Medical Imaging

"Seeing Through the Human Body"

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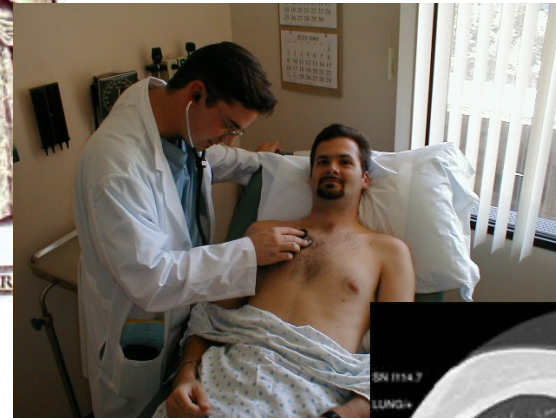
September 2021

History of medicine

LE MALADE IMAGINAIRE

- From humours…

Until 19th century western medicine was based on Galen's theory of humours, or principal fluids: black bile, yellow bile, phlegm (strange liquid related to tumors), and blood

- …to auscultation

Stethoscope: Laennec in 1816

- … and imaging

It all started in 1845 with the first X-ray image

Roentgen's wife

Von Kolliker

History of Medical Imaging

X Ray

- **1845**: Discovery of X-ray by **Wilhelm Conrad Röntgen**, german physicist.
- **1972**: First scanner set up by **Allan Mc Cornack** et **Godfrey N. Hounsfield**, Nobel prize in 1979 for this work.

US

- **1915**: Ultrasound propagation principles for SONAR (SOund NAvigation Ranging).
- **1955**: First echography by **Inge Edler** (1911-2001), swedish cardiologist.

MRI

- **1945**: Discovery of nuclear resonance under a magnetic field by **Edward Purcell** and **Felix Bloch**, both nobel prize winners in 1952.
- **1973**: First MRI image on an animal by the american chemist **Paul Lauterbur.** P. Lauterbur and P. Mansfield won the Nobel Prize for Physiology or Medicine in 2003 for the development of MRI.
- **1980**: Spectroscopy by magnetic resonance.

Nuclear

- **1934**: Discovery of natural radioactivity by **Henri Becquerel**, **Pierre** et **Marie Curie.** Discovery of artificial radioactivity by **Irène et Frédéric Joliot-Curie**
- **1990**: Nuclear medicine development with scintigraphy and positron emission tomography.

Terminology

- **Transmission:** Photons passing through the body
- **Absorption:** Partial or total absorption of energy in the patient
- **Scatter:** Radiation diverted in a new direction
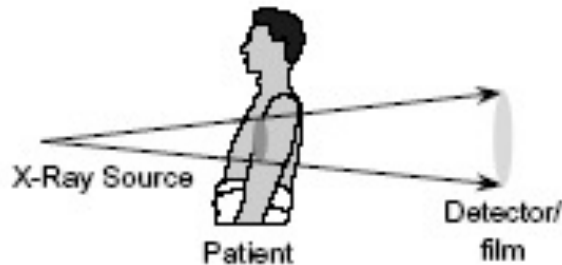
Source: Utrecht University, NL

- **Axial** - plane normal to a vector from head to toe.
- **Coronal** - plane normal to a vector from front to back
- **Sagittal** - plane normal to a vector from left to right.
- **Oblique** – otherwise.

Image types

- 2D:
  - A single slice.
  - A projection image.
- 3D:
  - A series of parallel slices with uniform spacing.
  - A series of slices with varying spacing and/or orientation.
  - A volumetric data set.

