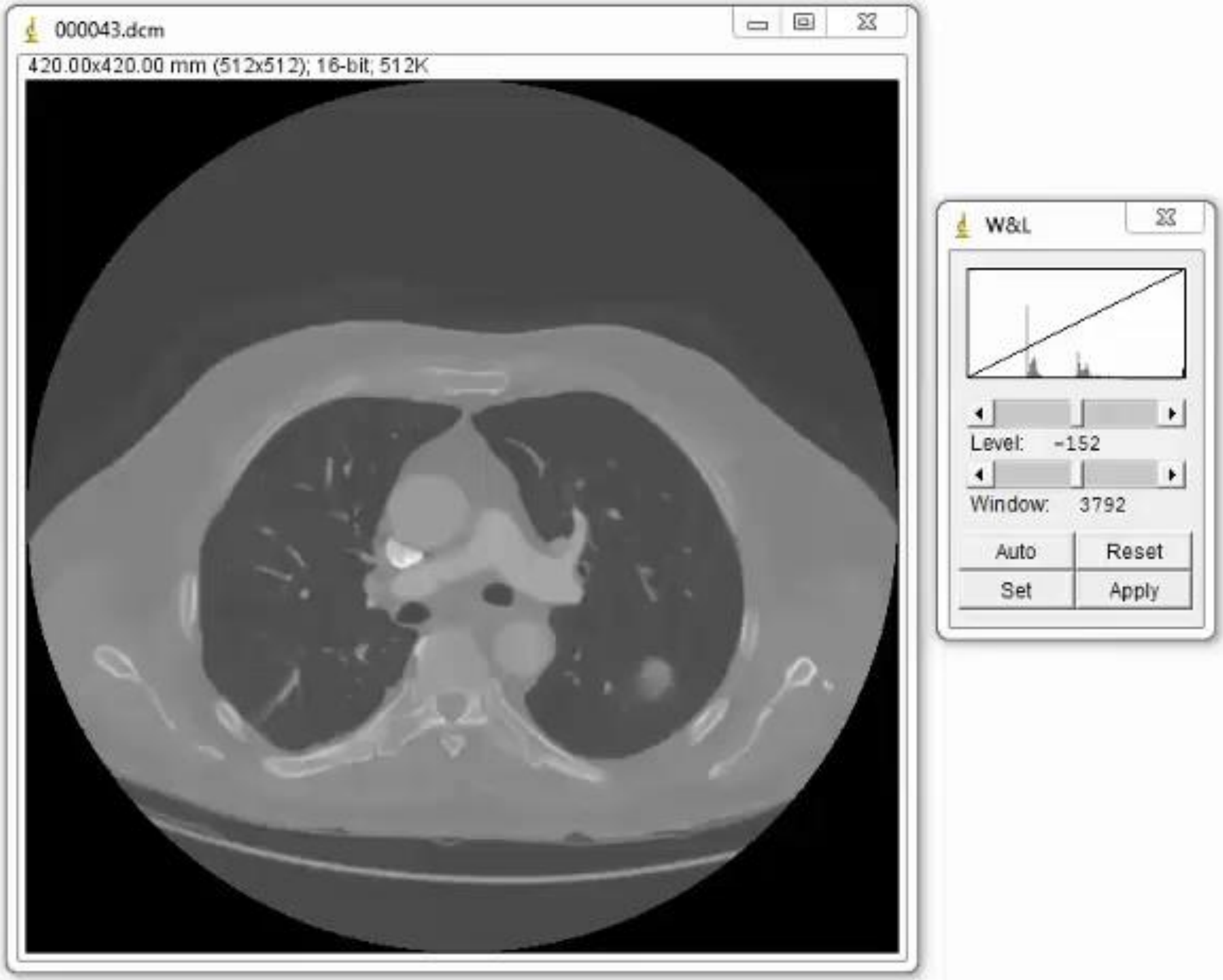
Display of CT Images

- Windowing method
  - To allow compatibility of images with available displays and human eye



