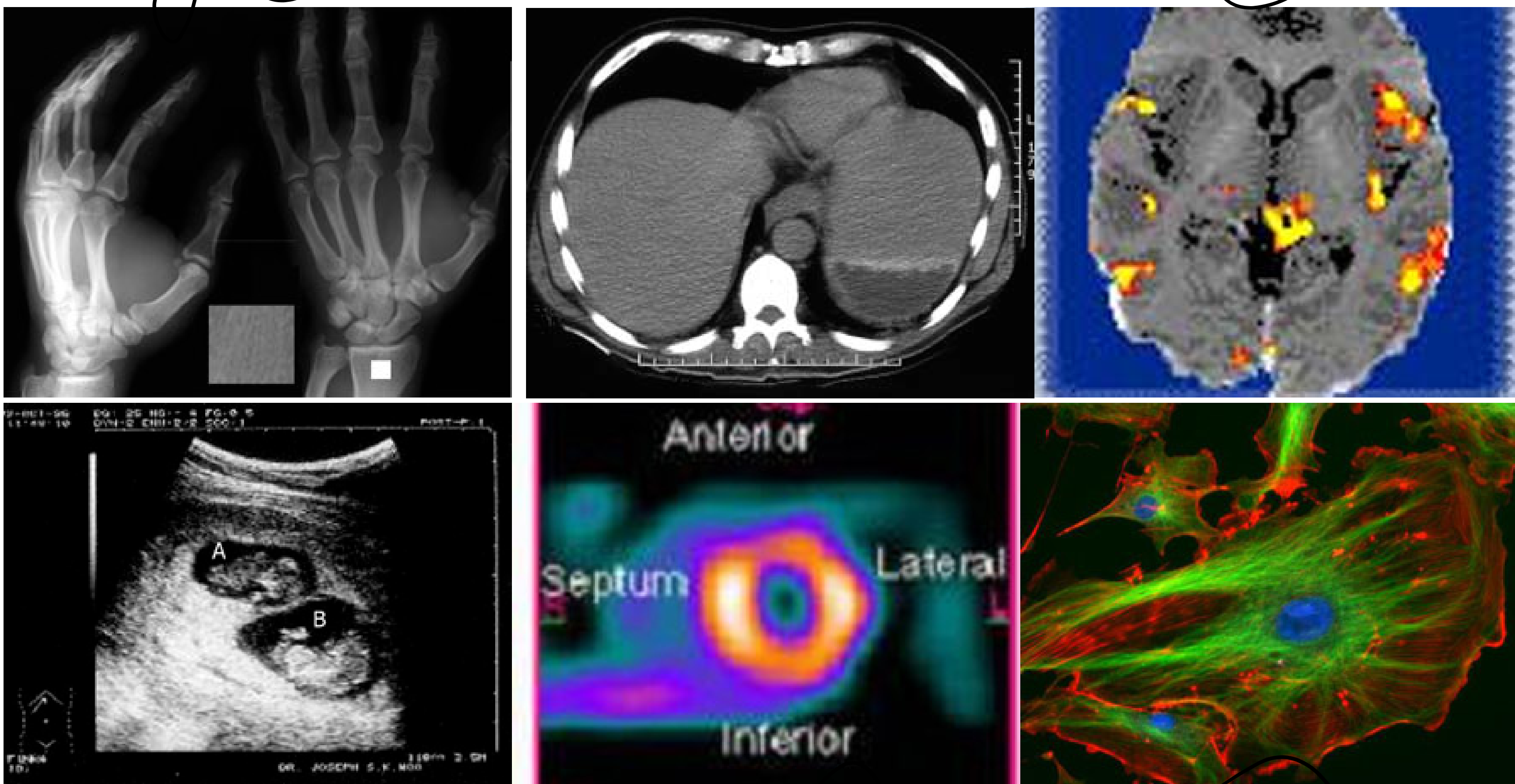
Biomedical Imaging

Examples of Medical Images

X-ray 1 2 CT 3 MRI



4 Ultrasound 5 PET 6

X-ray

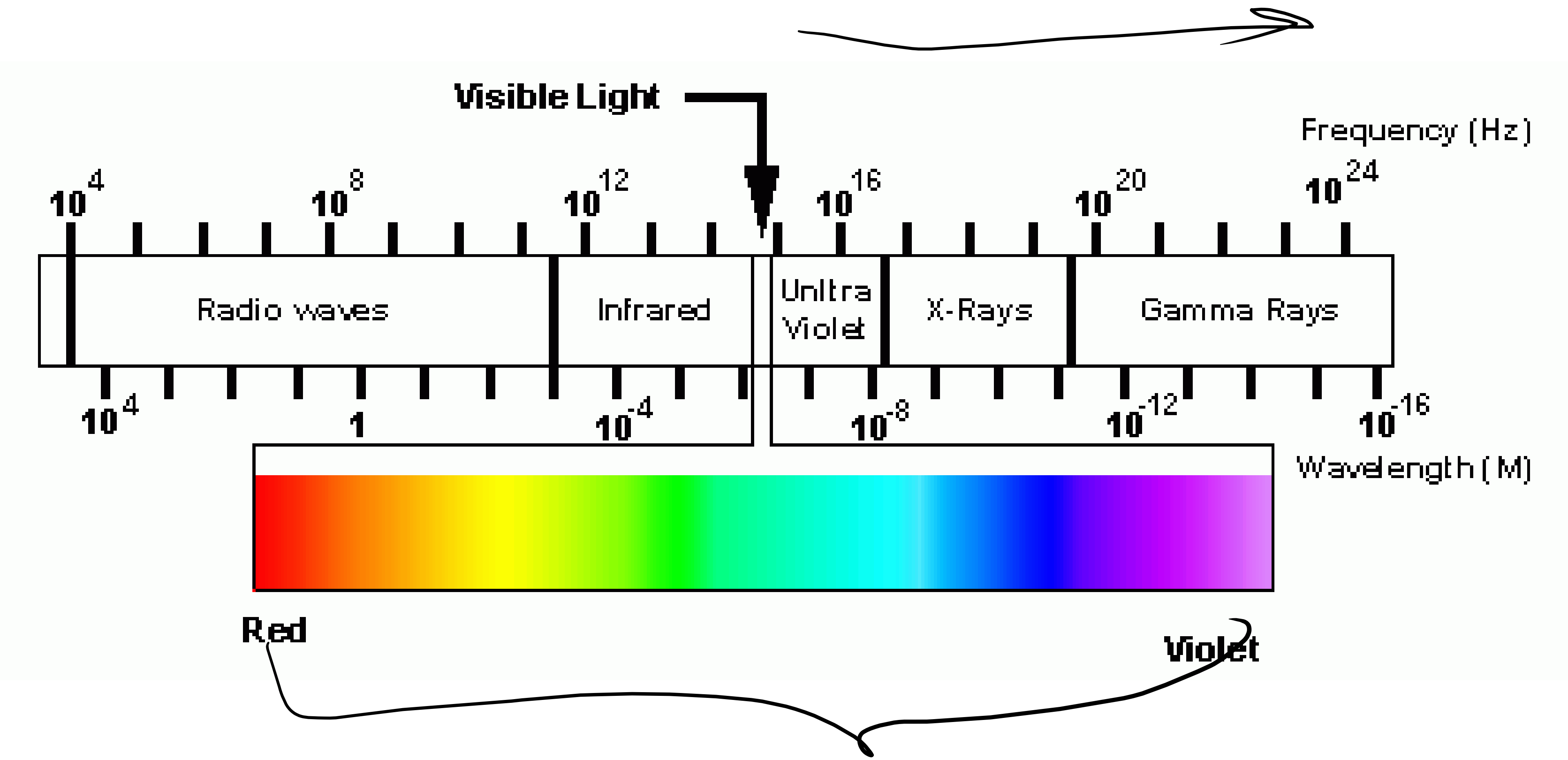
Discovery of X-rays

In December 1895, German physicist Wilhelm Roentgen discovered these mysterious rays X-rays, with X standing for unknown. In recognition of his discovery, Roentgen in 1901 became the first Nobel laureate in physics.

What are X-rays?

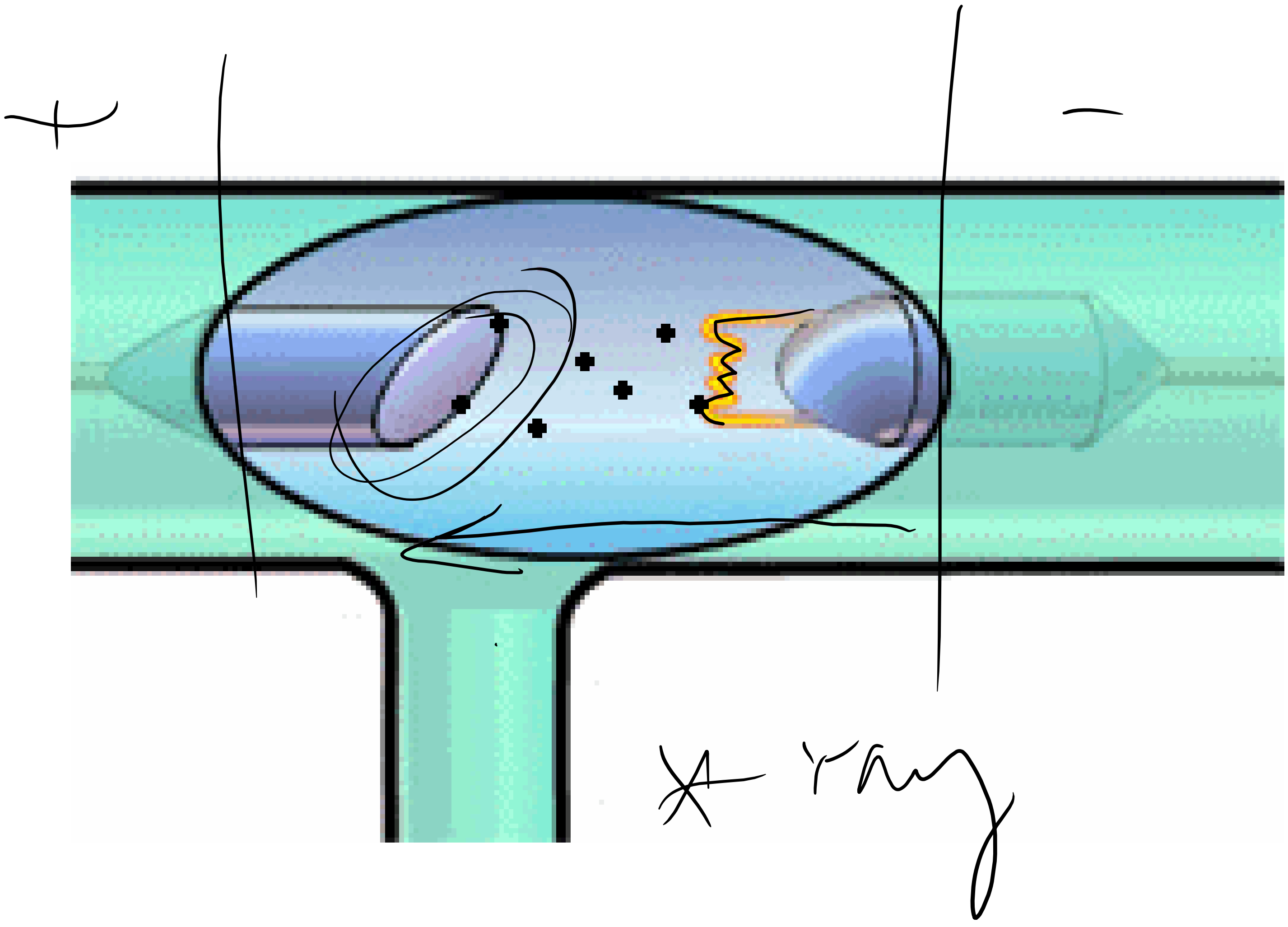
- They are an electromagnetic radiation emitted by charged particles interactions
- Photons which can penetrate through matter
- They have no mass or charge
- They travel at the speed of light
- Energy = $h\gamma = hc/\lambda$

EM Spectrum

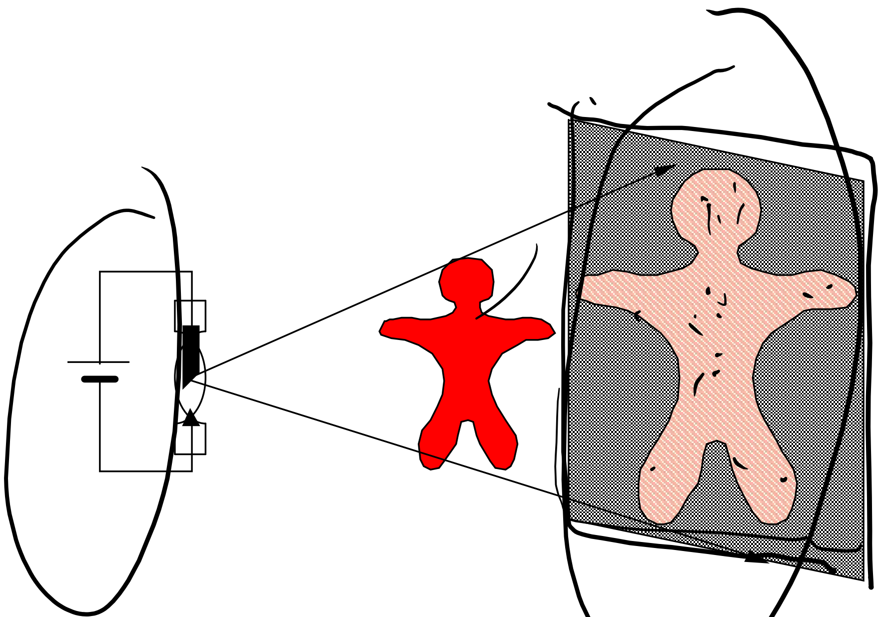


Visible Light
Frequency (Hz)
10 4
10 8
10 12
10 16
10 20
10 24
Radio waves
Infrared
Unltra Violet
X-Rays
Gamma Rays
10 4
1
10 -4
10 -8
10 -12
10 -16
Wavelength (M)
Red
Violet

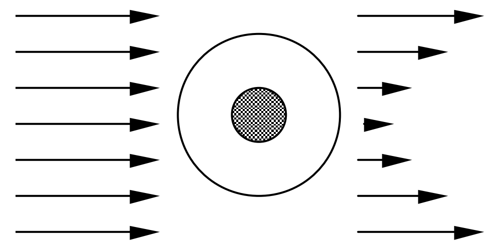
X-ray Production



X-ray Imaging: How it works.



X-ray shadow cast by an object



Strength of shadow depends on composition and thickness.

Damage to DNA

- **Direct damage to DNA molecule**
- **Indirect damage to DNA** by Ionisation of water and the release of free radicals:

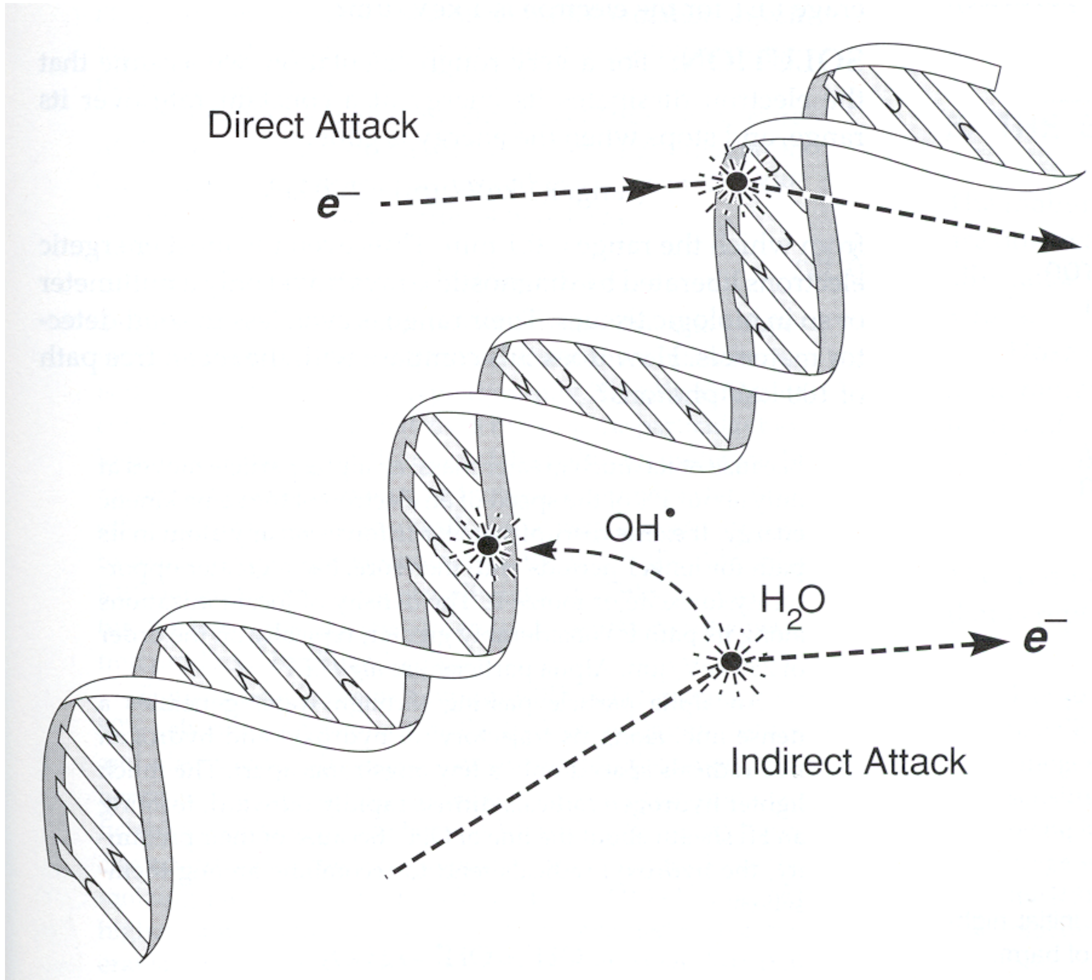
$$H_20 \rightarrow H_20^+ + e^-$$

$$H_20^+ \rightarrow H^+ + OH \text{ (free radical)}$$

$$OH + OH \rightarrow H_2O_2 \text{ (Hydrogen peroxide)}$$

$$\text{Release of } H_2O_2 \rightarrow \text{DNA damage}$$

Damage to DNA



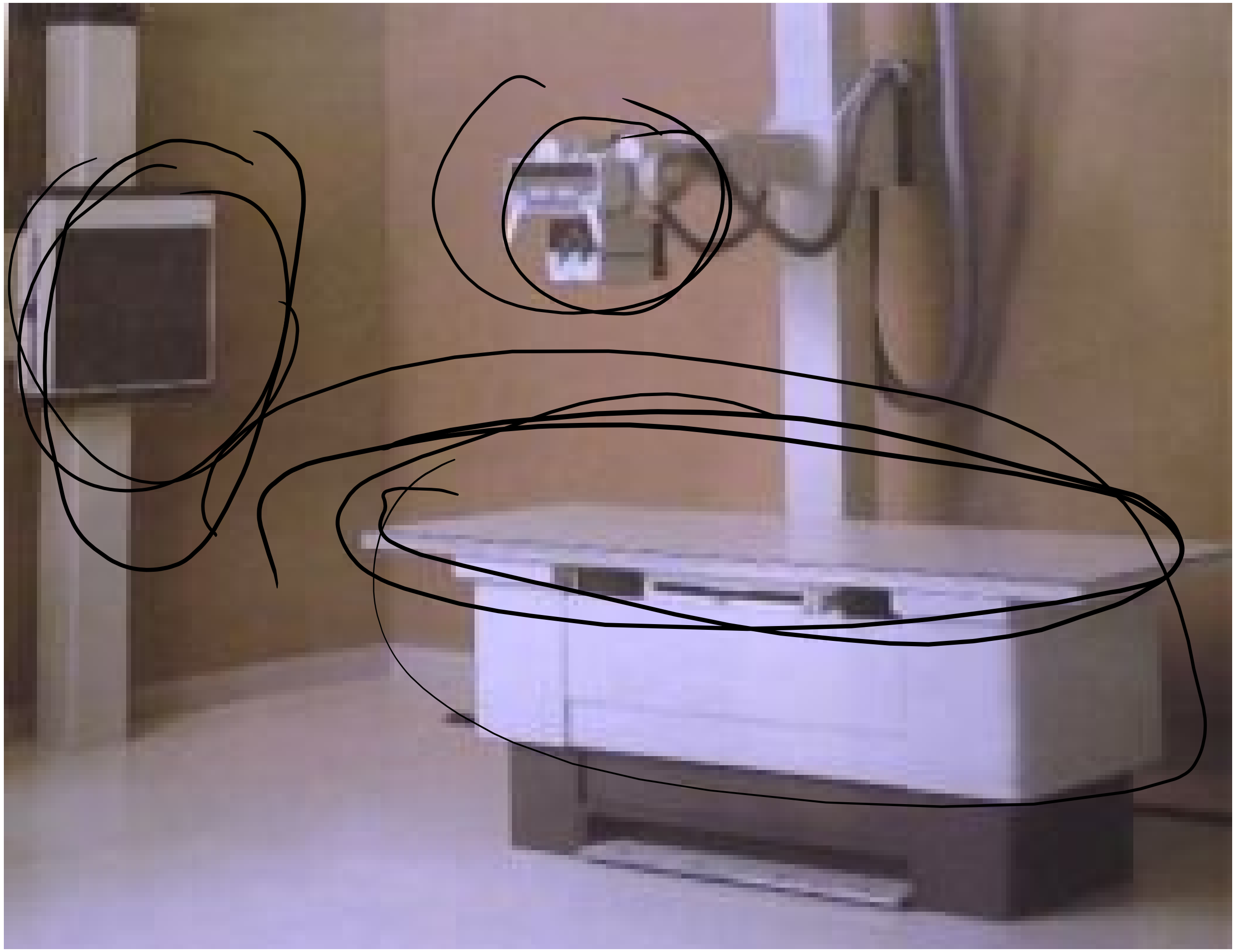
Biological Effects

Stage	Timescale	Effect
Initial Physical Interaction	10^{-17}-10^{-15}s	Ionization and Excitations
Chemical	10^{-14}-10^{-3}s	Creation of free radicals & excited molecules yielding biologically harmful products
Bio-molecular	Sec - Hours	Damage to DNA, proteins, nucleic acids, etc.
Biological	Hours-Decades	Cell damage, death, mutations