Imaging Support

**Films
(hard copy)**

**Digital Display
(soft copy)**

Imaging Modalities

- X-Ray:
  - Traditional
  - Computerized Tomography (CT)
- Ultrasound (US)
- Magnetic Resonance Imaging (MRI)
- Nuclear Imaging

X-rays

CT
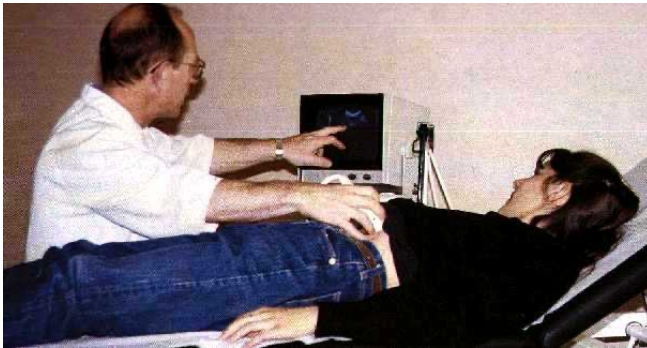
Ultrasound

MRI

etc.

A lot of differences

- Physical principles (important to correctly interpret the images!)
- Irradiation
- Resolution
- 2D / 3D
- Slice / projection
- Temporal sequences
- Differenciation of tissues
- Anatomy / function or metabolism
- Instrumentation
- …

Research in image processing and understanding for medical applications

- Reconstruction

- Improve image quality

- Organ detection, classification, segmentation, recognition

- Pathology detection and recognition

- Quantitative measurements

- Modeling

- 3D visualization

- Registration and information fusion

- Functional analysis, neurosciences

- Aid to diagnosis, therapeutical or surgical planning

- Follow-up

- …

Complex and multi-disciplinary domain

- Physics
- Mathematics
- Computer science
- Biology
- Medicine, anatomy
- Neuroscience, psychology
- Clinical studies and research
- Strong interaction and communication needed among actors
- And the patient …

Principle of X-ray imaging

Electromagnetic spectrum

| Penetrates Earth's Atmosphere? | Y | | N | | Y | | N | | | |

Radiation Type	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
Wavelength (m)	10^3	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

Approximate Scale of Wavelength

| Buildings | Humans | Butterflies | Needle Point | Protozoans | Molecules | Atoms | Atomic Nuclei |

Frequency (Hz)

10^4 10^8 10^{12} 10^{15} 10^{16} 10^{18} 10^{20}

Temperature of objects at which this radiation is the most intense wavelength emitted

| 1 K | 100 K | 10,000 K | 10,000,000 K |
| $-272\ °C$ | $-173\ °C$ | $9,727\ °C$ | $\sim 10,000,000\ °C$ |

Source: Wikipedia

Conventional X-Ray

Conventional X-Ray

Physics Principles

- Accelerating & decelerating electrons generate electromagnetic radiation

- Bombardment of a target material with a beam of fast electrons

- Electrons are emitted thermally from a heated cathode (C) and are accelerated toward the anode target (A) by the applied voltage potential V (~kV).

- Electromagnetic radiation is produced by the quick deceleration of the electrons when hitting the target (Bremsstrahlung).
    - ~99% of energy converted into heat.
    - Few generated X-ray photons with wavelength set by the amount of energy loss   E=hν=E2-E1