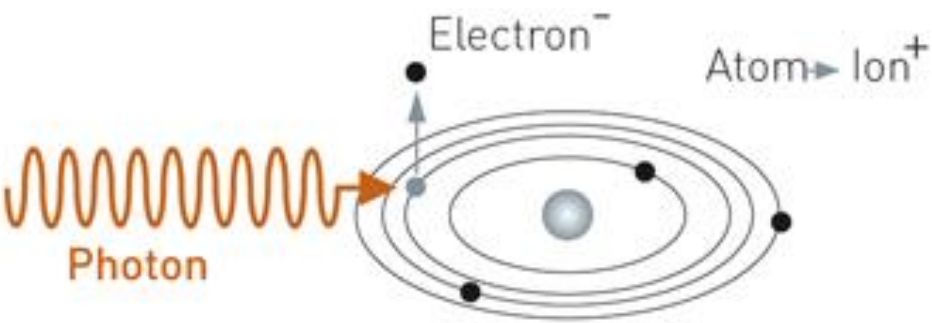


Demo of Actual CT Image Windowing



Bioeffects of X-Rays

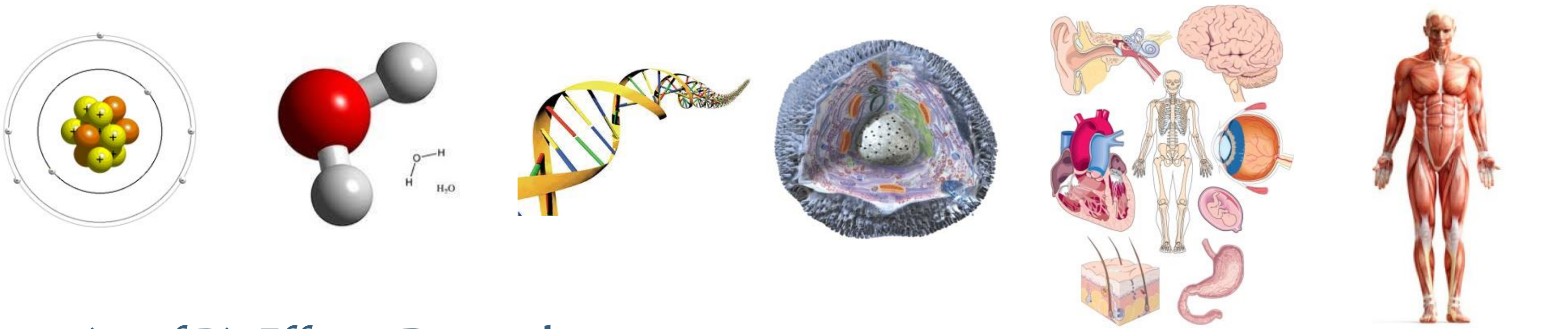
- X-Ray is ionizing radiation
  - X-Rays interact with atoms inside human tissues and results in having high speed electrons going out
  - High-speed electrons are known to break chemical and genetic bonds which have profound short and long term bioeffects



$$H_2O \xrightarrow{Photon} H_2O^+ + e^-$$
$$H_2O^+ \rightarrow H^+ + OH$$
$$e^- + H_2O \rightarrow H + OH^-$$

Sequence of X-Ray Bioeffects

Atoms → Molecules → Genes → Cells → Organs → Body



Severity of BioEffects Depends on:

- Type of Cell
- Cell division Stage
- Organ Exposed
- Age
- General Health Condition

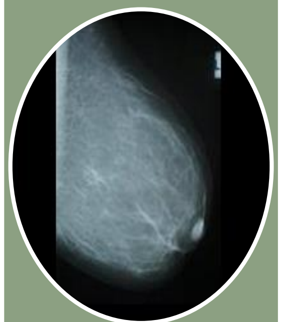
X-Ray Exposure Dose (Micro Sievert)

5

- Dental

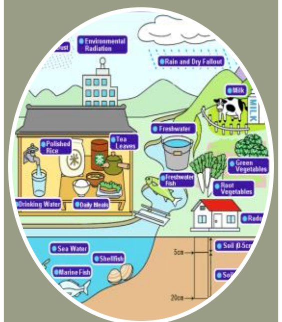
100

- Chest



400

- Breast

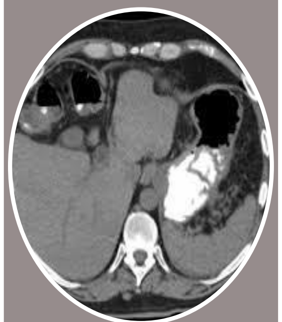


3000

- Average Normal Yearly Exposure

10000

- Virtual Colonoscopy

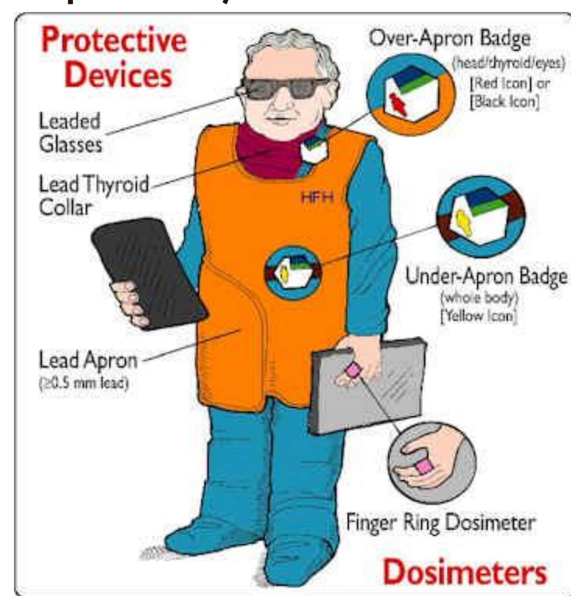


15000

- CT on Abdomen and Pelvis

Precautions for X-Ray Exposure

- Patient (medical exposure)
  - Use for diagnostic purposes only done by doctor or x-ray technologist
  - Minimizing time and dose as much as possible
  - Never to be used during pregnancy
  - Minimization of exposure for reproductive organs
- Doctors and X-Ray Technologists (occupational exposure)
  - Dose is cumulative with time
  - Protective devices must be used
  - Dosimeters must be periodically checked



Suggested Readings and Assignments

- Handouts for download on class web site

- Homework posted on web site