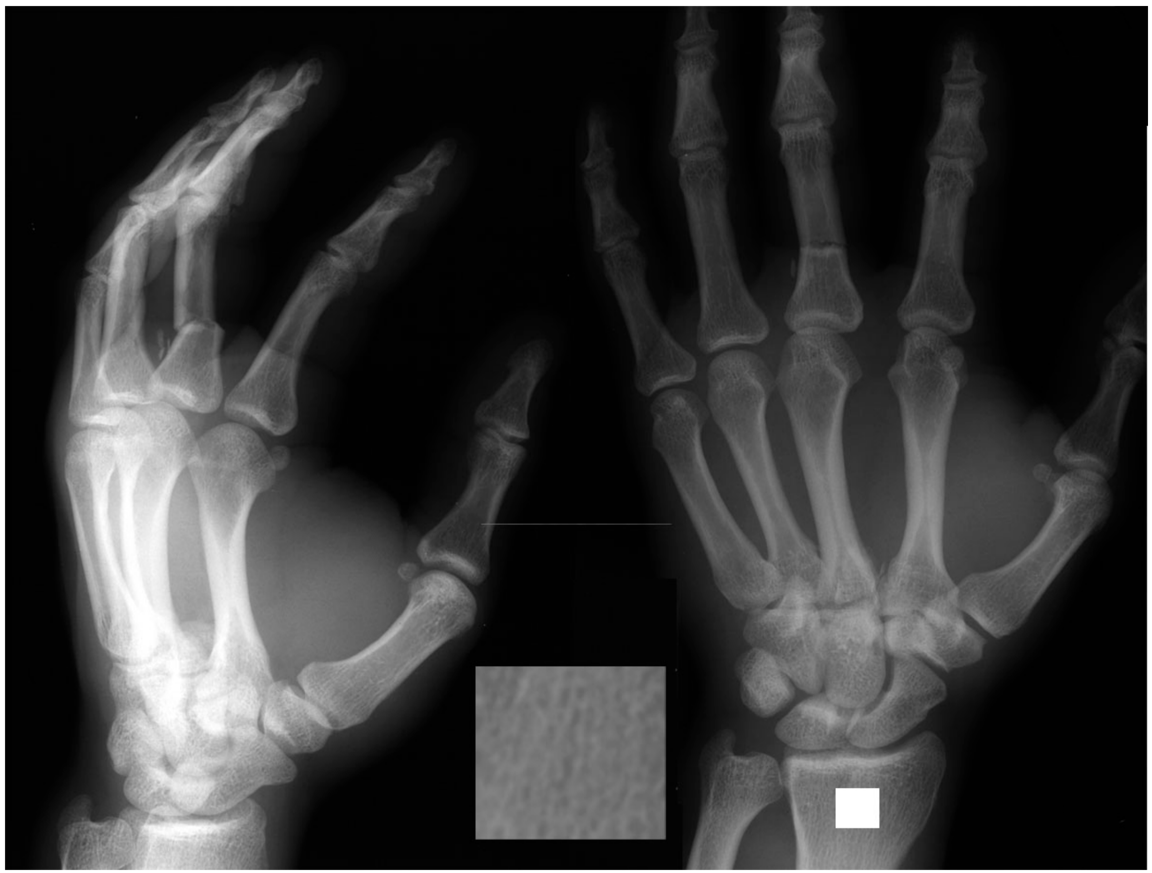
Estimated Risk of Cancer

X-ray examination	***Estimated risk of fatal cancer***
Dental intra-oral	1 in 2 000 000
Chest	1 in 1 000 000
Barium meal	1 in 6 700
CT head	1 in 10 000
CT chest	1 in 2 500
Car Accident	1 in 10 000

X-ray Radiography Machine



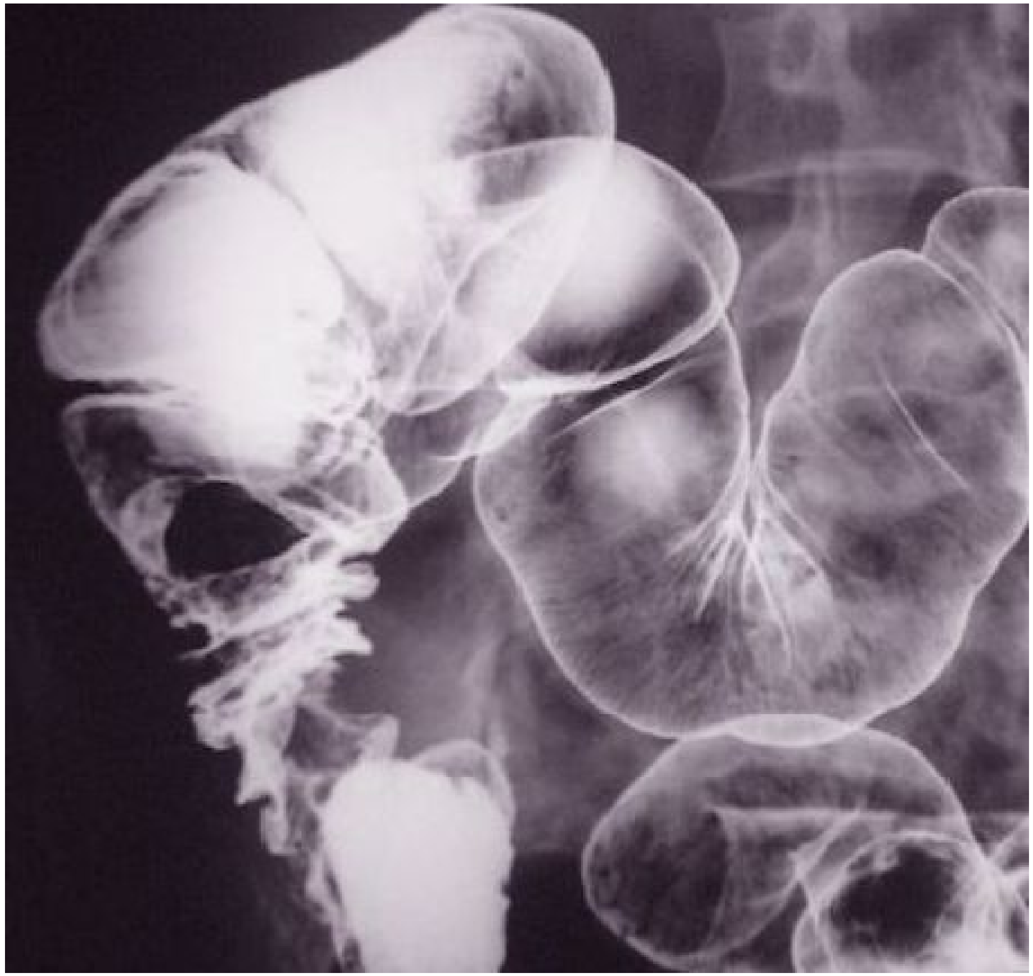
X-ray Image



Fluoroscopy

Enables radiologists to visualize X-ray images in real time on a television monitor. In most instances the procedure would involve the administration of some form of 'contrast' agent to outline the region of interest

Fluoroscopy Images



Barium Used to Visualize Intestines

Mammography

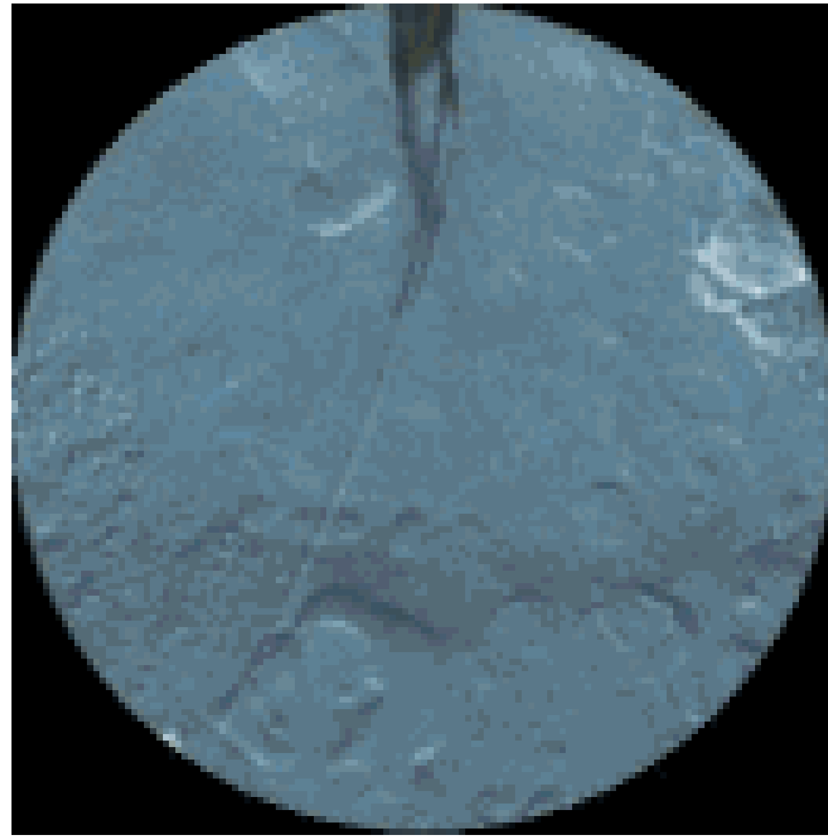
A mammography machine is an X-ray machine dedicated to breast images. Compared with conventional X-ray techniques, mammograms are obtained with much lower energy X-rays of around 20,000 volts.

Digital Angiography

It is a diagnostic procedure that produces X-ray pictures of blood vessels. A catheter is inserted in the vessel to inject contrast fluid

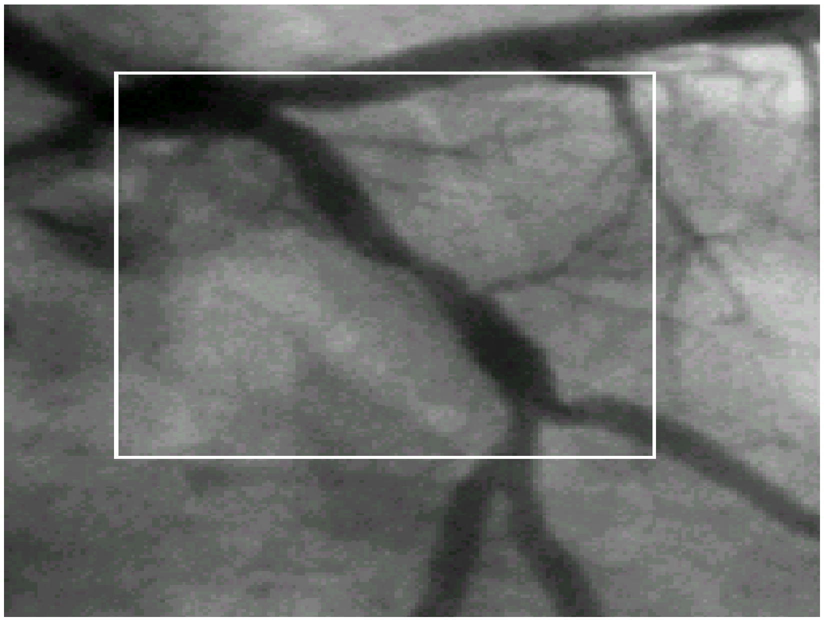
Digital Angiography Images

First Angiogram(1896, Hankel):
Mercury was injected in a post mortem hand



Digital Subtraction Angiography (Mistretta, 1980s)

Digital Angiography Images



Angiogram of The Coronary Arteries

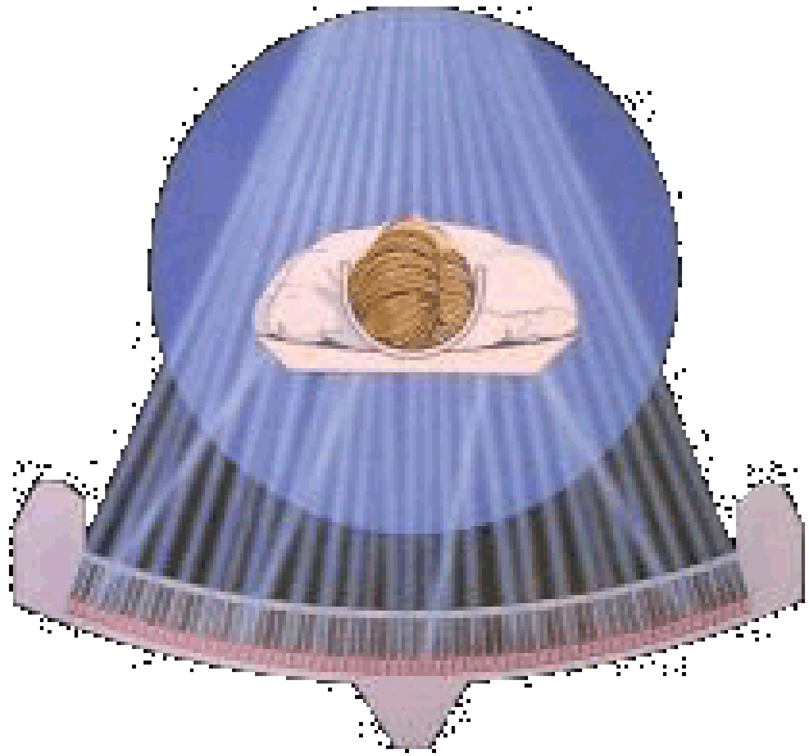
3-D Angiogram of The Brain Arteries

Summary: X-ray Imaging

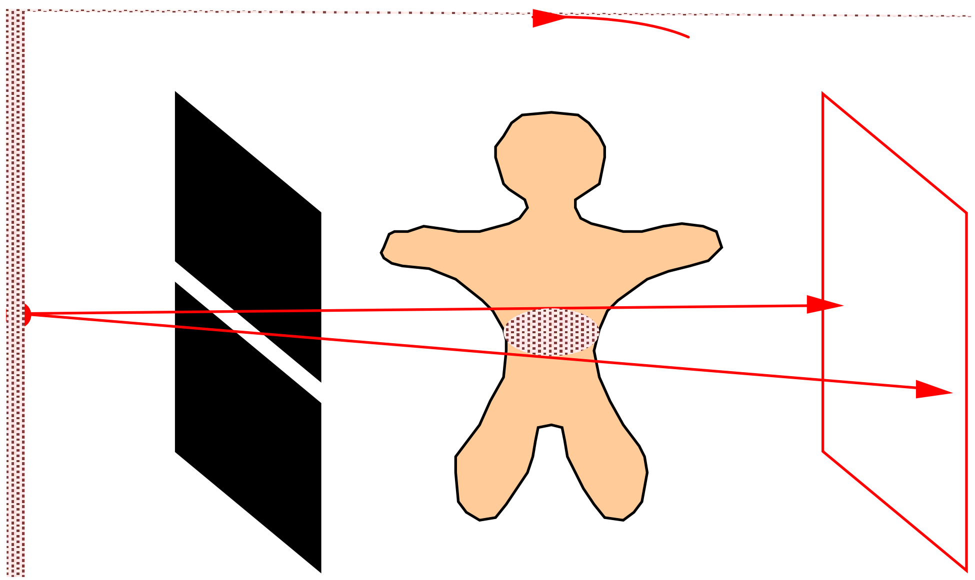
- Oldest non-invasive imaging of internal structures
- Rapid, short exposure time, inexpensive
- Real time X-ray imaging is possible and used during interventional procedures.
- Ionizing radiation: risk of cancer.
- Unable to distinguish between soft tissues in head, abdomen

Computerized Tomography (CT)

The technique of CT scanning was developed in 1973 by Hounsfield. A thin fan beam of X-rays generated by a conventional X-ray tube passes through a single 'slice' of a patient through to a bank of X-ray detectors.

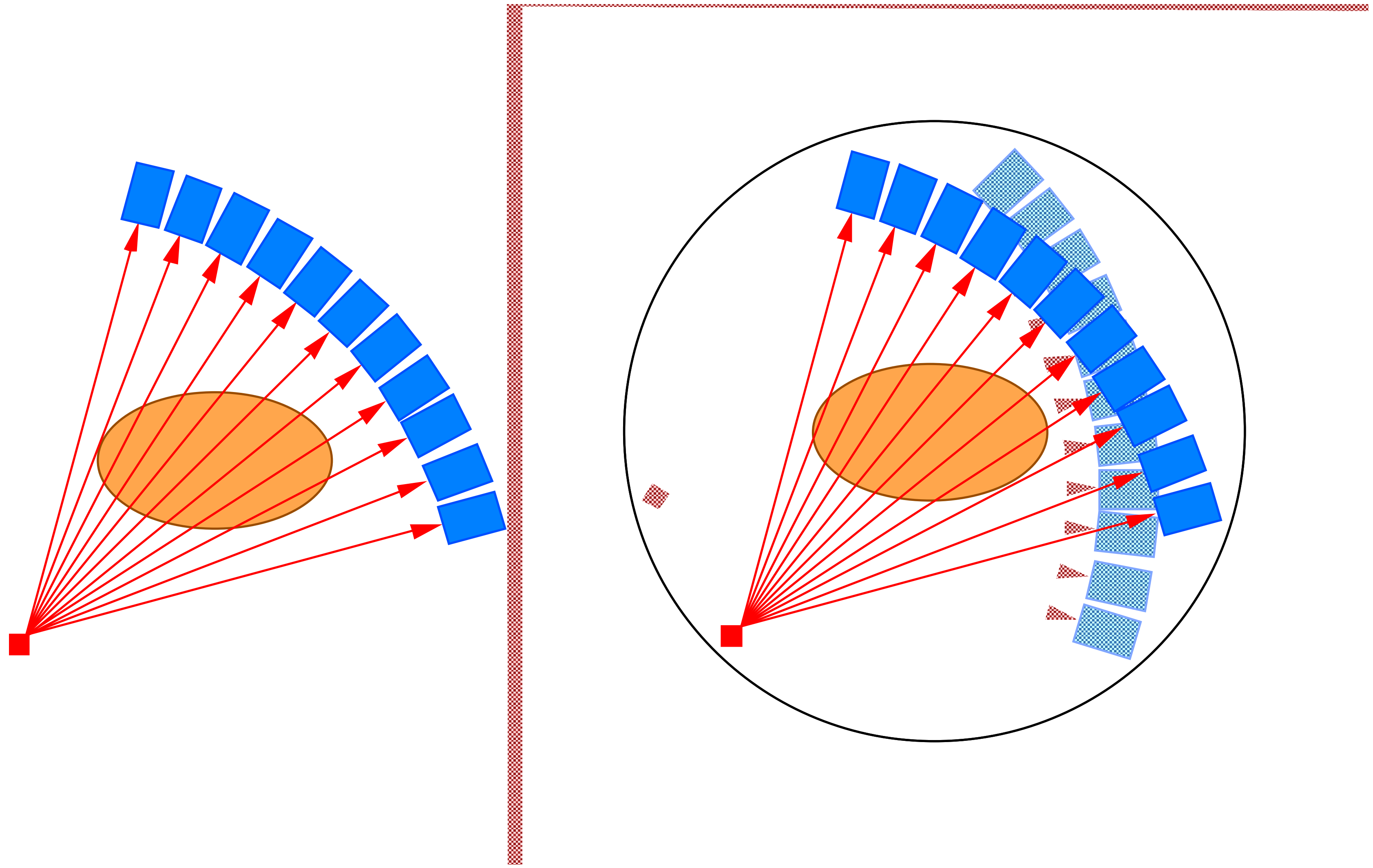


Computer Tomography: How It Works

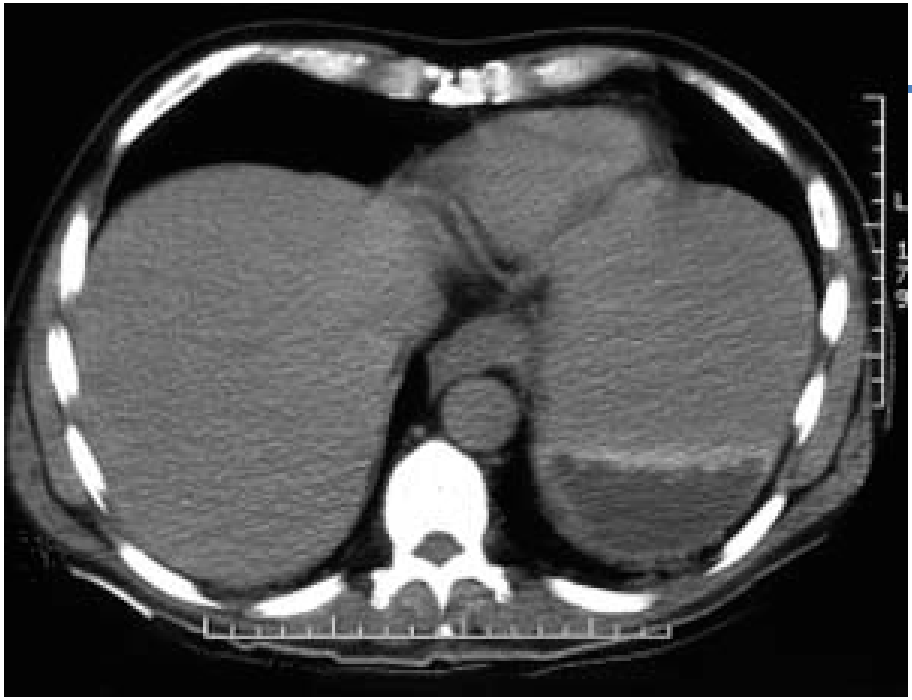


Only one plane is illuminated. Source-subject motion provides added information.