X-rays
$E \approx 5\text{-}150keV$

e⁻

A

C

V = 5-150kV

$h\nu$

E1

Nucleus

E2
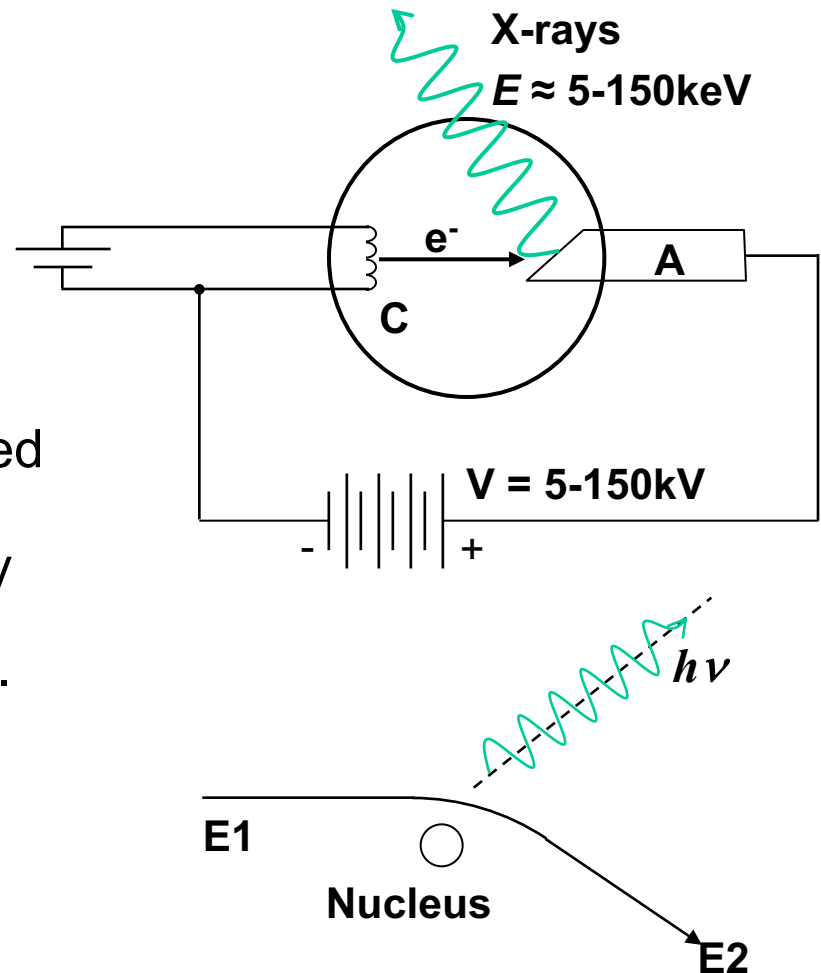
Conventional X-Ray

Image Formation

- X-ray beam goes though the patient, which decreases energy, depending on the absorption pattern inside the body.

Primary X-rays

patient

collimator

Screen + detector
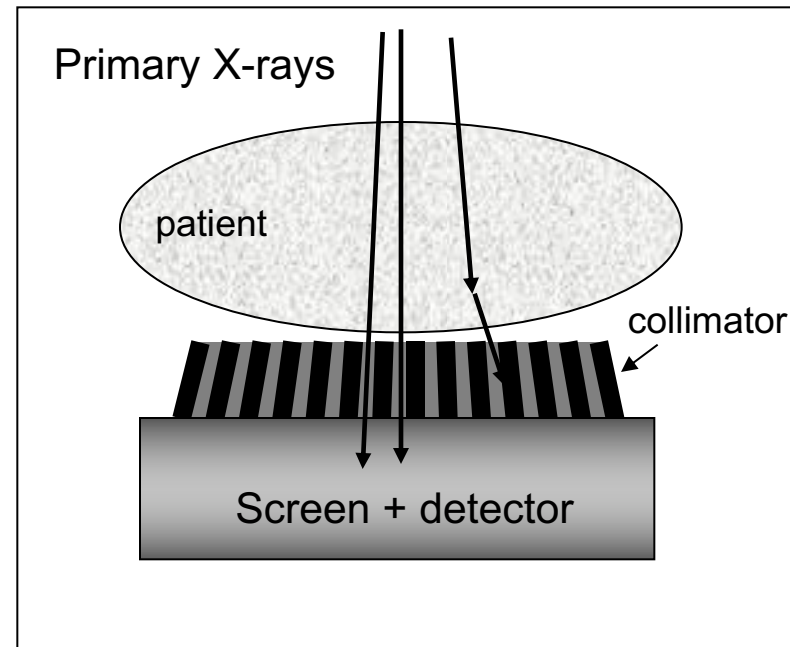
Conventional X-Ray

Image Capture

- Image captured on phosphor screen, with conversion to visible light.

- Recording on film (negative image)

- Display on video monitor (positive image)

Primary X-rays

patient

lead

detector
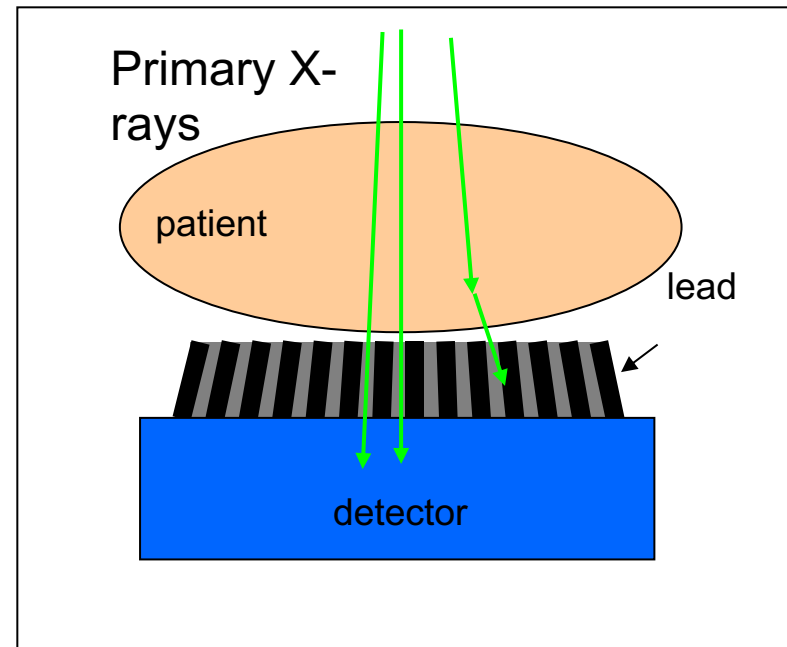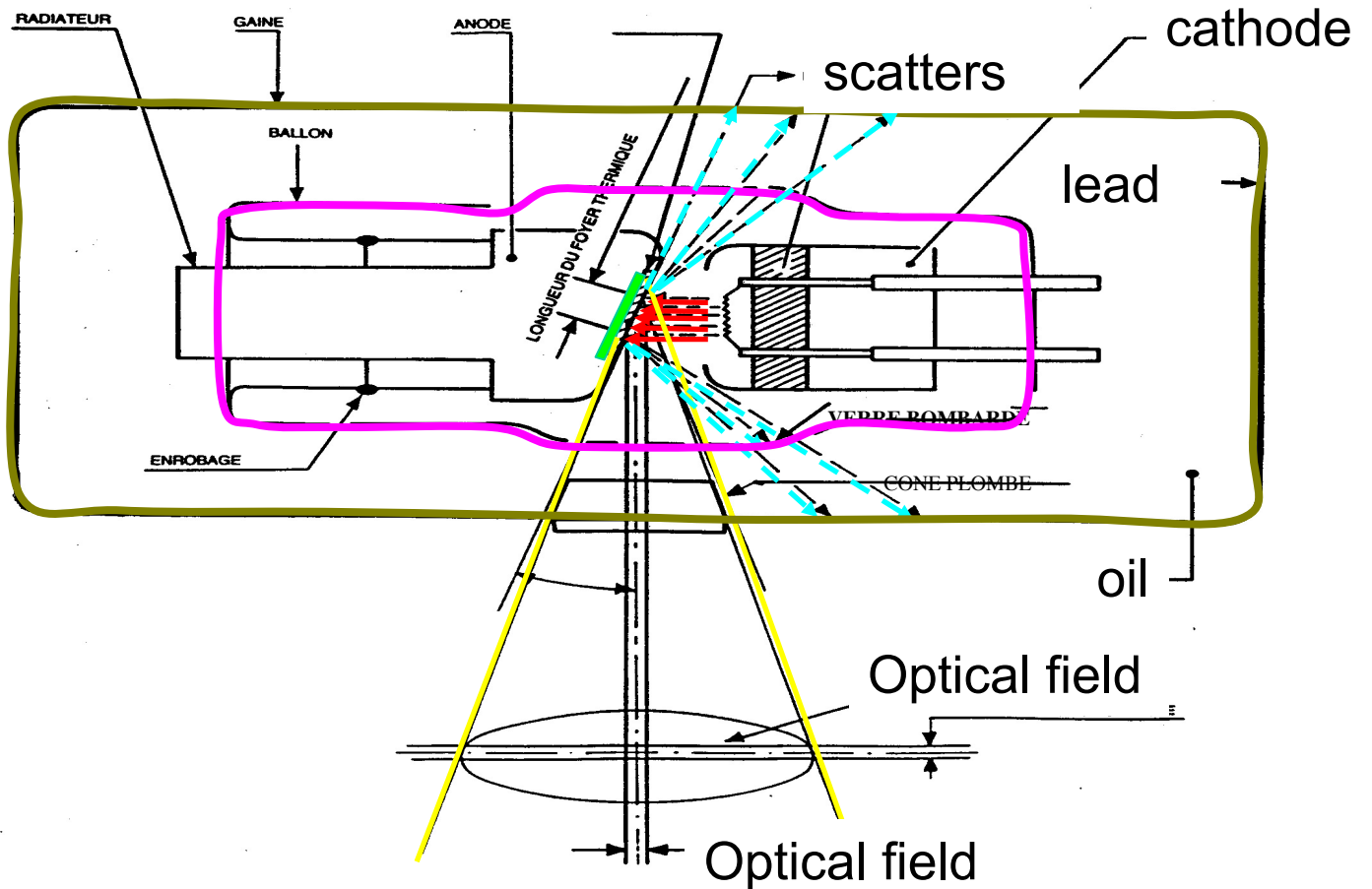
Conventional X-Ray