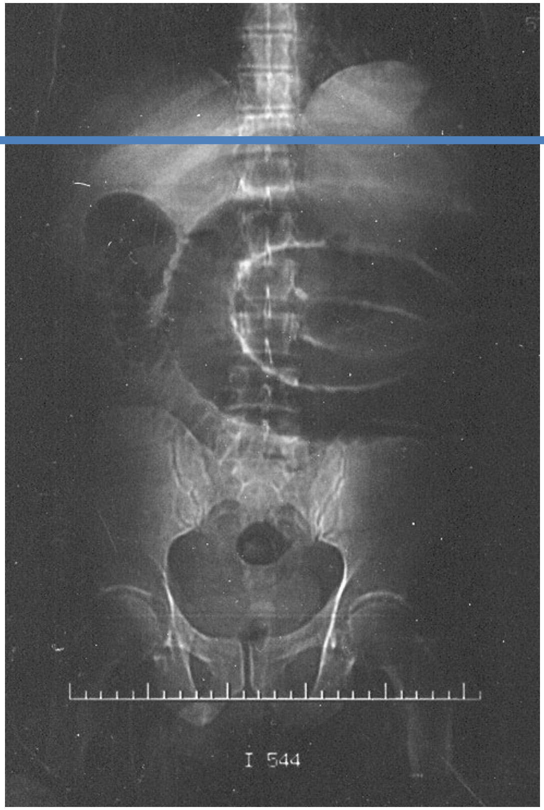
Fan-Beam Computer Tomography



CT (Computed Tomography)



CT Image of plane through
liver and stomach

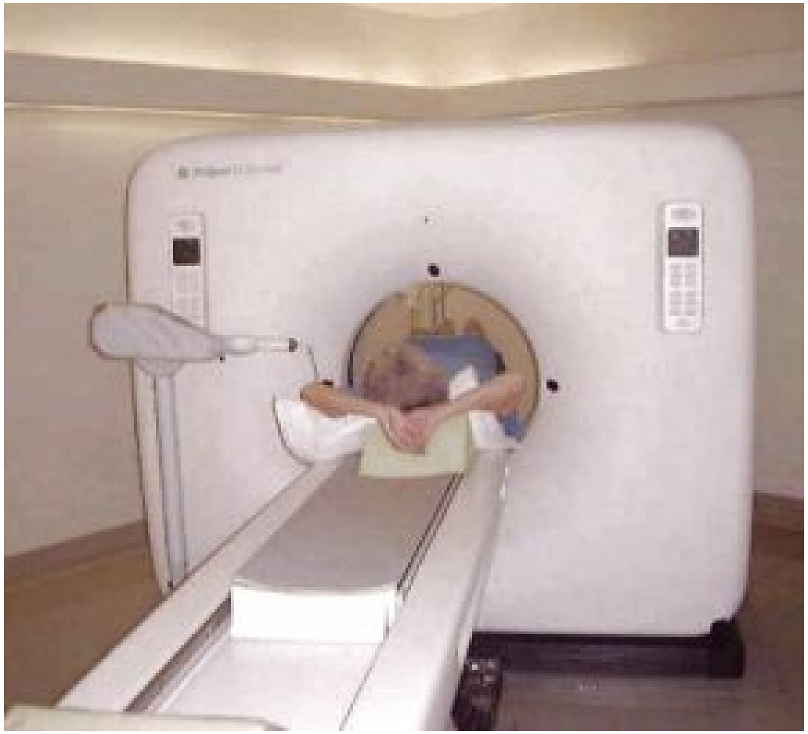


Projection image
from CT scans

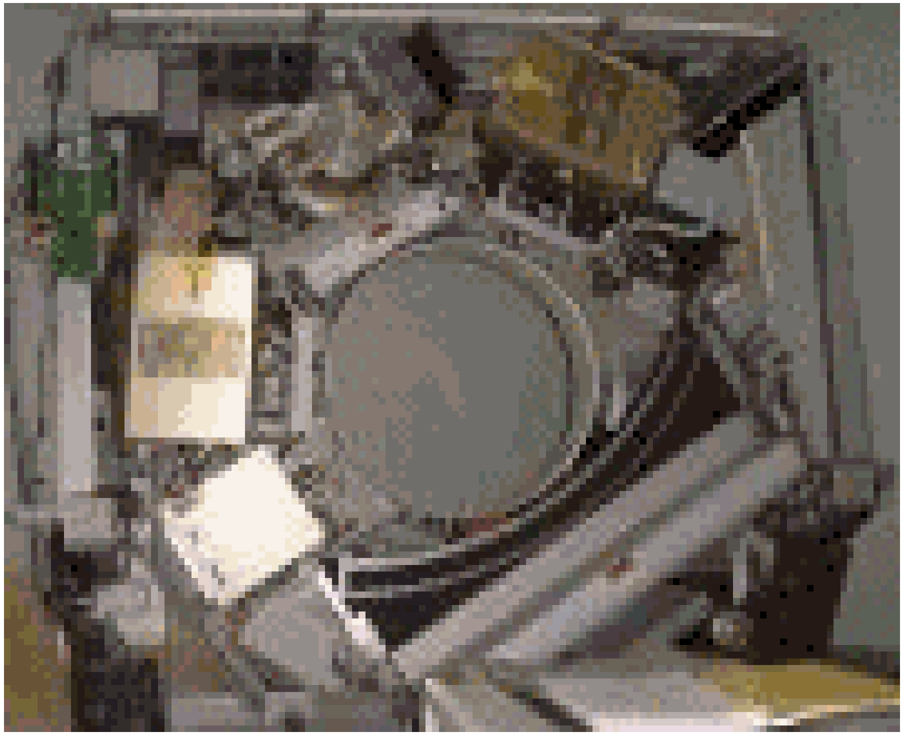
What Is It?

- Computer Tomography image of section through upper abdomen of patient prior to abdominal surgery.
- Section shows ribs, vertebra, aorta, liver (image left), stomach (image right) partially filled with liquid (bottom).

CT Machine

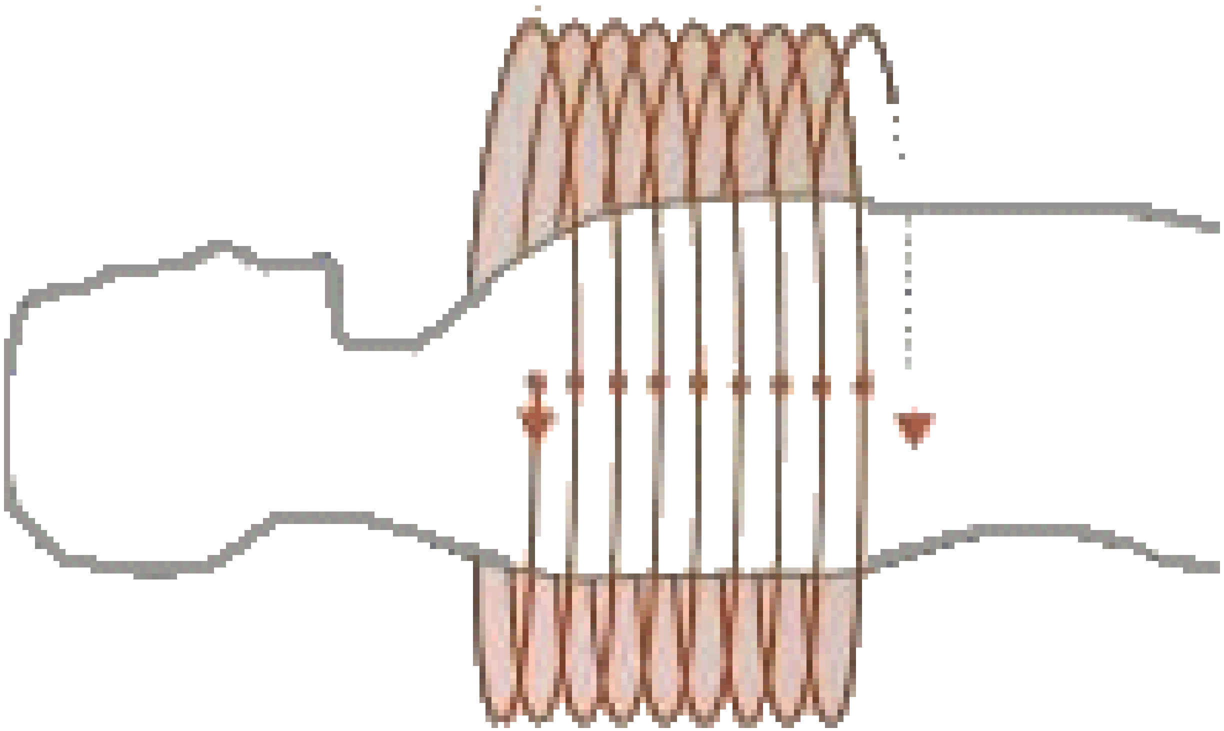


CT Machine



CT Machine Rotating Parts

Helical CT



Summary of X-Ray CT

- Images of sectional planes (tomography) are harder to interpret
- CT can visualize small density differences, e.g. grey matter, white matter, and CSF. CT can detect and diagnose disease that cannot be seen with X-ray.
- More expensive than X-ray, lower resolution.
- Ionizing radiation.

Magnetic Resonance Imaging

MRI

Timeline of MR Imaging

1924 - Pauli suggests that nuclear particles may have angular momentum (spin).

1937 – Rabi measures magnetic moment of nucleus. Coins “magnetic resonance”.

1944 – Rabi wins Nobel prize in Physics.

1946 – Purcell shows that matter absorbs energy at a resonant frequency.

1946 – Bloch demonstrates that nuclear precession can be measured in detector coils.

1952 – Purcell and Bloch share Nobel prize in Physics.

1959 – Singer measures blood flow using NMR (in mice).

1972 – Damadian patents idea for large NMR scanner to detect malignant tissue.

1973 – Lauterbur publishes method for generating images using NMR gradients.

1973 – Mansfield independently publishes gradient approach to MR.

1975 – Ernst develops 2D-Fourier transform for MR.

NMR becomes MRI

1985 – Insurance reimbursements for MRI exams begin.

MRI scanners become clinically prevalent.

1990 – Ogawa and colleagues create functional images using endogenous, blood-oxygenation contrast.

1920 1930 1940 1950 1960 1970 1980 1990 2000

Nobel Prizes for Magnetic Resonance

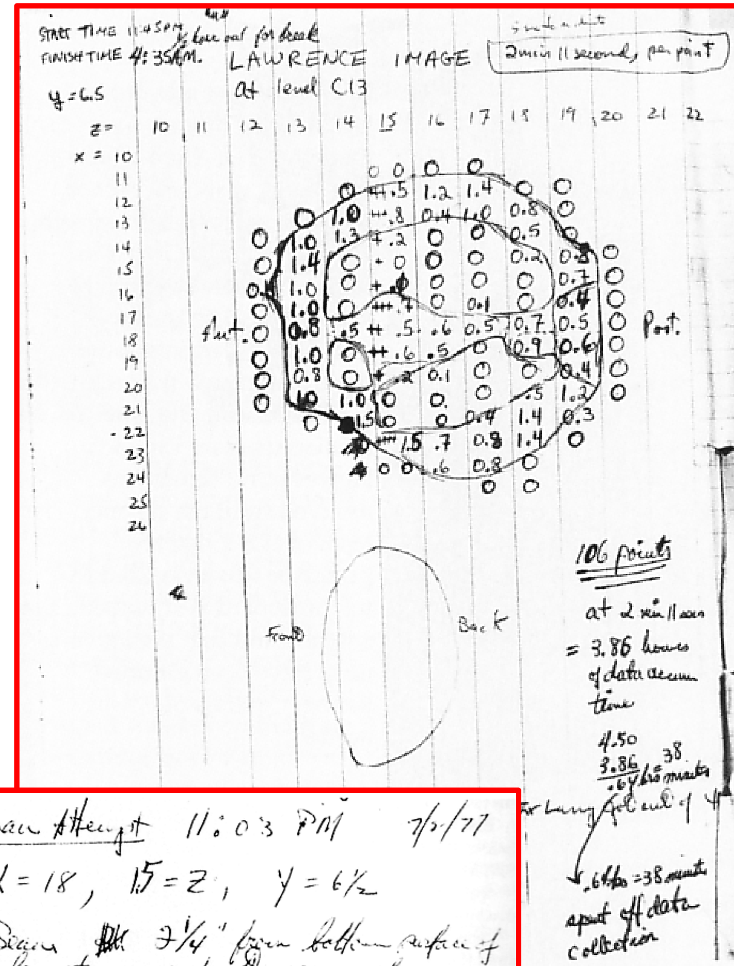
- 1944: Rabi
  Physics (Measured magnetic moment of nucleus)
- 1952: Felix Bloch and Edward Mills Purcell
  Physics (Basic science of NMR phenomenon)
- 1991: Richard Ernst
  Chemistry (High-resolution pulsed FT-NMR)
- 2002: Kurt Wüthrich
  Chemistry (3D molecular structure in solution by NMR)
- 2003: Paul Lauterbur & Peter Mansfield
  Physiology or Medicine (MRI technology)

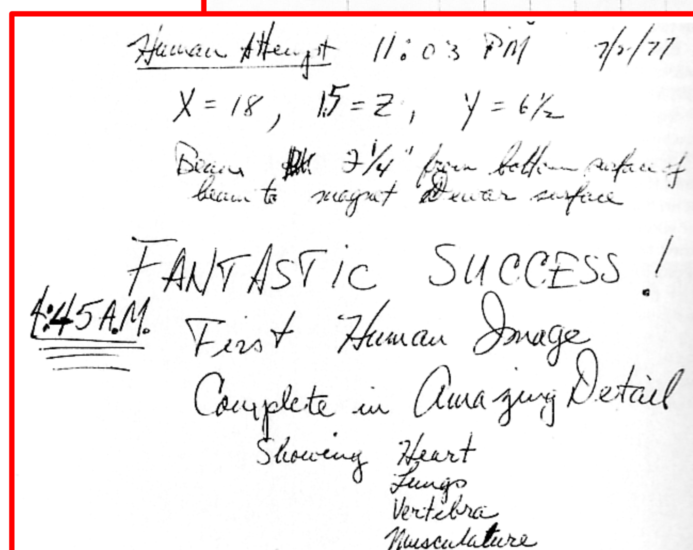
Early Uses of NMR

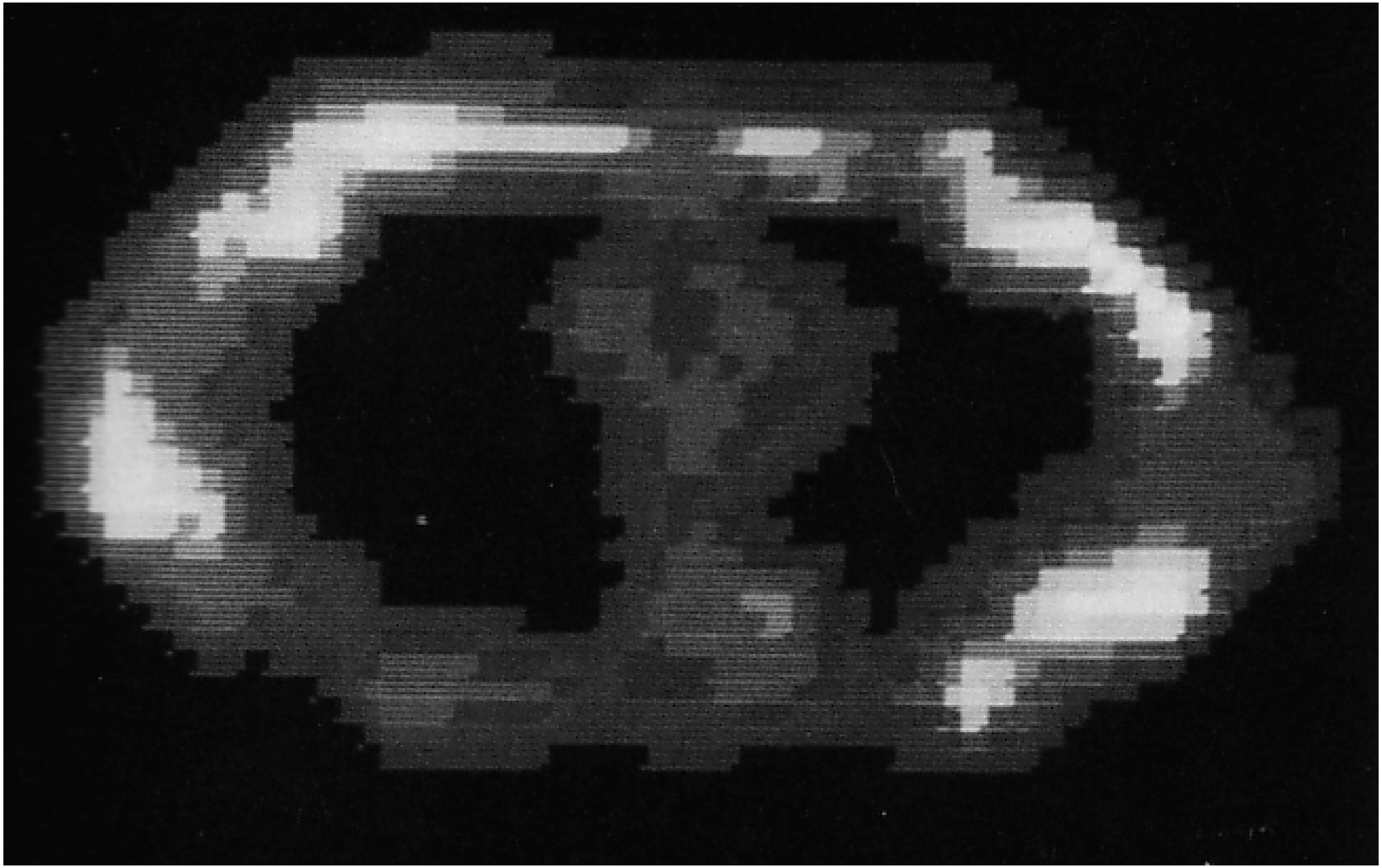
- Most early NMR was used for chemical analysis
  - No medical applications
- 1971 – Damadian publishes and patents idea for using NMR to distinguish healthy and malignant tissues
  - "Tumor detection by nuclear magnetic resonance", *Science*
  - Proposes using differences in relaxation times
  - No image formation method proposed
- 1973 – Lauterbur describes projection method for creating NMR images
  - Mansfield (1973) independently describes similar approach

Early Human MR Images (Damadian)

© Fonar Corporation



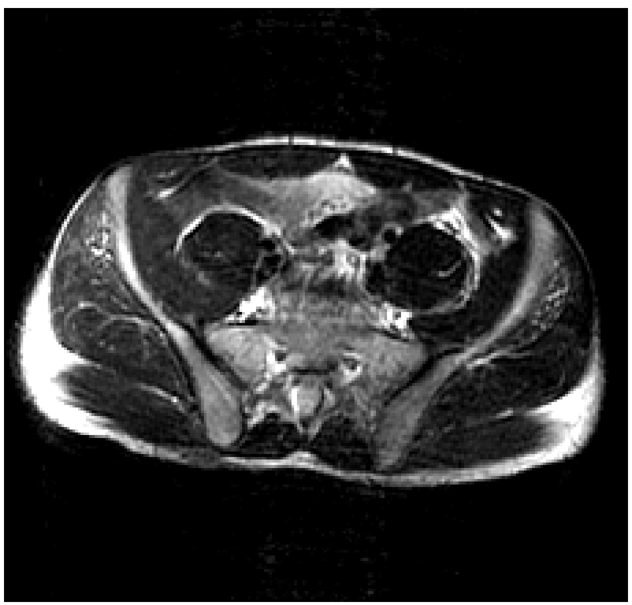




Mink5 Image – Damadian (1977)

Magnetic Resonance Imaging

- Non-invasive medical imaging method, like ultrasound and X-ray.
- Clinically used in a wide variety of specialties.



Abdomen

Spine

Heart / Coronary

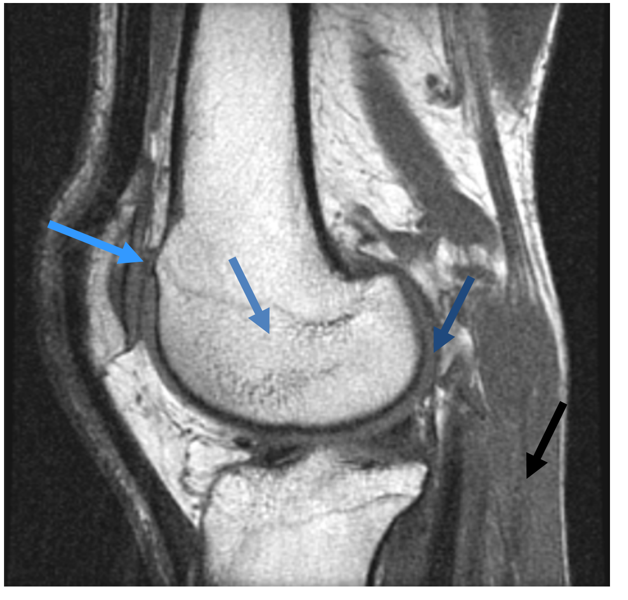
Magnetic Resonance Imaging

Advantages:

- Excellent / flexible contrast
- Non-invasive
- No ionizing radiation
- Arbitrary scan plane

Challenges:

- New contrast mechanisms
- Faster imaging

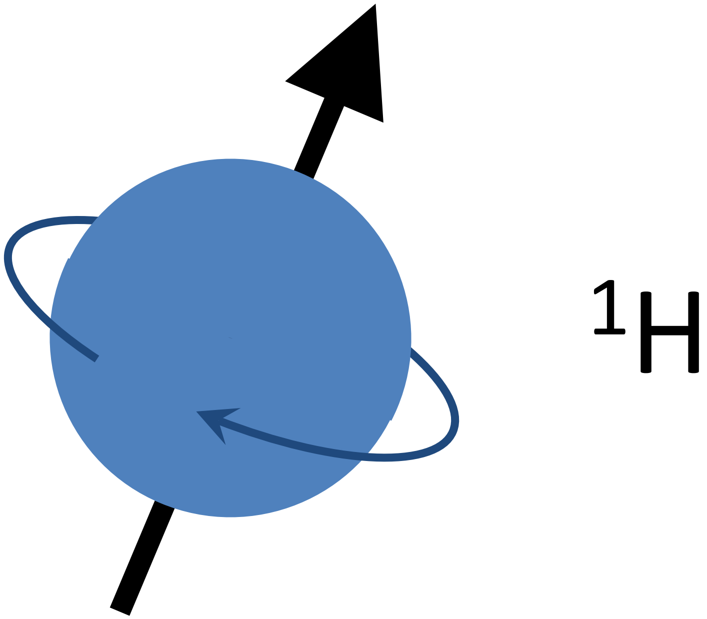


MRI Systems

At $2 million, the most expensive equipment in the hospital…

Magnetic Resonance

- Certain atomic nuclei including ^{1}H exhibit nuclear magnetic resonance.
- Nuclear “spins” are like magnetic dipoles.