System Design

Conventional X-Ray

System Design

Film Chest X-ray   Digital Chest X-ray
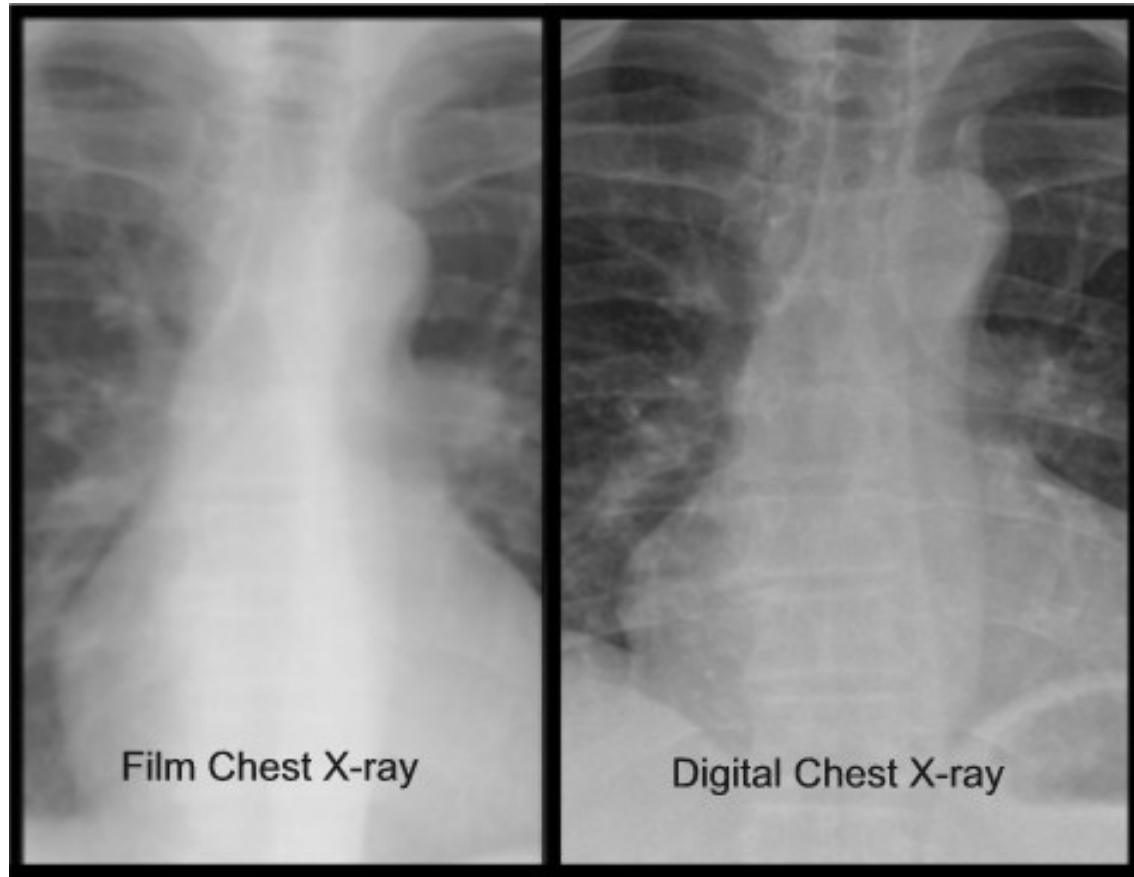
Conventional X-Ray