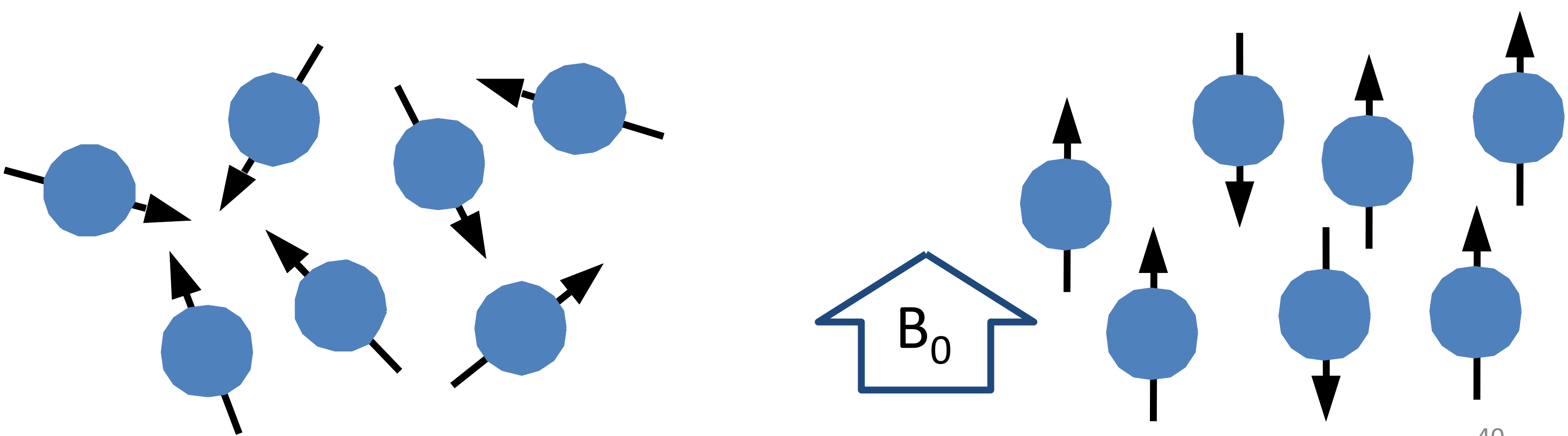


Polarization

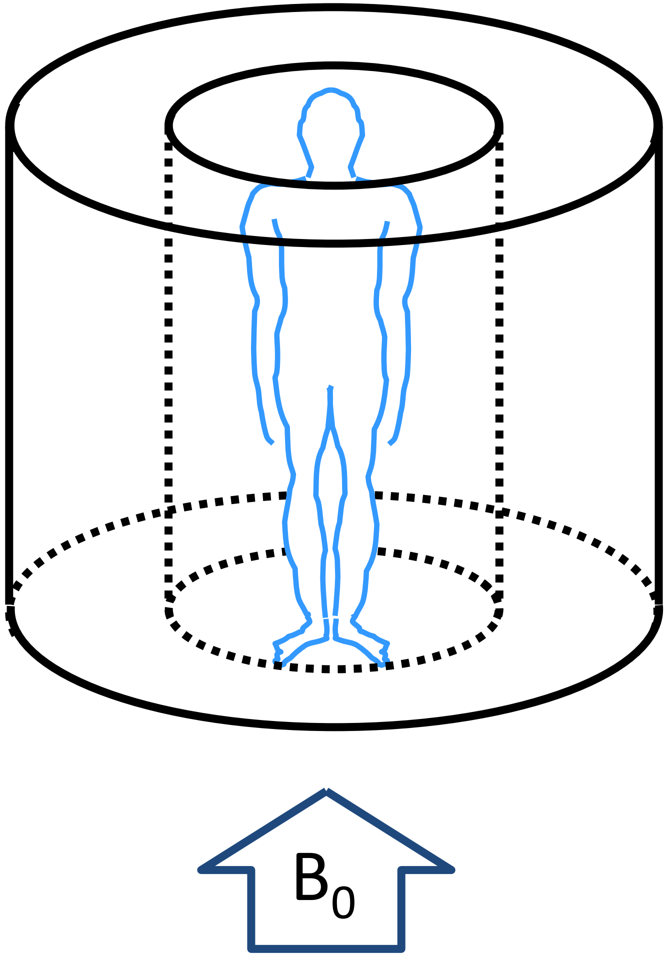
- Spins are normally oriented randomly.
- In an applied magnetic field, the spins align with the applied field in their equilibrium state.
- Excess along B_0 results in net magnetization.

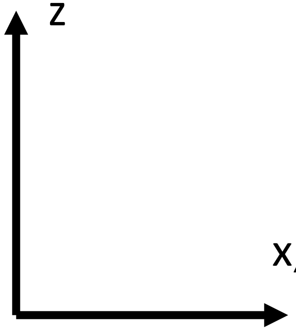
No Applied Field

Applied Field



Static Magnetic Field



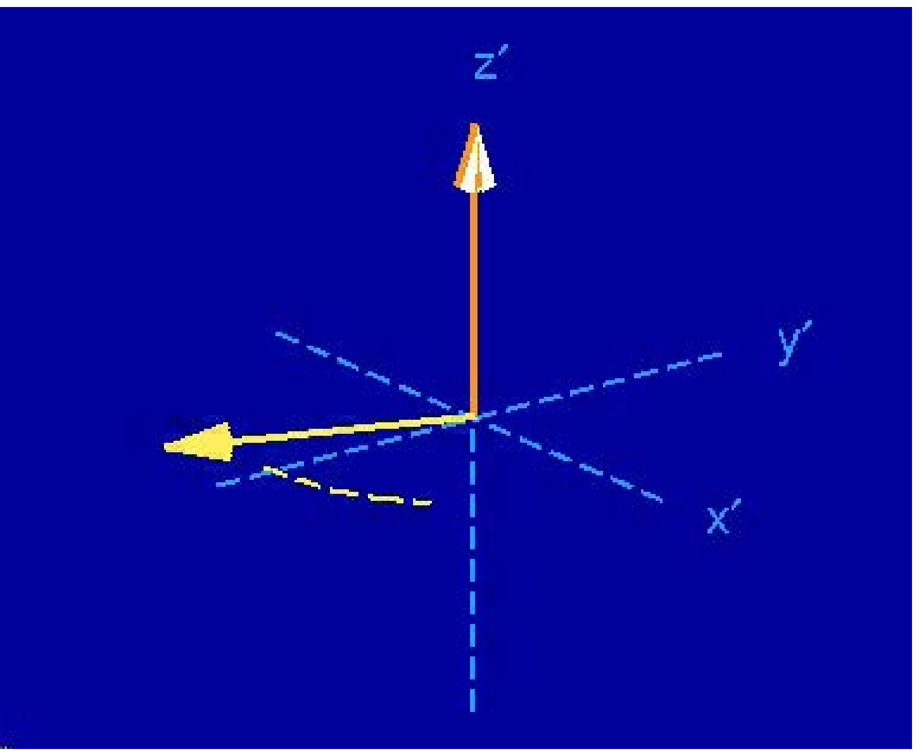


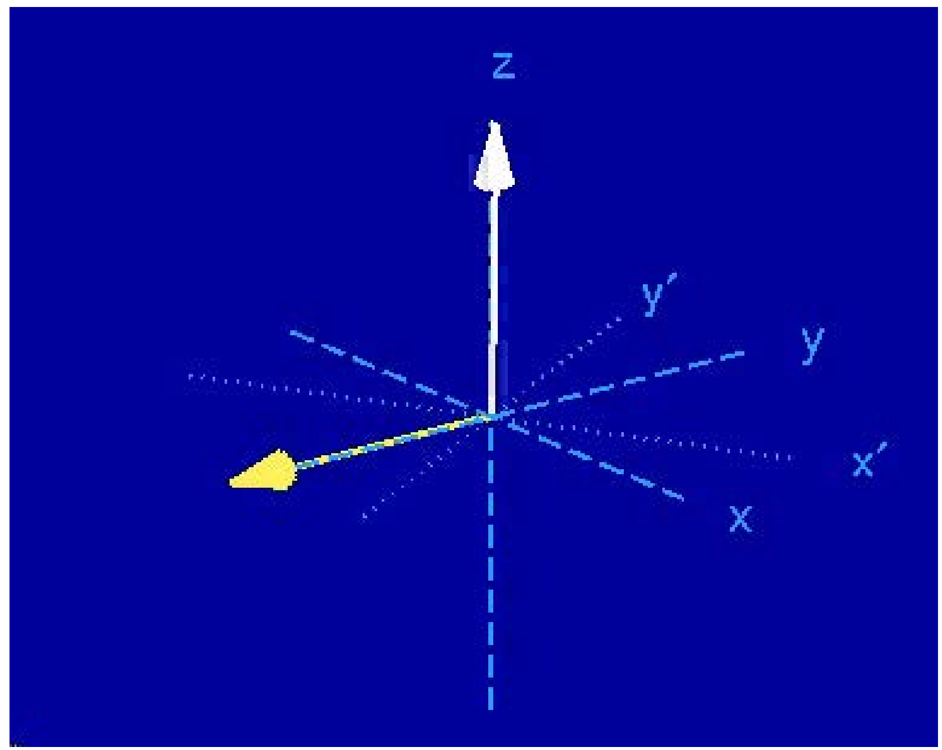
Excitation

- "Excite" spins out of their equilibrium state.
- Transverse RF field (B_1) rotates at γB_0 about z-axis.

B_1

Magnetization



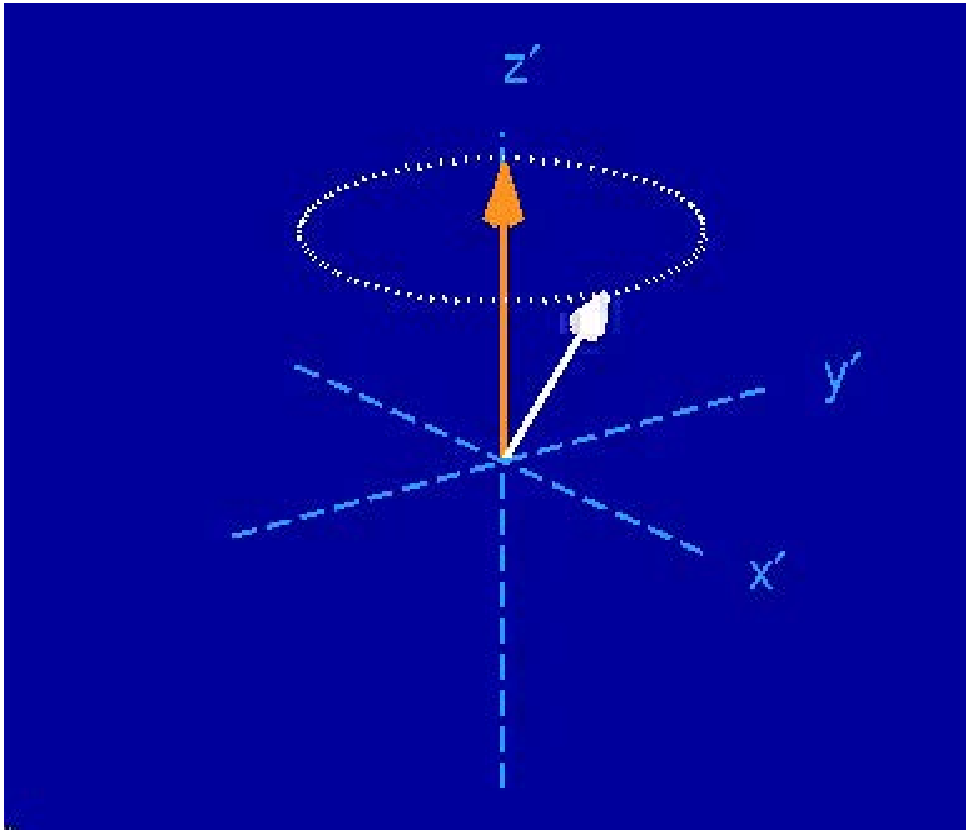


Rotating Frame

Precession

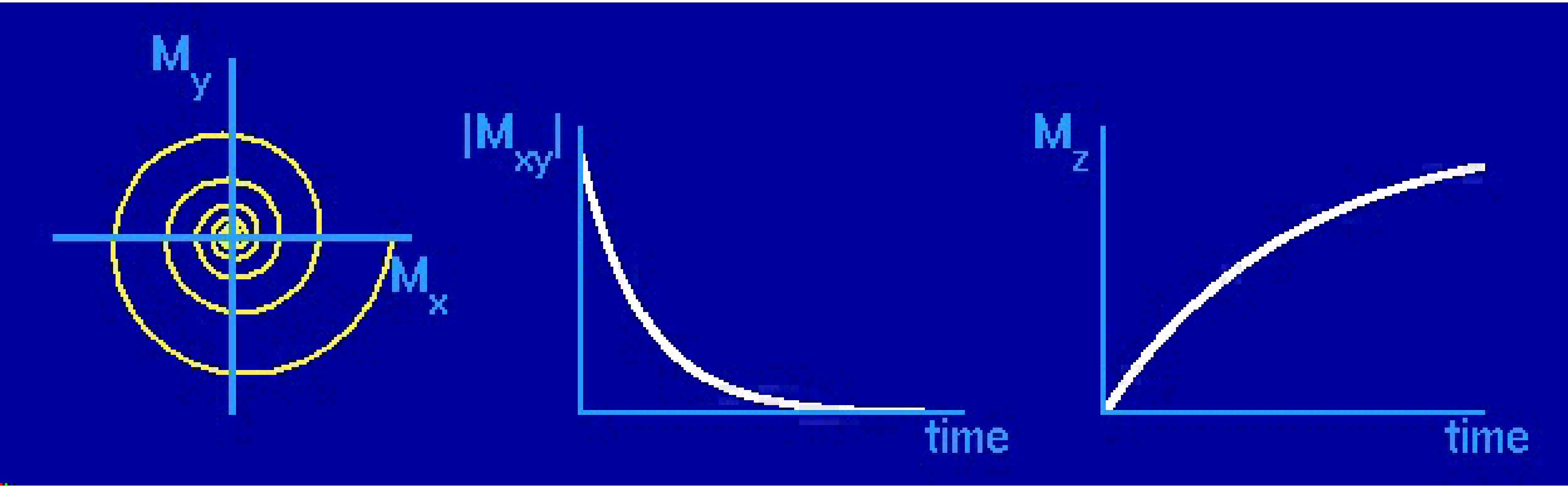
- Spins precess about applied magnetic field, B_0, that is along z axis.
- The frequency of this precession is proportional to the applied field:

$$\omega = \gamma B$$



Relaxation

- Magnetization returns exponentially to equilibrium:
  - Longitudinal *recovery* time constant is T_1
  - Transverse *decay* time constant is T_2
- Relaxation and precession are independent.



Precession Decay Recovery

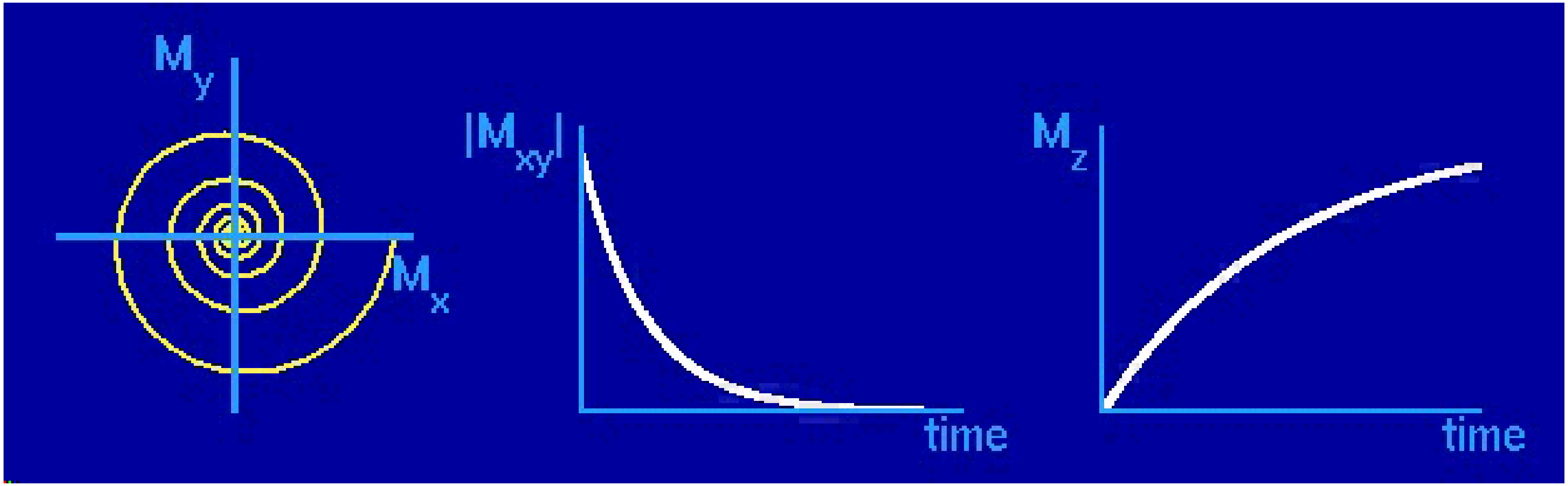
Contrast

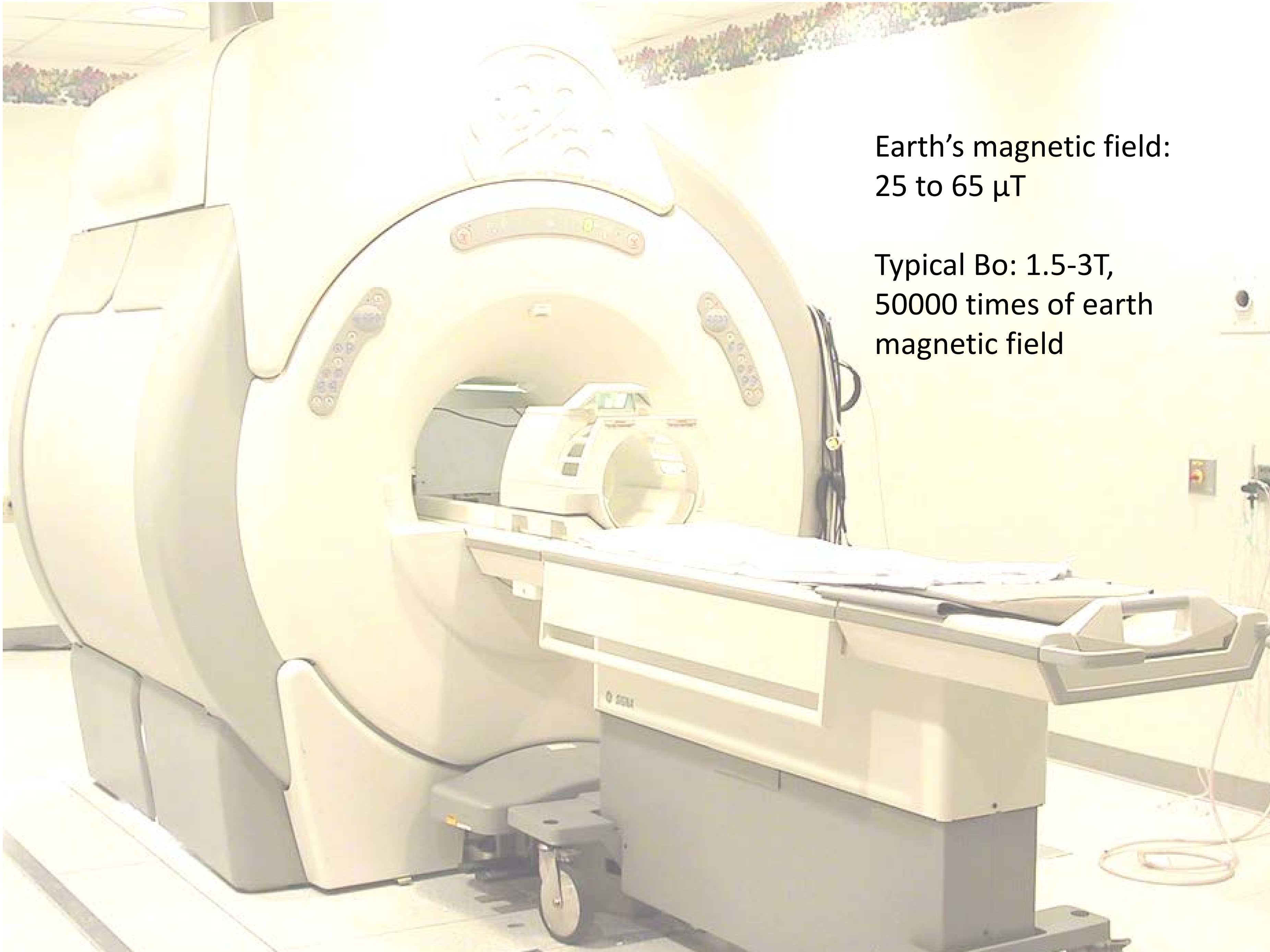
- Contrast is the difference in appearance of different tissues in an image.

X-ray contrast is based on transmission.

Contrast in MRI

- Hydrogen (water) density results in contrast between tissues.
- Many other mechanisms, some based on relaxation.

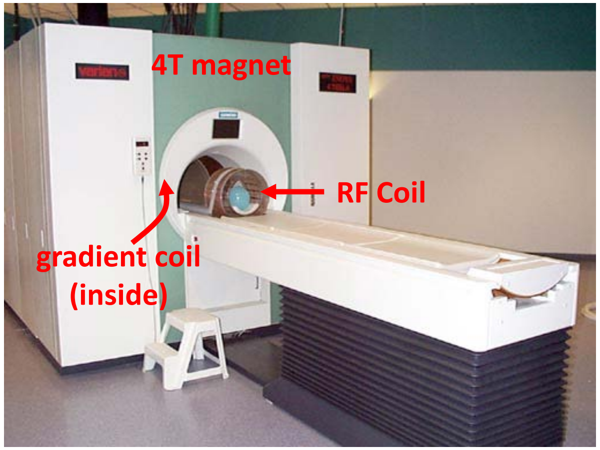


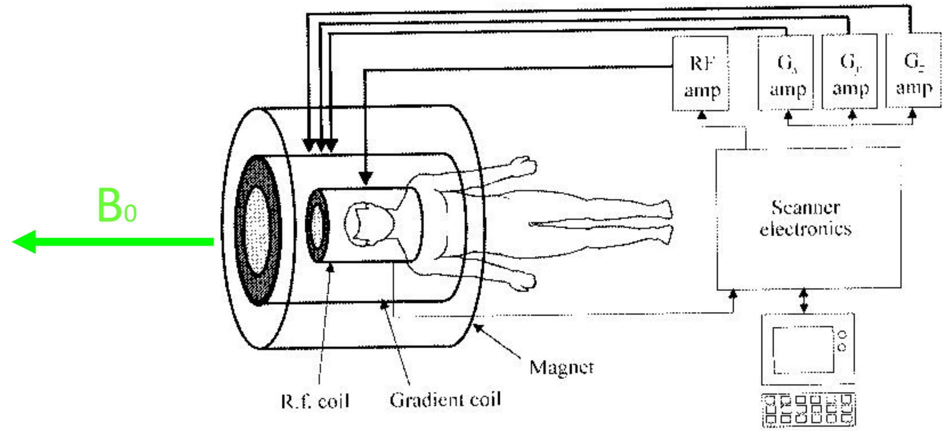


Earth’s magnetic field:
25 to 65 µT

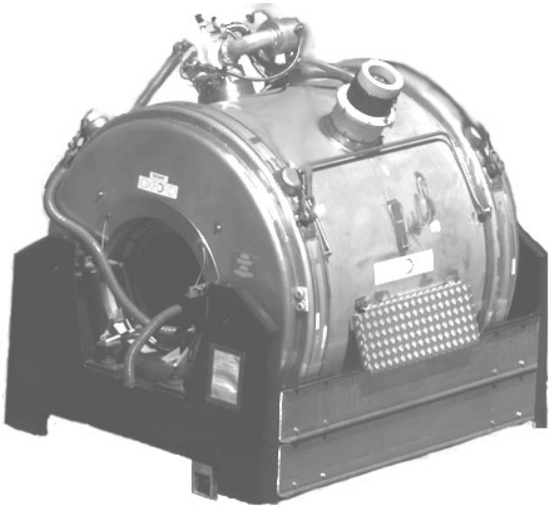
Typical Bo: 1.5-3T,
50000 times of earth
magnetic field

Equipment



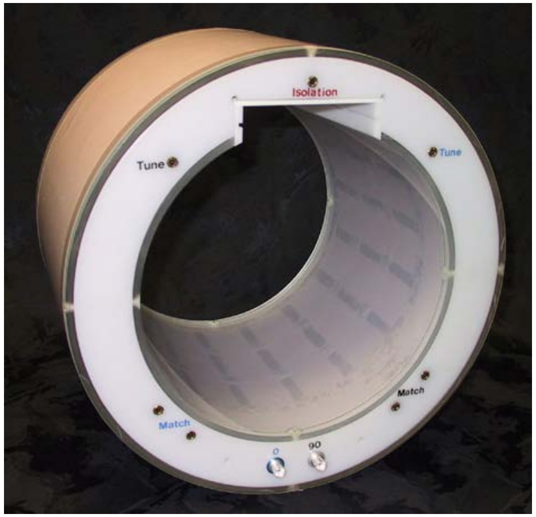


Magnet



Gradient Coil

RF Coil

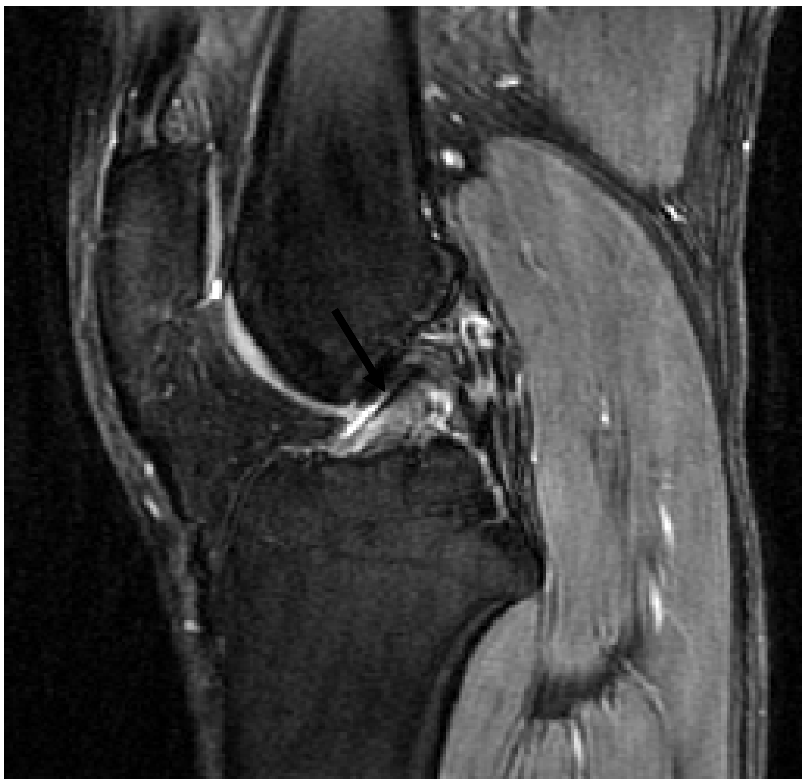


Some Applications of MRI

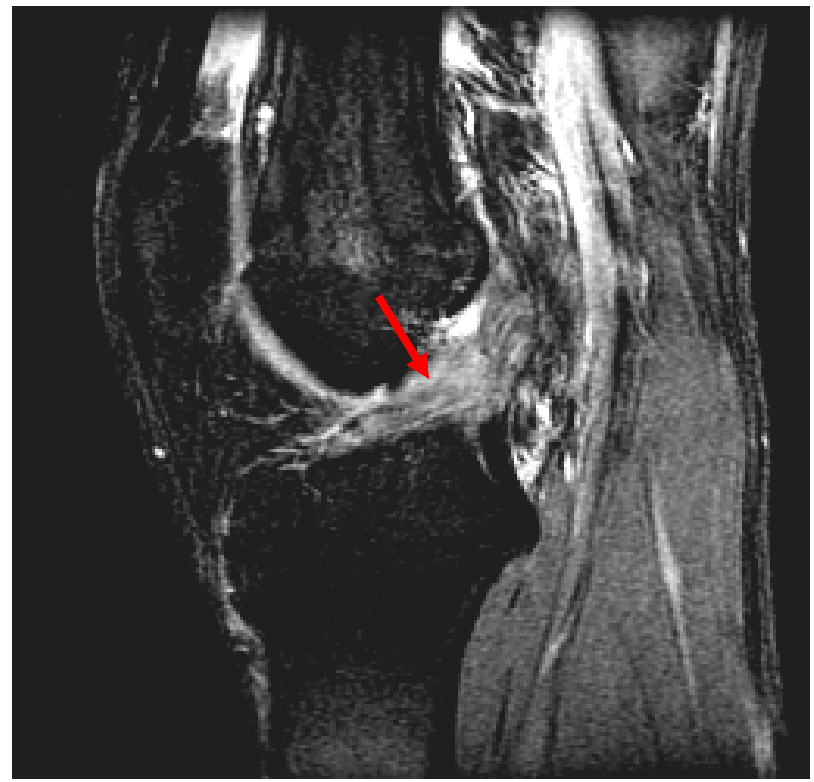
- Brain / Spine imaging
- Knee Imaging
- Cardiac Imaging

Knee Imaging - Ligaments

- MRI is 97% accurate in diagnosing an ACL tear.



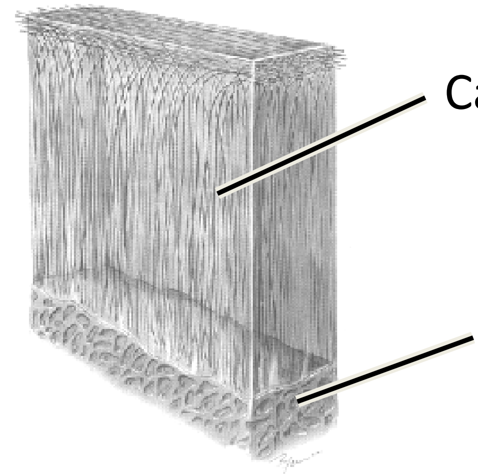
Healthy ACL



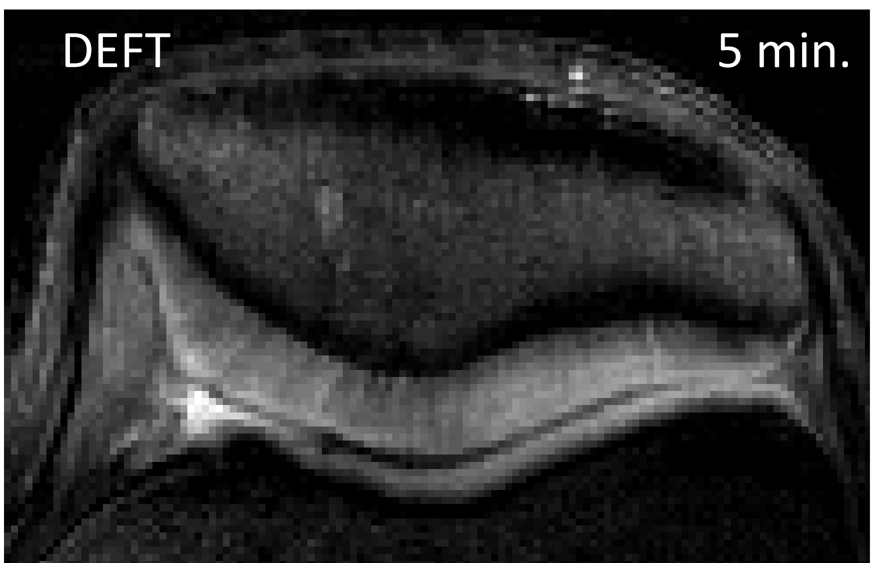
Full-Thickness ACL Tear

Knee Imaging - Cartilage

- High resolution images begin to show cartilage structure:
  - 0.4 x 0.4 x 2 mm^3 resolution
  - 5 minute scan time



(from Erickson– 1997)



Real-Time Interactive MRI

- Shows “live” images.
- Useful when there is motion, such as in the chest.
- Imaging is very fast, but SNR is lower.
- Interactive imaging allows us to move the scan plane in real-time.

Summary

- B_0 polarizes atomic nuclei
- Spins precess and relax to align with B_0.
- B_1 allows manipulation of magnetization.
- Excitation sequences provide image contrast.

What is fMRI?

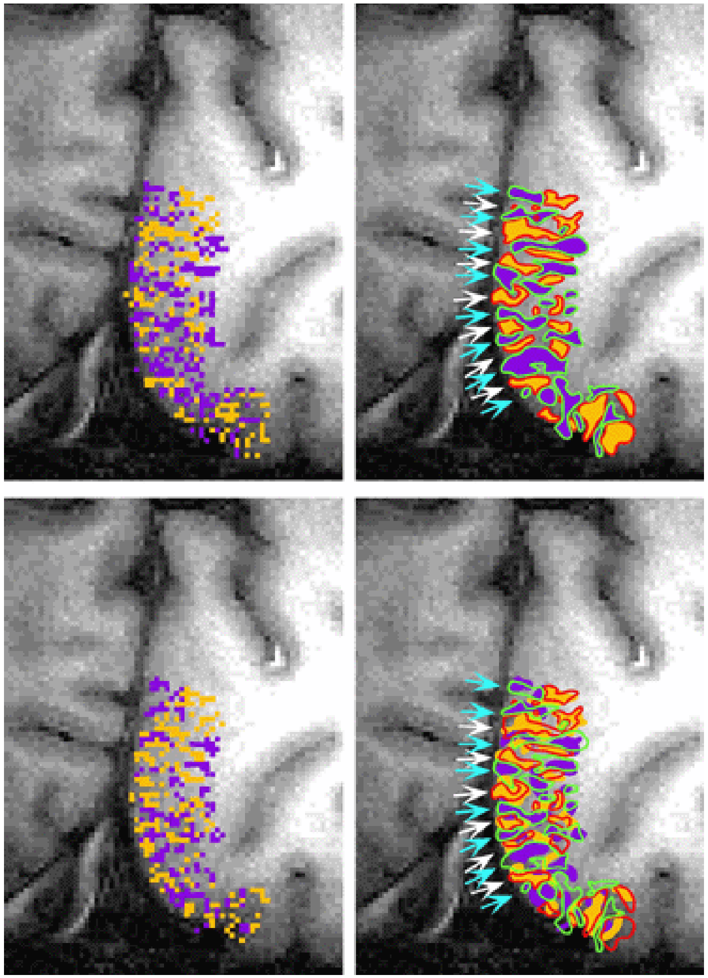
- A technique for measuring changes in brain activity over time using principles of magnetic resonance.
- Scanning procedures and restrictions are generally similar to clinical MR.
- Most fMRI studies use changes in BOLD contrast, although other measures exist.

Why fMRI?

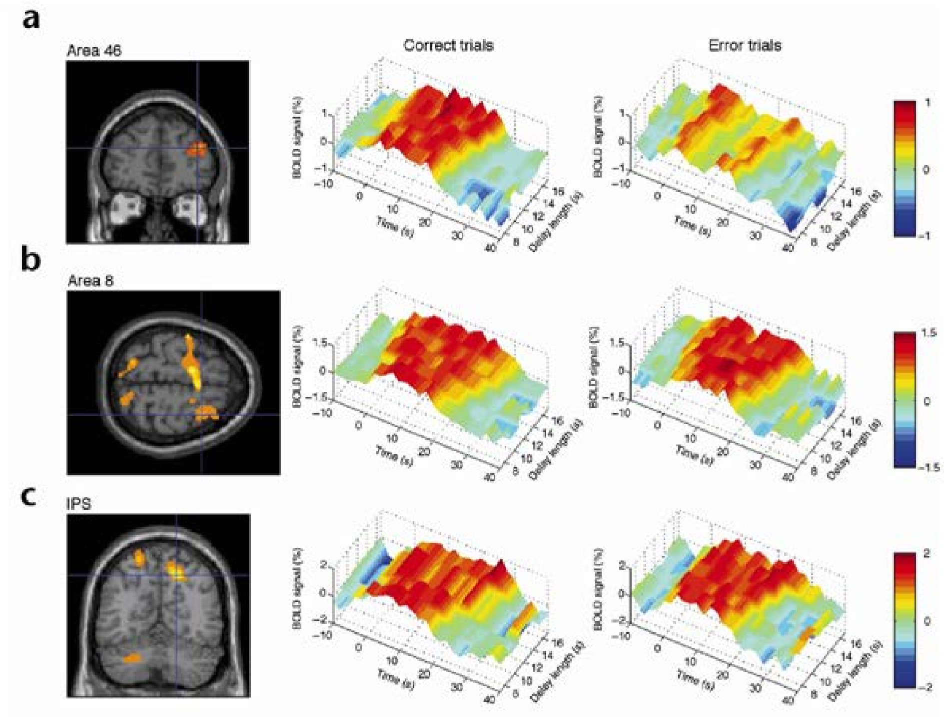
- Powerful
  - Improved ability to understand cognition
  - Better spatial resolution than PET
  - Allows new forms of analysis
- High benefit/risk ratio
  - Non-invasive (no contrast agents)
  - Repeated studies (multisession, longitudinal)
- Accessible
  - Uses clinically prevalent equipment
  - No isotopes required
  - Little special training for personnel

New Cognitive Analyses

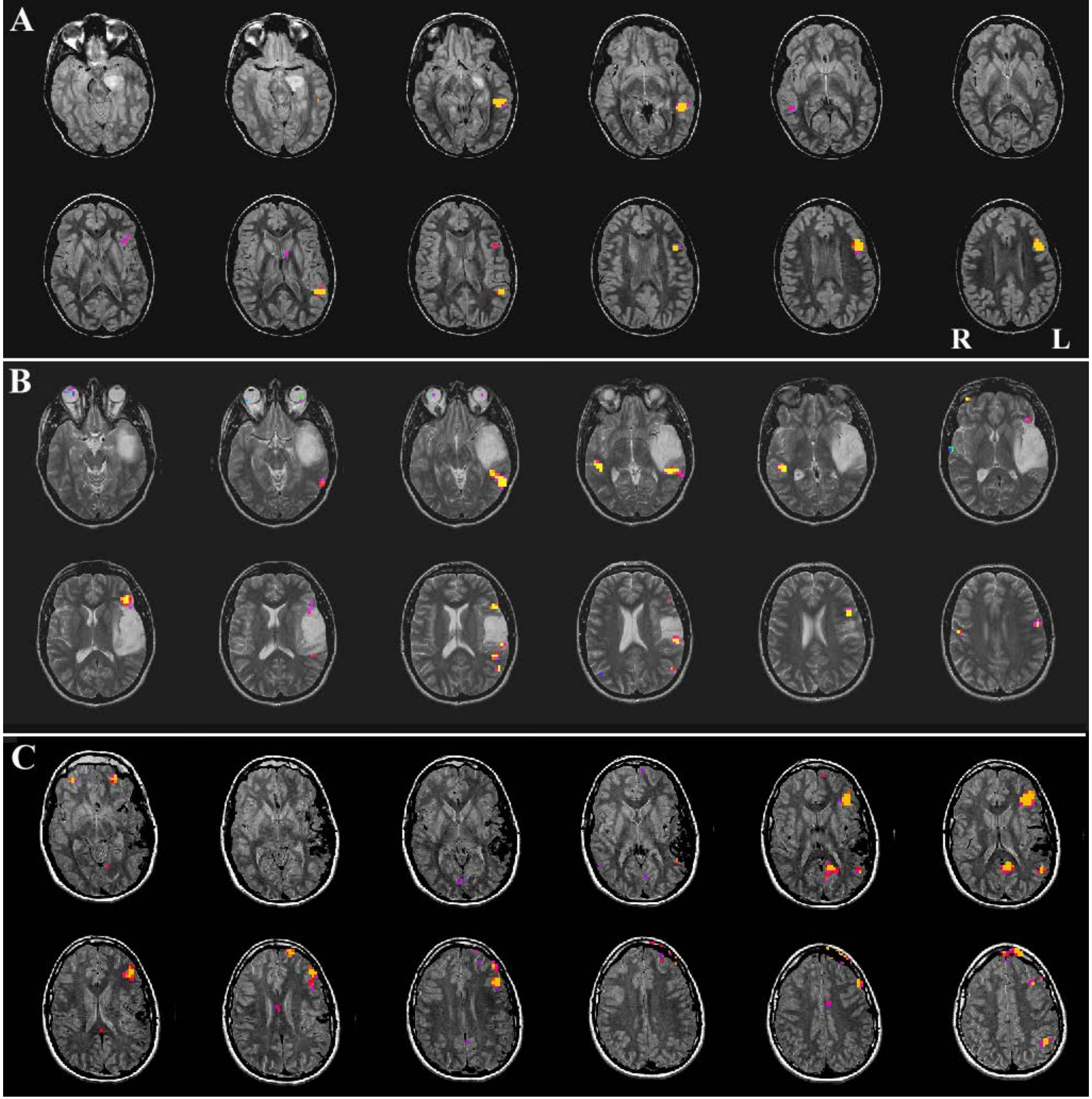
- Sampling rate affects experimental design
  - PET: >30s/data point ; fMRI: 1s/data point
  - Cognitive processes being measured must change more slowly than sampling rate
- New forms of analyses
  - Event-related: sorting trials by accuracy, response time, type of condition
  - Rapid stimulus presentation
- Allows creation of process models of activity
  - Difference in activation timing between regions is often on order of 100-1000ms