- **Advantages:**
  - Fast.
  - Inexpensive.
- **Disadvantages:**
  - Ionizing radiation involved.
  - Projection images.
  - Poor blood vessel and soft-tissue contrasts.

Conventional X-Ray

- **Applications:**
  - Lungs, breasts.
  - Gastro-intestinal track.
  - Blood vessels (contrast agent).
  - Bones, joints.

Conventional X-Ray
Examples: Bones
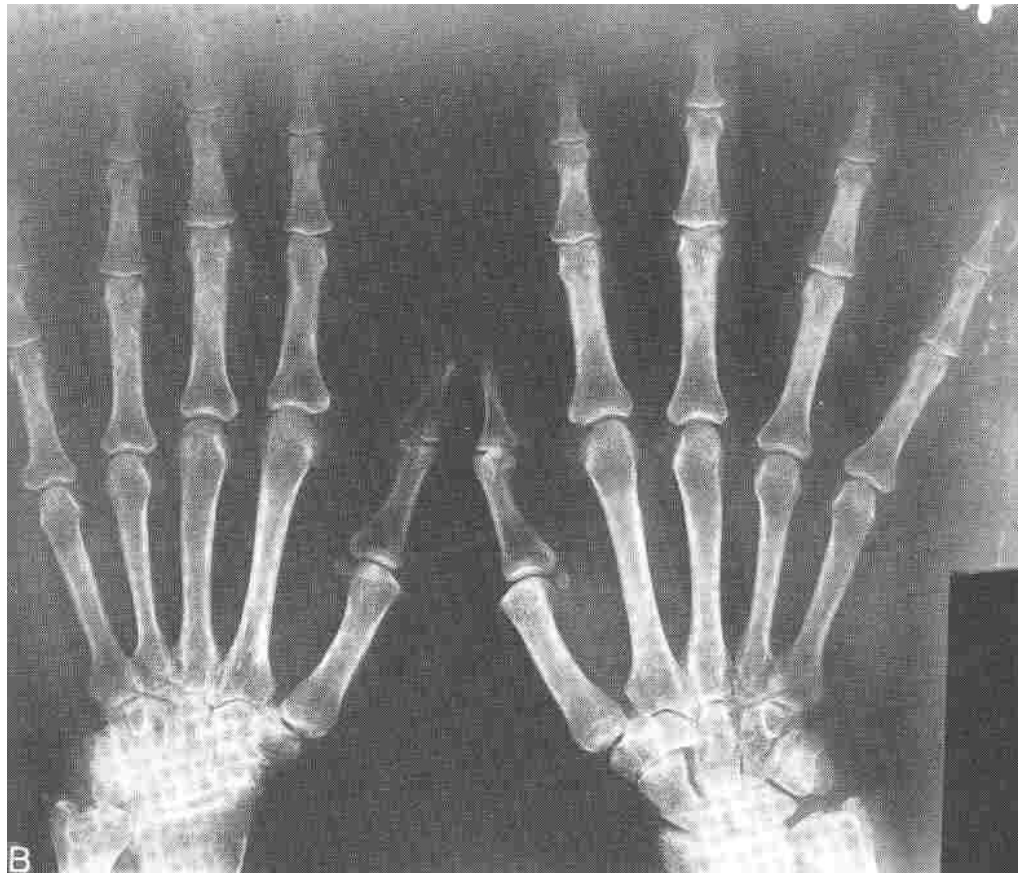
Conventional X-Ray
Examples: Lungs