Cheng, Waggoner, & Tanaka (2001) *Neuron*



Sakai, Rowe, & Passingham (2002) *Nature Neuroscience*

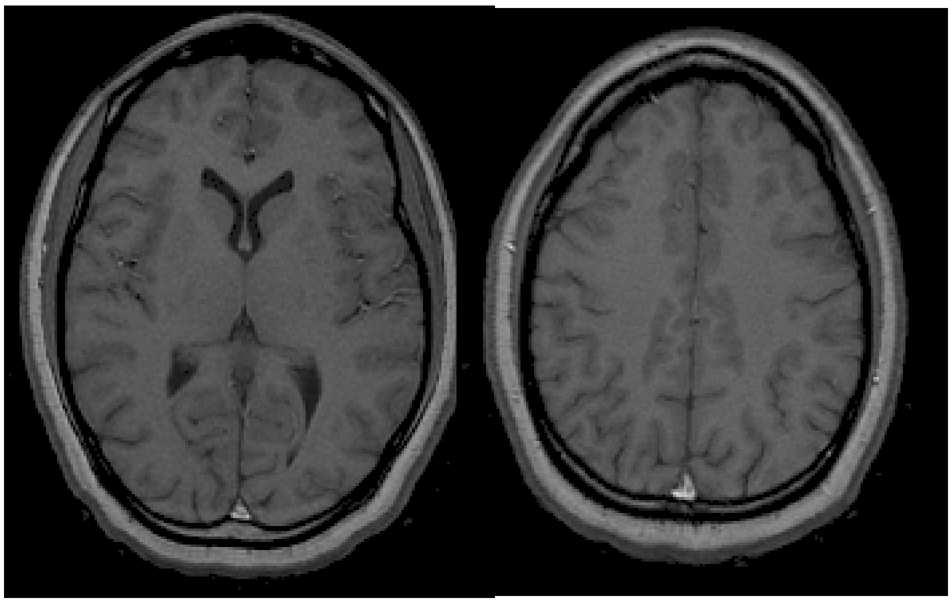


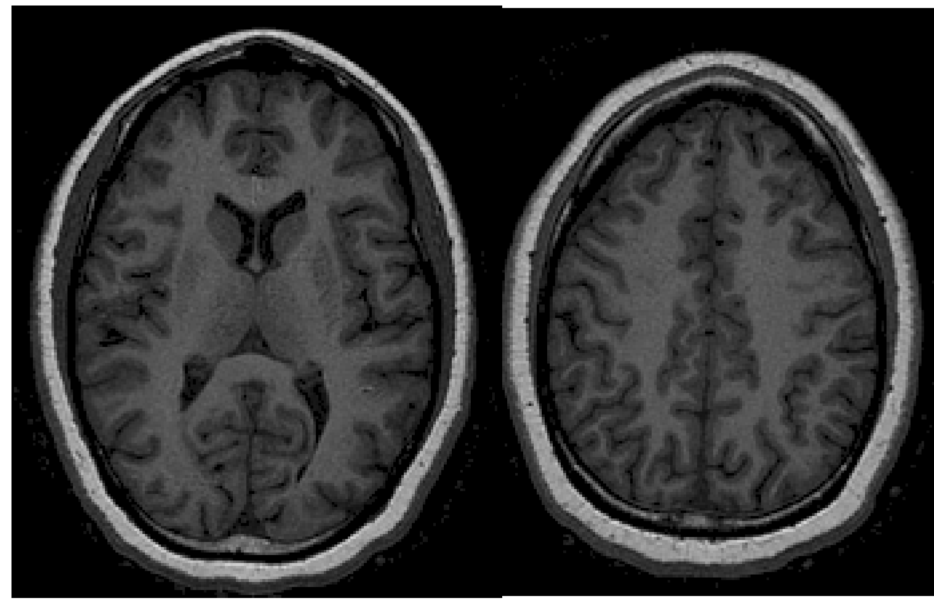
A
R
L
B
C

Key Concepts

- Contrast
- Spatial Resolution
- Temporal Resolution
- Functional Resolution

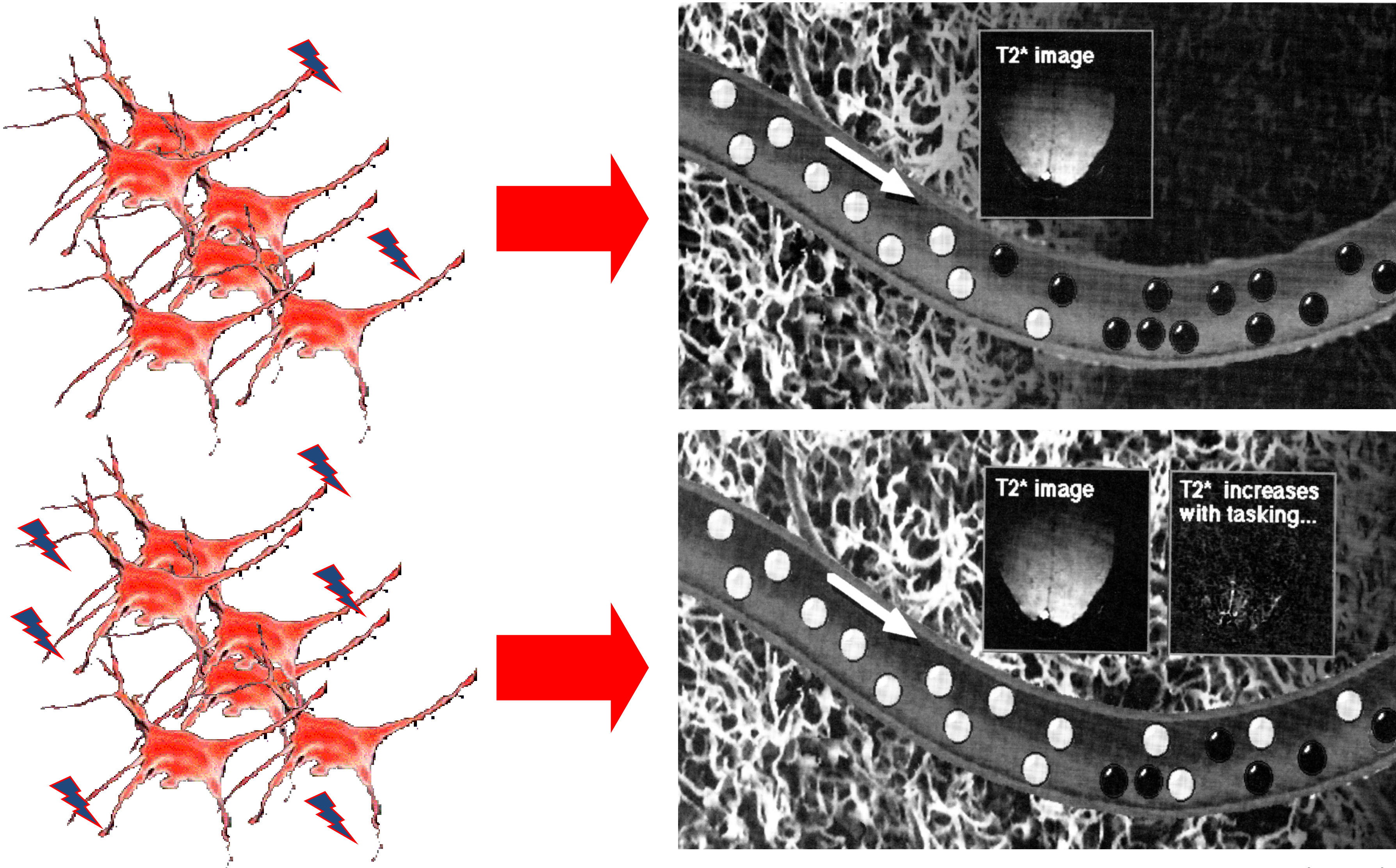
Anatomical Contrast





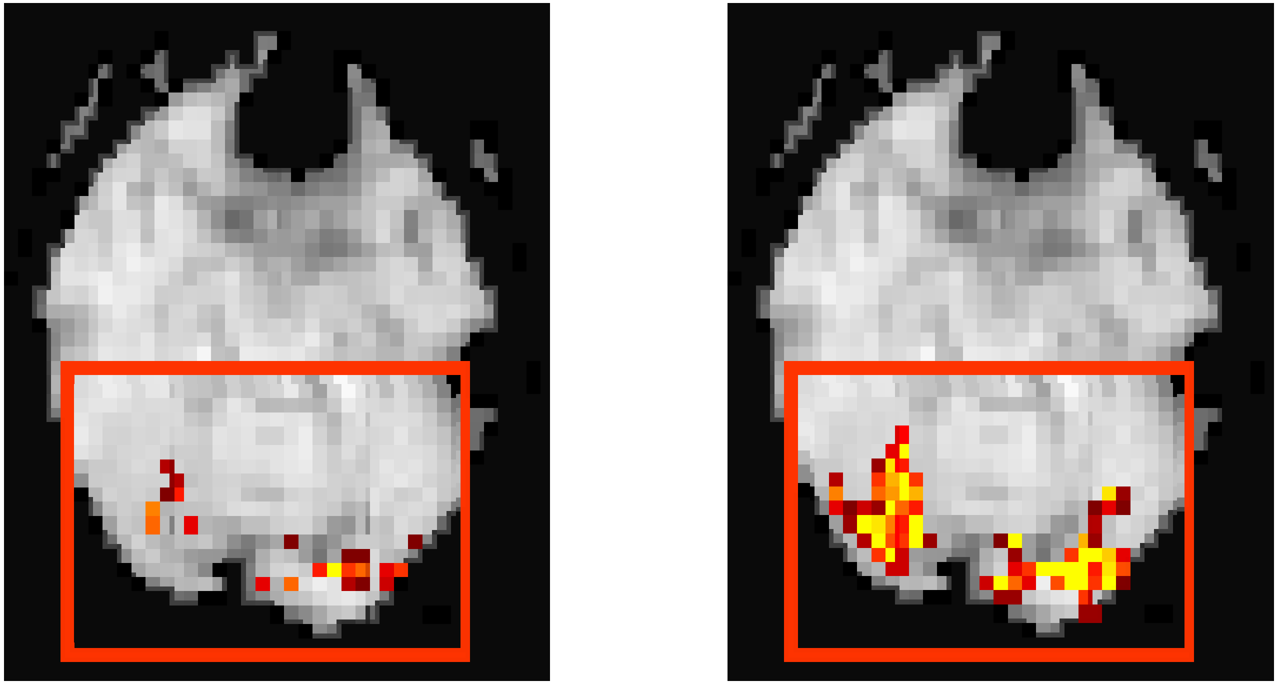
Definition: The ability to distinguish between two (or more) different properties of tissue.

Blood Oxygenation Level Dependent (BOLD) Contrast



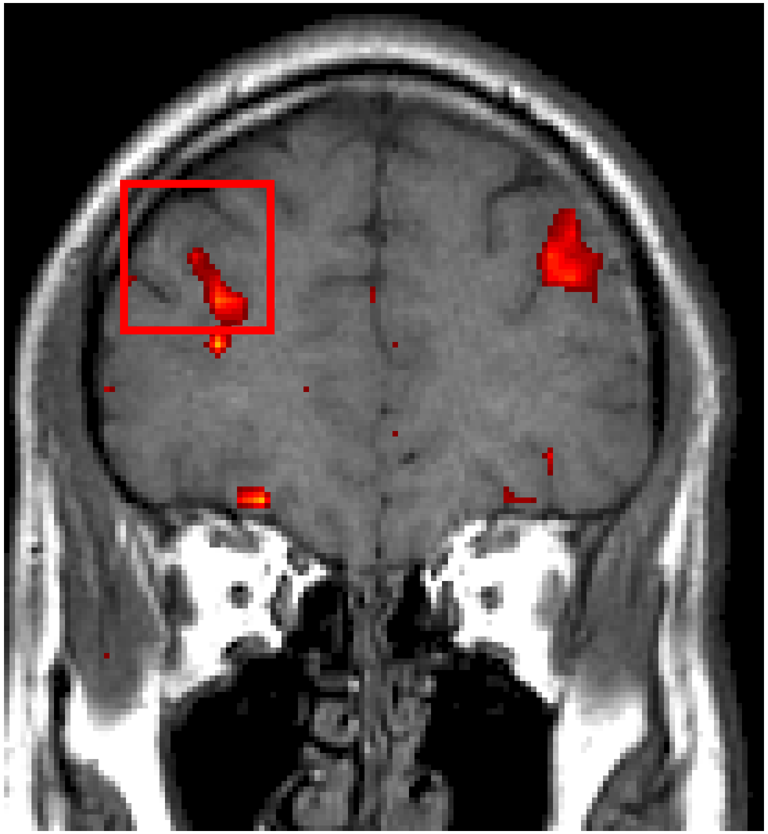
From Mosley & Glover (1995)

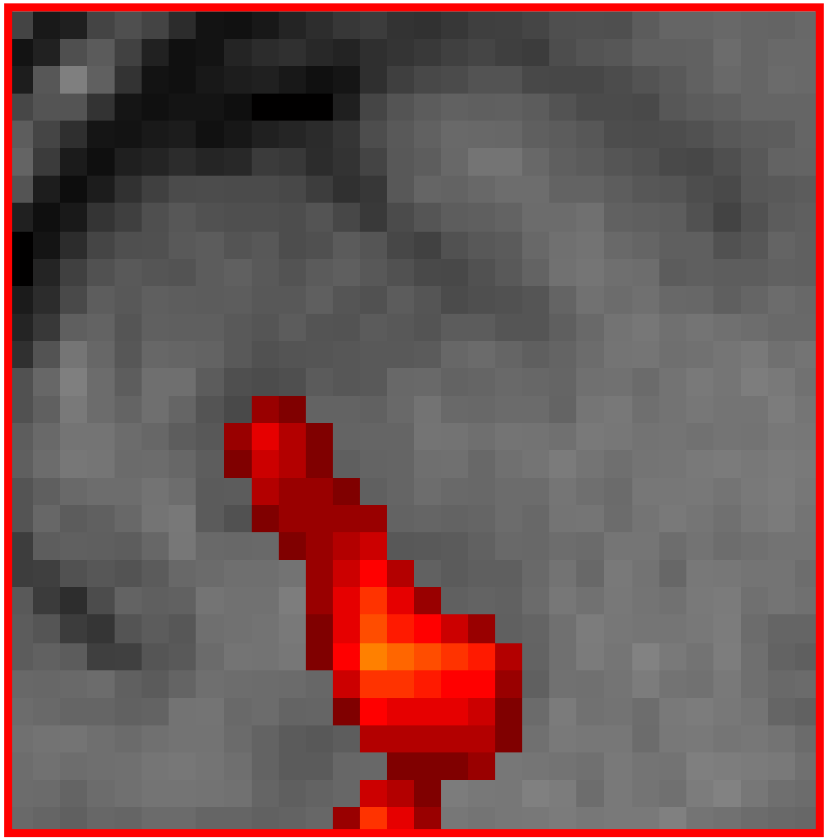
Design Effects on Functional Contrast



Contrast should really be considered as “contrast to noise”: how effectively can we decide whether a given brain region has property X or property Y?

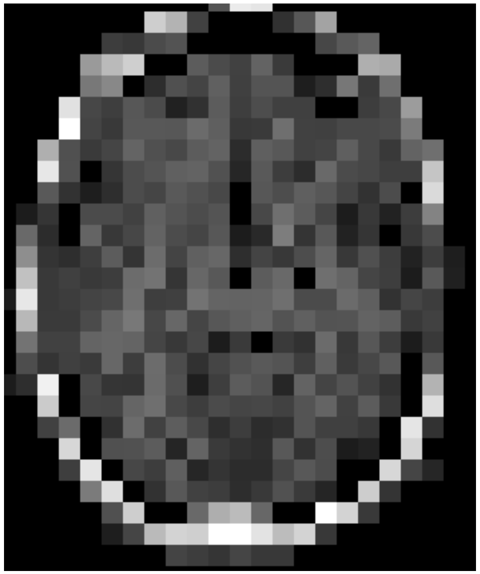
Spatial Resolution: Voxels



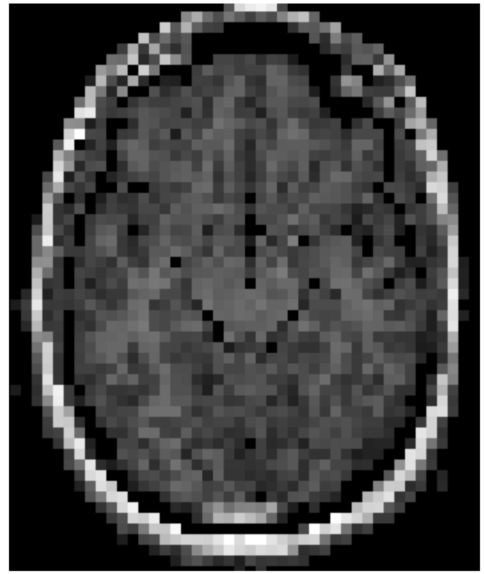


<u>Voxel</u>: A small rectangular prism that is the basic sampling unit of fMRI.
Typical functional voxel: $(4mm)^3$. Typical anatomical voxel: $(1.5mm)^3$.

Spatial Resolution: Examples

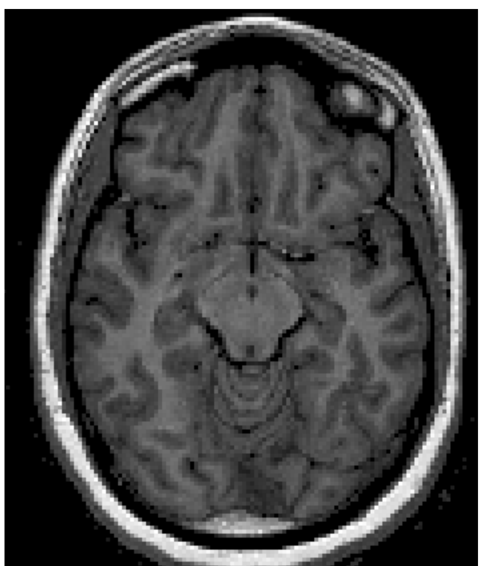


~8mm^2

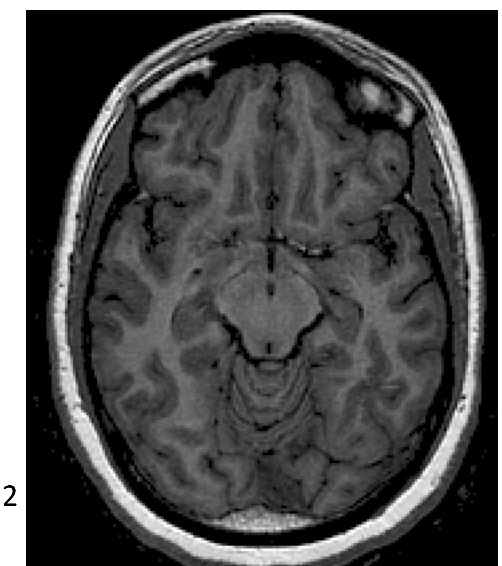


~4mm^2

~2mm^2



~1.5mm^2



~1mm^2

Temporal Resolution

- Importance depends upon research question
  - Type I: Detection
    - Temporal resolution is only indirectly important if your study investigates whether or not a given brain region is active.
  - Type II: Estimation
    - Temporal resolution is extremely important when attempting to understand the properties of an active region.

- Determining factors
  - Sampling rate, usually <u>repetition time</u> (TR)
  - Dependent variable, usually BOLD response
    - BOLD response is sluggish, taking 2-3 seconds to rise above baseline and 4-6 seconds to peak
  - Experimental design

MRI Safety

Issue: The appropriate risk level for a research participant is much lower than for a clinical patient.

Hospital Nightmare

Boy, 6, Killed in Freak MRI Accident

> **July 31, 2001 — A 6-year-old boy died after undergoing an MRI exam at a New York-area hospital when the machine's powerful magnetic field jerked a metal oxygen tank across the room, crushing the child's head. …**

ABCNews.com

MR Incidents

- Pacemaker malfunctions leading to death
  - At least 5 as of 1998 (Schenck, JMRI, 2001)
  - E.g., in 2001 an elderly man died in Australia after being twice asked if he had a pacemaker
- Blinding due to movements of metal in the eye
  - At least two incidents (1985, 1990)
- Dislodgment of aneurysm clip (1992)
- Projectile injuries (most common incident type)
  - Injuries (e.g., cranial fractures) from oxygen canister (1991, 2001)
  - Scissors hit patient in head, causing wounds (1993)
- Gun pulled out of policeman’s hand, hitting wall and firing
  - Rochester, NY (2000)

Issues in MR Safety

- Magnetic Field Effects
- Known acute risks
  - Projectiles, rapid field changes, RF heating, claustrophobia, acoustic noise, etc.
- Potential risks
  - Current induction in tissue at high fields
  - Changes in the developing brain
- Epidemiological studies of chronic risks
  - Extended exposure to magnetic fields
- Difficulty in assessing subjective experience
  - In one study, 45% of subjects exposed to a 4T scanner reported unusual sensations (Erhard et al., 1995)

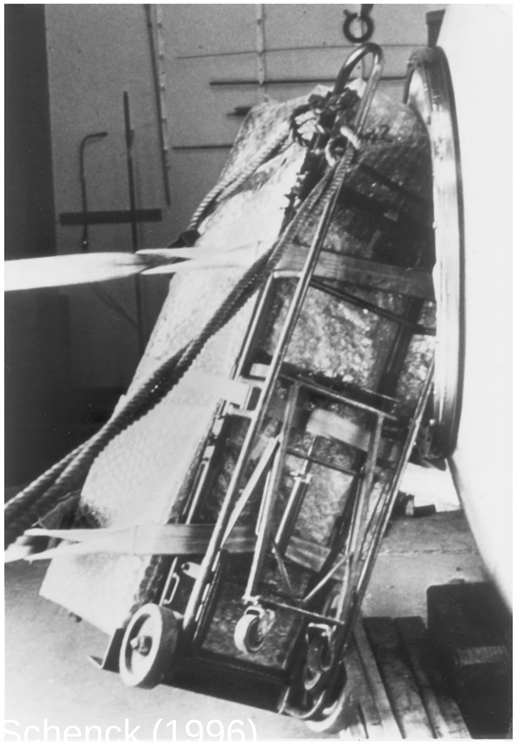
Possible Effects of Magnetic Fields

- Physiological
  - Red blood cells (especially sickled) may alter shape in a magnetic field
  - Some photoreceptors may align with the field.
- Sensory (generally reported in high-field)
  - Nausea
  - Vertigo
  - Metallic taste
  - Magnetophosphenes

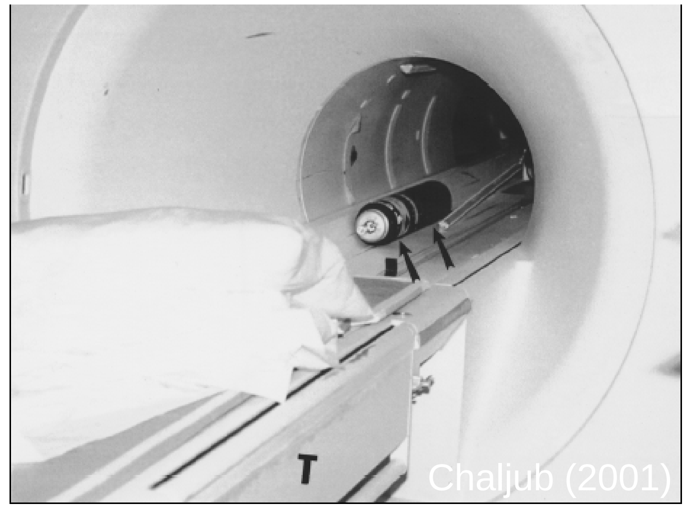
Risks of MRI

- Projectile Effects: External
- Projectile Effects: Internal
- Radiofrequency Energy
- Gradient field changes
- Acoustic Noise
- Quenching

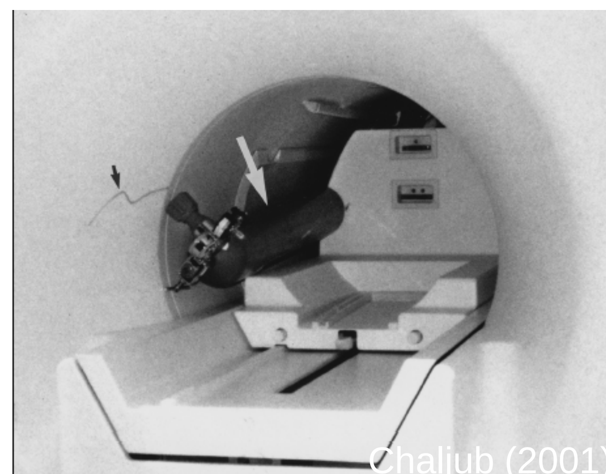
Projectile Effects: External



Schenck (1996)



Chaljub (2001)



Chaljub (2001)

"Large ferromagnetic objects that were reported as having been drawn into the MR equipment include a defibrillator, a wheelchair, a respirator, ankle weights, an IV pole, a tool box, sand bags containing metal filings, a vacuum cleaner, and mop buckets."

-Chaljub et al., (2001) *AJR*

Radiofrequency Energy

- Tissue Heating
  - Specific Absorption Rate (SAR; W/kg)
    - Pulse sequences are limited to cause less than a one-degree rise in core body temperature
    - Scanners can be operated at up to 4 W/kg (with large safety margin) for normal subjects, 1.5 W/kg for compromised patients (infants, fetuses, cardiac)
  - Weight of subject critical for SAR calculations

- Burns
  - Looped wires can act as RF antennas and focus energy in a small area
    - Most common problem: ECG leads
    - Necklaces, earrings, piercings, pulse oximeters, any other cabling

Projectile/Torsion Effects: Internal

- Motion of implanted medical devices
  - Clips, shunts, valves, etc.
- Motion or rotation of debris, shrapnel, filings
  - Primary risk: Metal fragments in eyes
- Swelling/irritation of skin due to motion of iron oxides in tattoo and makeup pigments

Acoustic Noise

- Potential problem with all scans
  - Short-term and long-term effects
- Sound level of BIAC scanners
  - 1.5T: 93-98 dB (EPI)
  - 4.0T: 94-98 dB (EPI)
- OSHA maximum exposure guidelines
  - 2-4 hours per day at BIAC levels
- Earplugs reduce these values by 14-29 dB, depending upon fit.

Gradient Field Changes

- Peripheral nerve stimulation
  - May range from distracting to painful
  - Risk greatly increased by conductive loops
    - Arms clasped
    - Legs crossed
- Theoretical risk of cardiac stimulation
  - No evidence for effects at gradient strengths used in MRI

Quenching

- Definition: Rapid decrease in magnetic field strength due to loss of superconductivity
  - Only initiated voluntarily due to danger to participant's life or health
- Effects
  - Magnets heat up with loss of current
  - Cryogenic fluids (Helium) boil off and fill the scanner room
    - Displaces breathable air from room
    - Cooling of room, condensation reduces visibility
  - Physical damage to the scanner may occur
  - Safety personnel must be cognizant of room conditions

Ultrasonic Imaging

ULTRASOUND PHYSICS

- What is sound/ultrasound?
- How is ultrasound produced
- Transducers - properties
- Effect of Frequency
- Image Formation
- Interaction of ultrasound with tissue
- Acoustic couplants
- Image appearance

Sound?

- Sound is a mechanical, longitudinal wave that travels in a straight line

- Sound requires a medium through which to travel

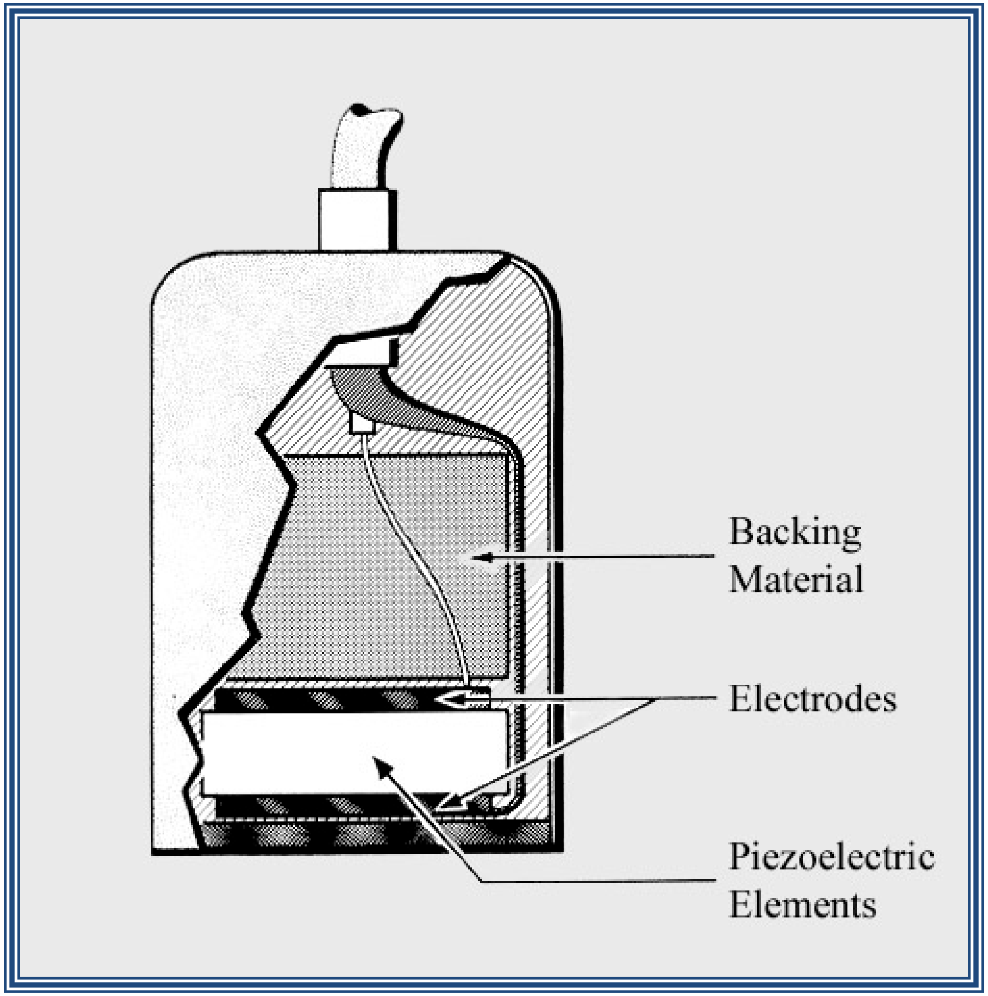
Ultrasound?

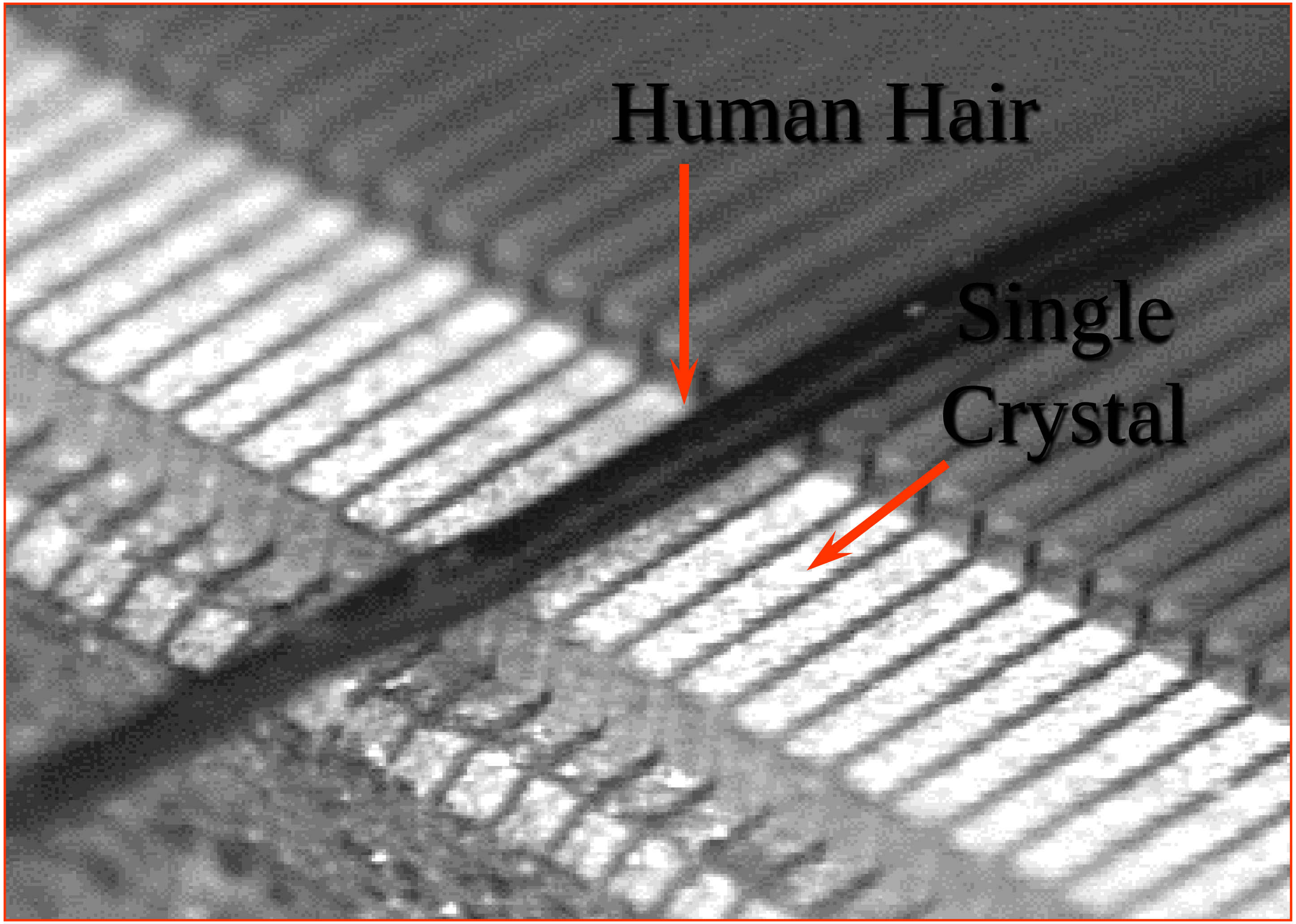
- Ultrasound is a mechanical, longitudinal wave with a frequency exceeding the upper limit of human hearing, which is 20,000 Hz or 20 kHz.
-

ULTRASOUND – How is it produced?

Produced by passing an electrical current through a piezoelectrical crystal

Transducer Construction





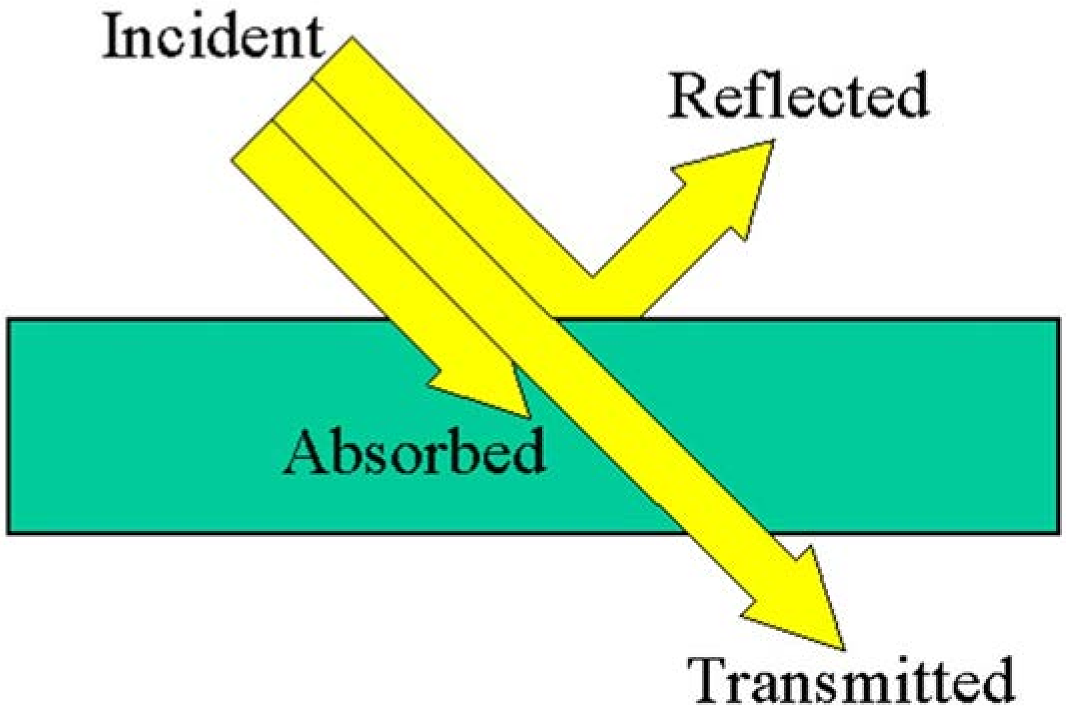
Microscopic view of scanhead

Piezoelectric material

- AC applied to a piezoelectric crystal causes it to expand and contract – generating ultrasound, and vice versa

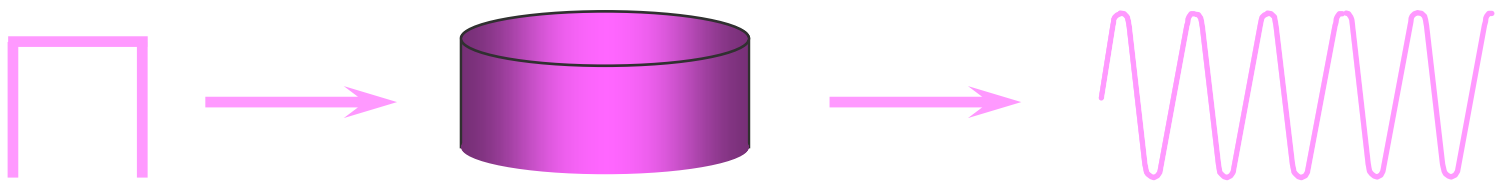
- Naturally occurring - quartz

- Synthetic - Lead zirconate titanate (PZT)


Incident
Reflected
Absorbed
Transmitted

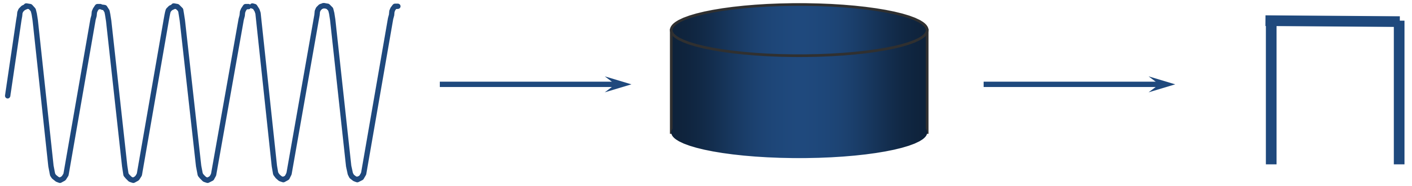
Ultrasound Production

- Transducer contains piezoelectric elements/crystals which produce the ultrasound pulses (transmit 1% of the time)
- These elements convert electrical energy into a mechanical ultrasound wave



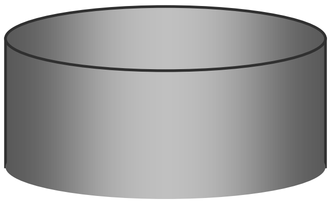
The Returning Echo

- Reflected echoes return to the scanhead where the piezoelectric elements convert the ultrasound wave back into an electrical signal
- The electrical signal is then processed by the ultrasound system

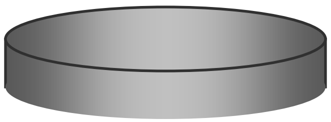


Piezoelectric Crystals

- The *thickness* of the crystal determines the frequency of the scanhead



Low Frequency
3 MHz



High Frequency
10 MHz

Frequency vs. Resolution

- The frequency also affects the QUALITY of the ultrasound image
  - The **HIGHER** the frequency, the **BETTER** the resolution
  - The **LOWER** the frequency, the **LESS** the resolution

Frequency vs. Resolution

- A 12 MHz transducer has very good resolution, but cannot penetrate very deep into the body

- A 3 MHz transducer can penetrate deep into the body, but the resolution is not as good as the 12 MHz

Transducer Design

Size, design and frequency depend upon the examination

Image Formation

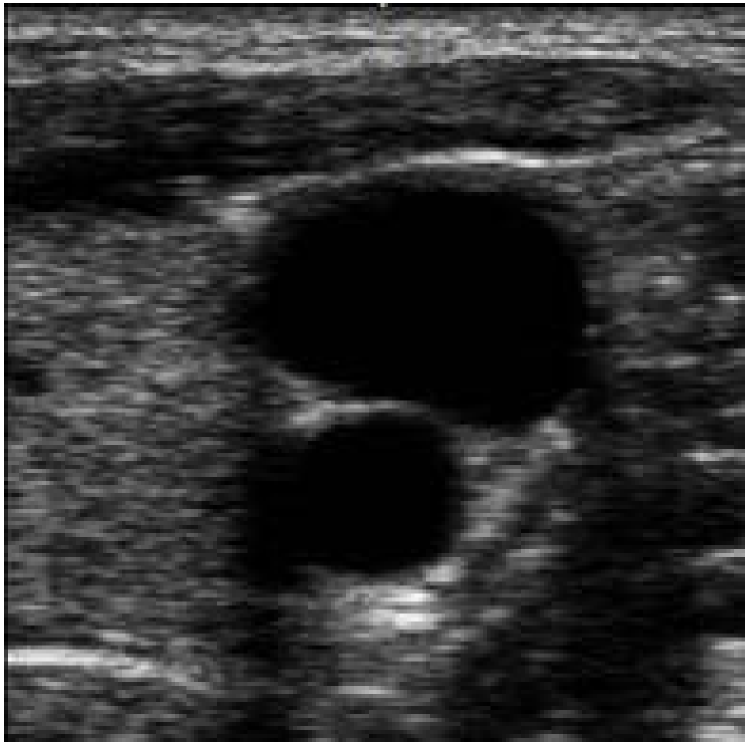
Electrical signal produces ‘dots’ on the screen

- Brightness of the dots is proportional to the strength of the returning echoes
- Location of the dots is determined by travel time. The velocity in tissue is assumed constant at 1540m/sec

$$\text{Distance} = \frac{\text{Velocity}}{\text{Time}}$$

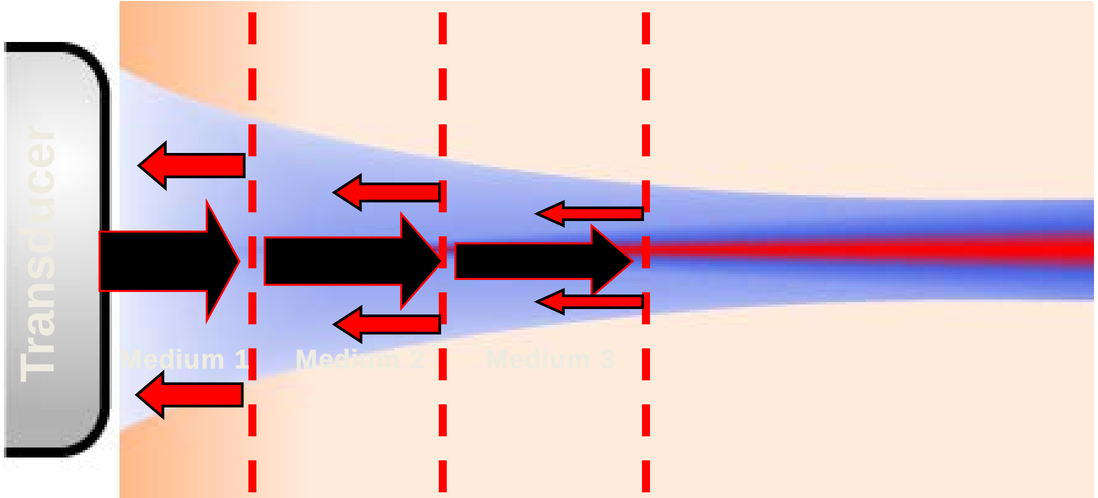
Image Formation

‘B’ mode



Interactions of Ultrasound with Tissue

- Acoustic impedance (AI) is dependent on the density of the material in which sound is propagated
  - *the greater the impedance the denser the material.*
- Reflections comes from the interface of different AI's
  - greater Δ of the AI = more signal reflected
  - works both ways (send and receive directions)



Interaction of Ultrasound with Tissue

- Greater the AI, greater the returned signal
    - largest difference is solid-gas interface
    - we don’t like gas or air
    - we don’t like bone for the same reason

GEL!!

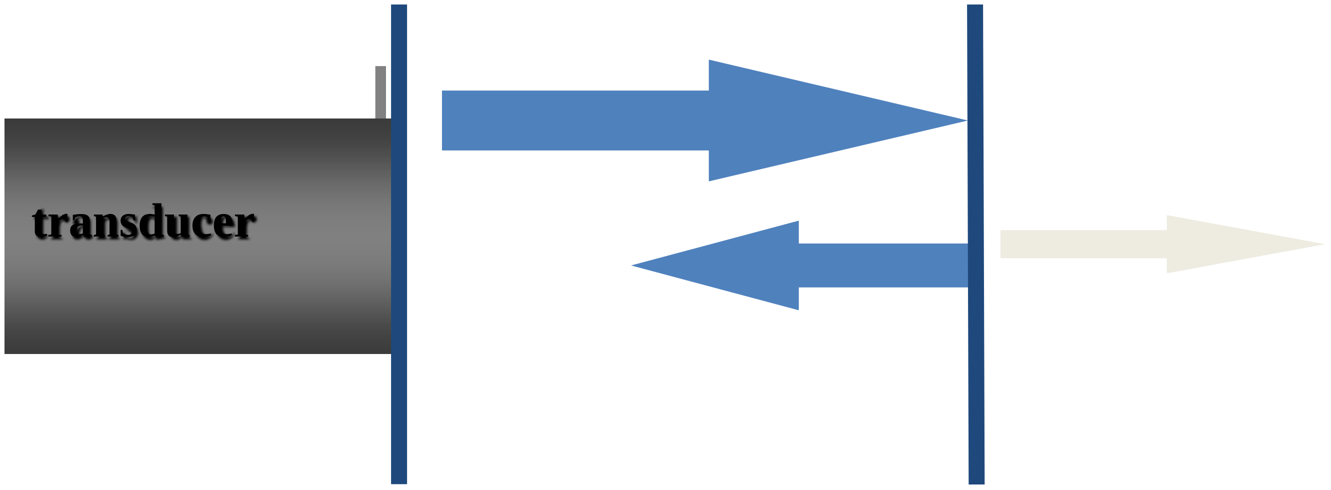
- Sound is attenuated as it goes deeper into the body

Interactions of Ultrasound with Tissue

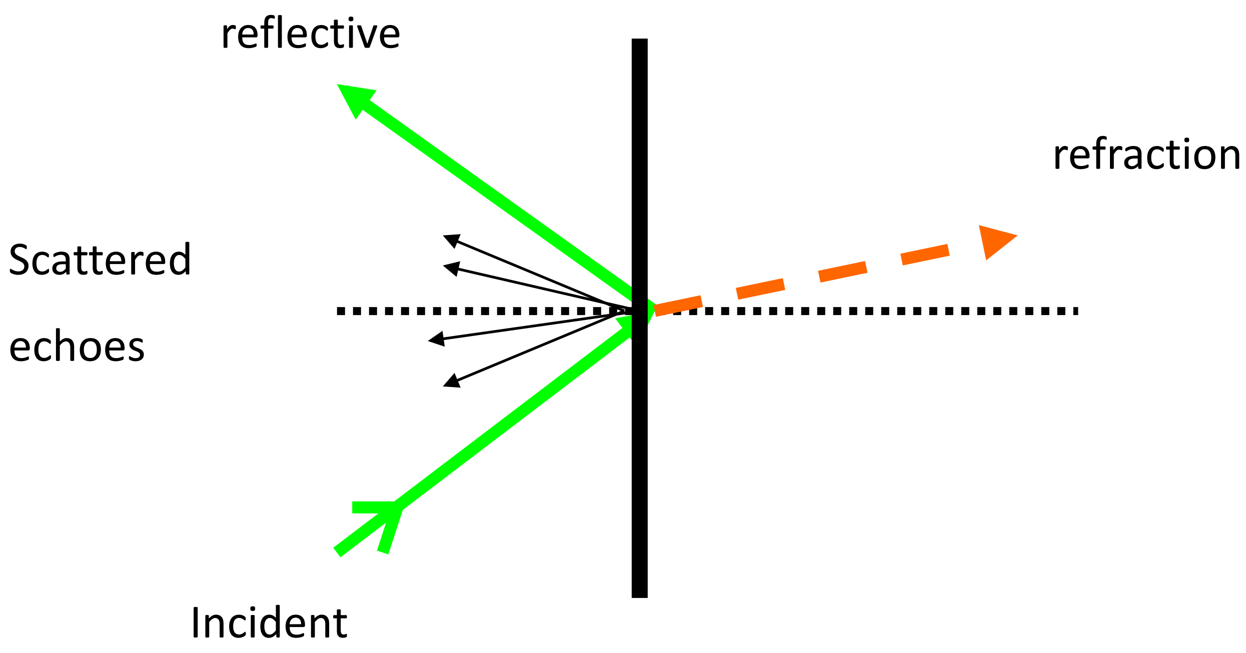
- Reflection
- Refraction
- Transmission
- Attenuation

Interactions of Ultrasound with Tissue

- **Reflection**
  - The ultrasound reflects off tissue and returns to the transducer, the amount of reflection depends on differences in acoustic impedance
  - The ultrasound image is formed from reflected echoes



Refraction

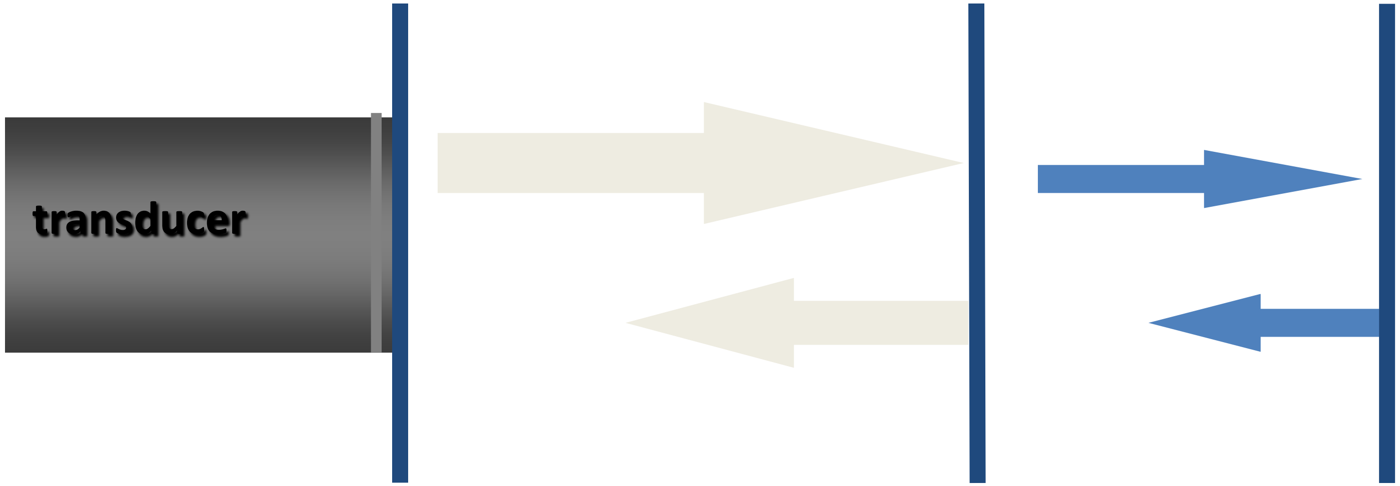


Angle of incidence = angle of reflection

Interactions of Ultrasound with Tissue

Transmission

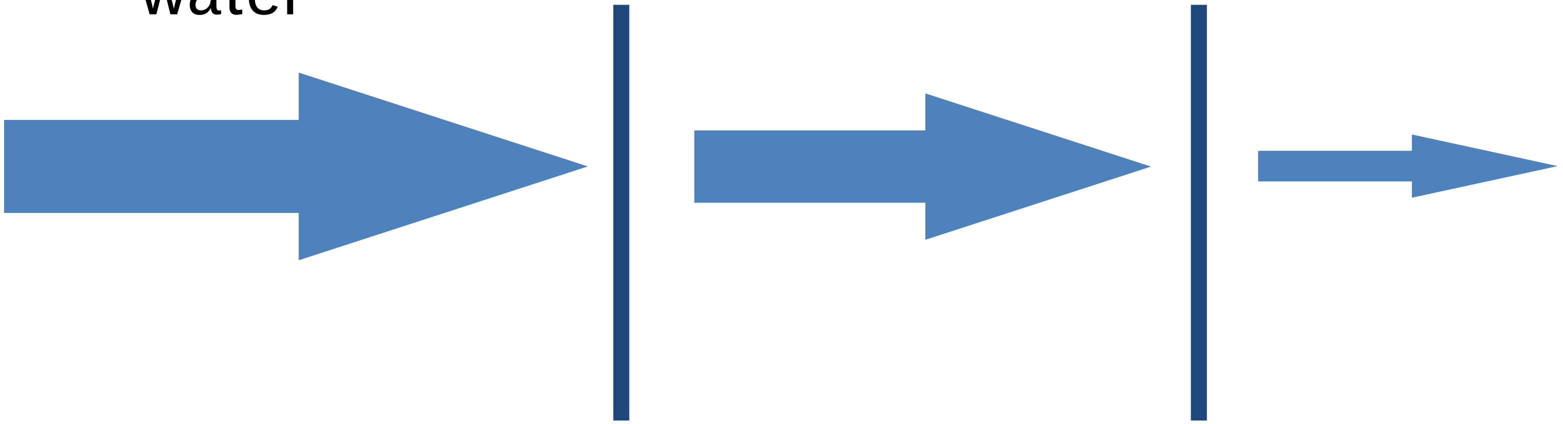
- Some of the ultrasound waves continue deeper into the body
- These waves will reflect from deeper tissue structures



Interactions of Ultrasound with Tissue

Attenuation

- Defined - the deeper the wave travels in the body, the weaker it becomes -3 processes: reflection, absorption, refraction
- Air (lung)> bone > muscle > soft tissue >blood > water



Ultrasound Gain

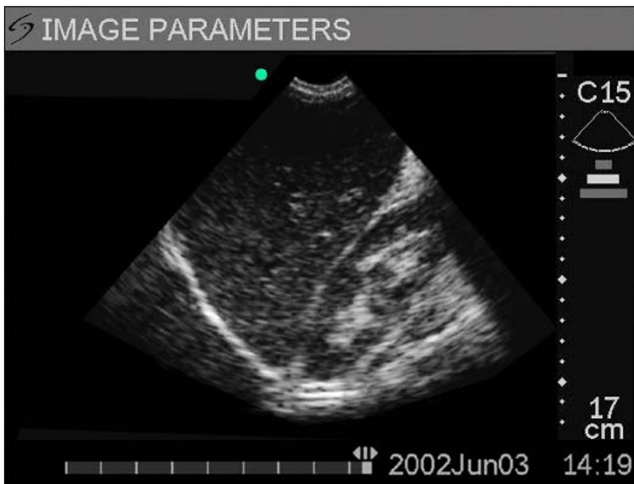
- Gain controls
  - receiver gain only
  - does **NOT** change power output
  - think: stereo volume
- Increase gain = brighter
- Decrease gain = darker

Balanced Gain

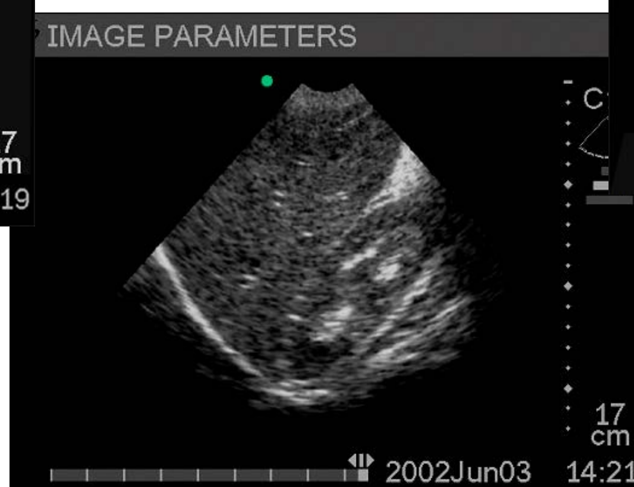
- Gain settings are important to obtaining adequate images.

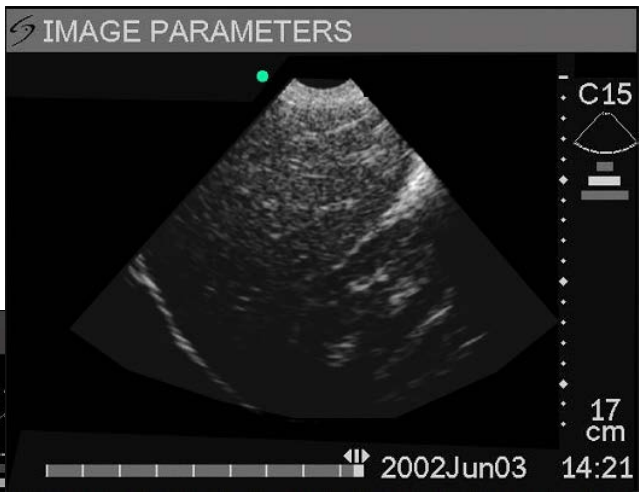
bad far field

bad near field



balanced



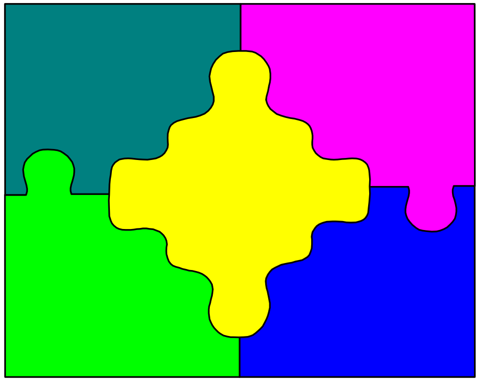


What determines how far ultrasound waves can travel?

- The FREQUENCY of the transducer
  - The **HIGHER** the frequency, the **LESS** it can penetrate
  - The **LOWER** the frequency, the **DEEPER** it can penetrate
  - Attenuation is directly related to frequency

Goal of an Ultrasound System

- The ultimate goal of any ultrasound system is to make like tissues look the same and unlike tissues look different

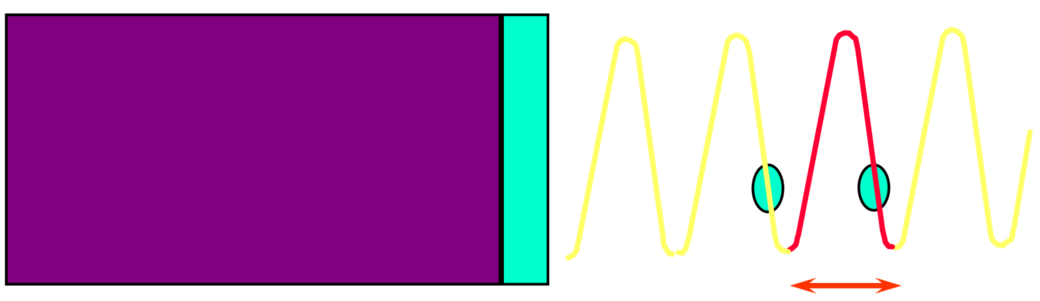


Accomplishing this goal depends upon…

- Resolving capability of the system
  - axial/lateral resolution
  - spatial resolution
  - contrast resolution
  - temporal resolution
- Processing Power
  - ability to capture, preserve and display the information

Types of Resolution

- Axial Resolution
  - specifies how close together two objects can be **along the axis** of the beam, yet still be detected as two separate objects
  - frequency (wavelength) affects axial resolution – frequency ↑ resolution ↑



Types of Resolution

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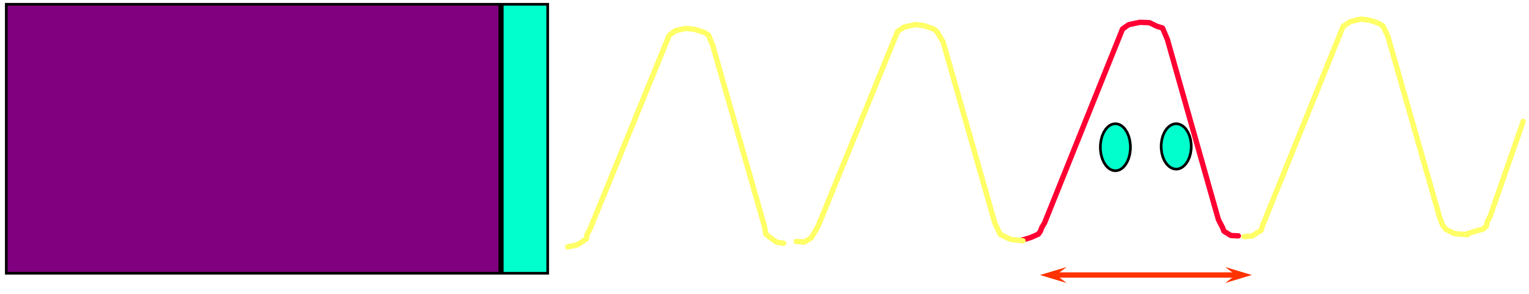
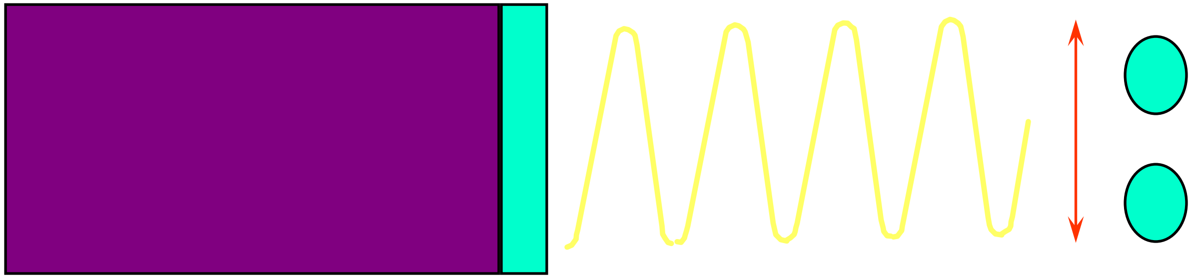


Types of Resolution

- Lateral Resolution
  - the ability to resolve two adjacent objects that are **perpendicular** to the beam axis as separate objects
  - beamwidth affects lateral resolution

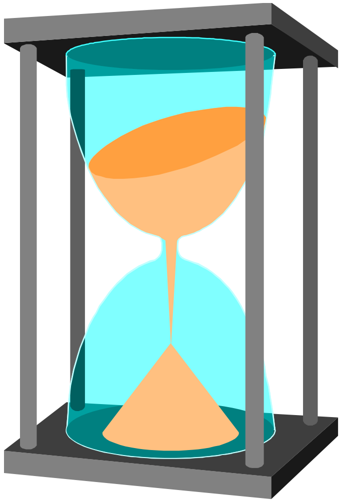


Types of Resolution

- Spatial Resolution
  - also called ***Detail*** Resolution
  - the combination of AXIAL and LATERAL resolution -

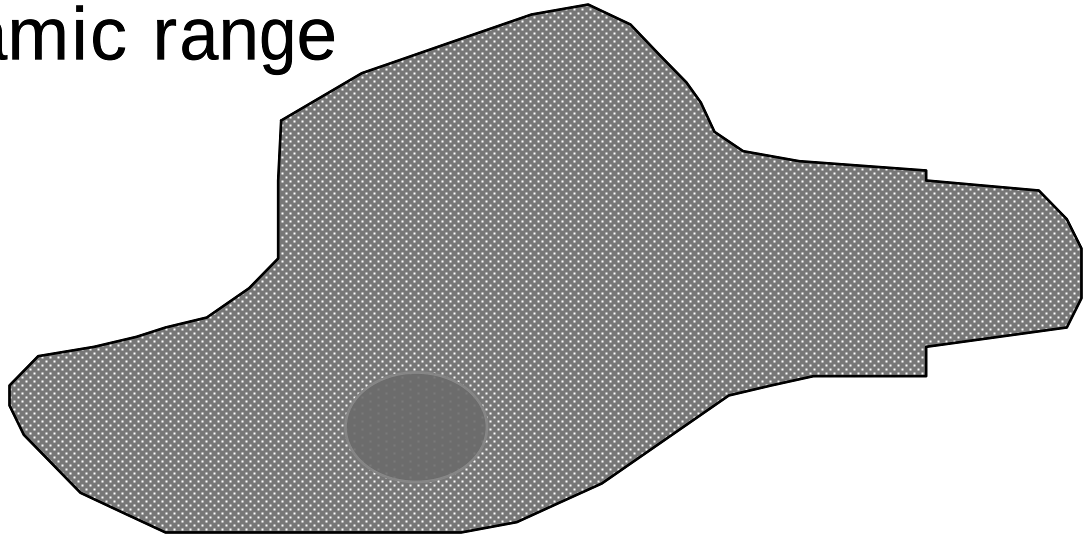
Types of Resolution

- Temporal Resolution
  - the ability to accurately locate the position of moving structures at particular instants in time
  - also known as frame rate



Types of Resolution

- Contrast Resolution
  - the ability to resolve two adjacent objects of similar intensity/reflective properties as separate objects - dependant on the dynamic range



Liver metastases

Ultrasound Applications

Visualisation Tool:

Nerves, soft tissue masses

Vessels - assessment of position, size, patency

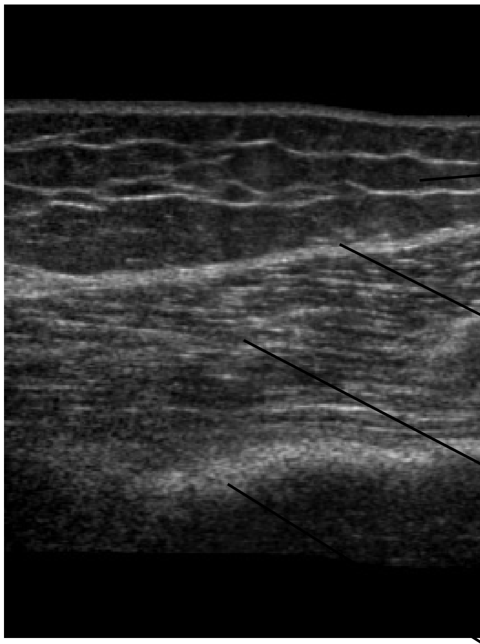
Ultrasound Guided Procedures in real time – dynamic imaging; central venous access, nerve blocks

Imaging

Know your anatomy – Skin, muscle, tendons, nerves and vessels

Recognise normal appearances – compare sides!

Skin, subcutaneous tissue



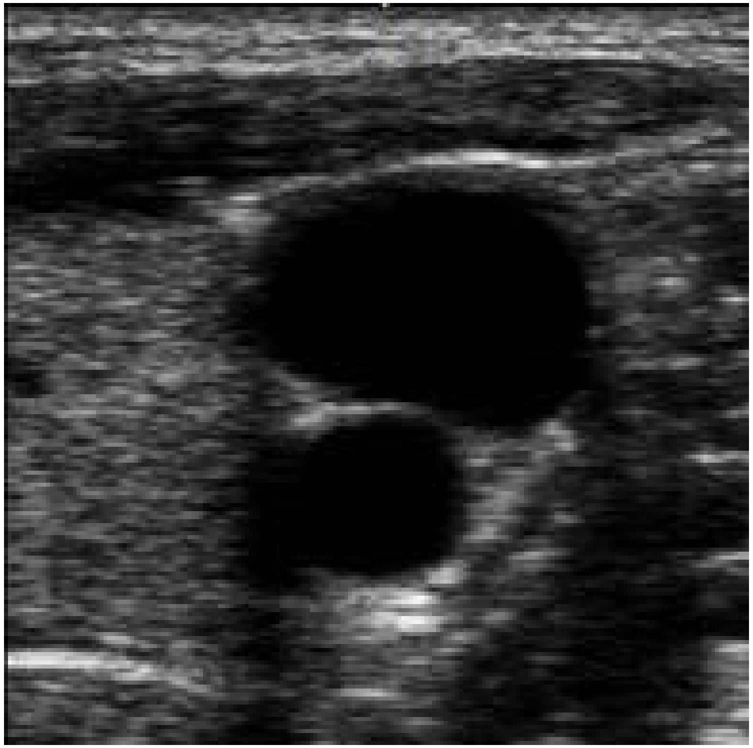
Epidermis

Loose connective tissue and subcutaneous fat is hypoechoic

Muscle interface

Muscle fibres interface

Bone



Transverse scan – Internal Jugular Vein and Common Carotid Artery


LT HAND
2005Dec10 11:48
Res
FLEXOR POLLICIS LONGUS TENDON
SmP
L38
100%
0
0
MI
1.1
2.0
Res
-2
Dual
Clips...
Biopsy
Page 2...