Patient with hemo-pneumothorax

Pleural line

air + fluid
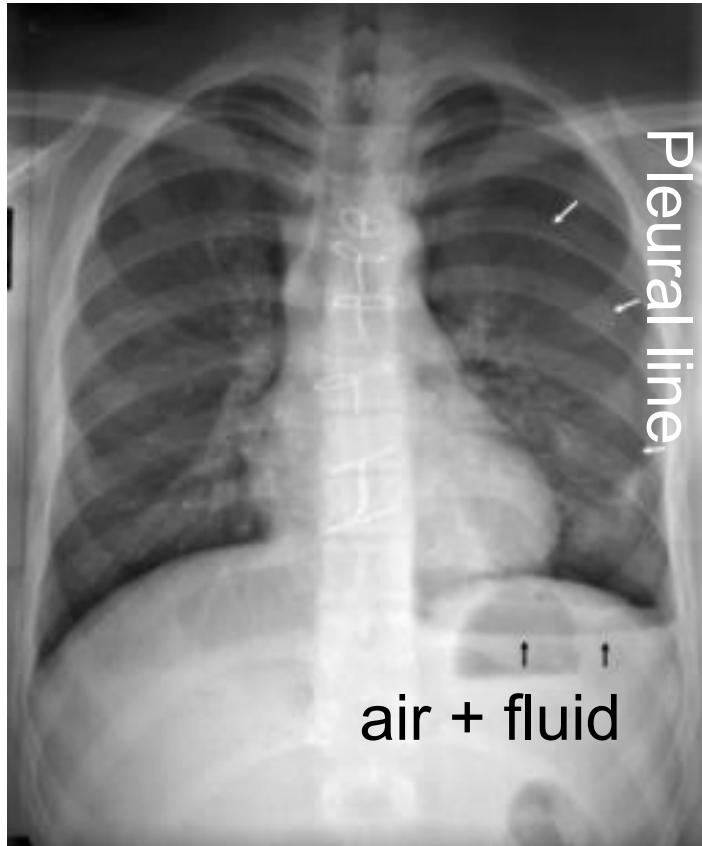
Patient with pacemaker

Conventional X-Ray

Examples: Mammography

- Low kV can be used (little attenuation) => sufficient photoelectric absorption to differentiate between normal tissue and pathology

- Dose must be limited.

- Breast must be compressed
  - To avoid motion.
  - To minimize focus/film distance.
  - To have equal tissue thickness.

Conventional X-Ray

Examples: Fluoroscopy

- Real-time X-ray imaging.

- Direct visualization on screen.

- Used for guidance of interventions (mainly vascular and orthopedic).

Ex: Fluoroscopic guidance with umbilical catheter injecting contrast agent in the small bowel.

Source: www.mypacs.net

Conventional X-Ray

Examples: Fluoroscopy

patient

C-arm

cathode
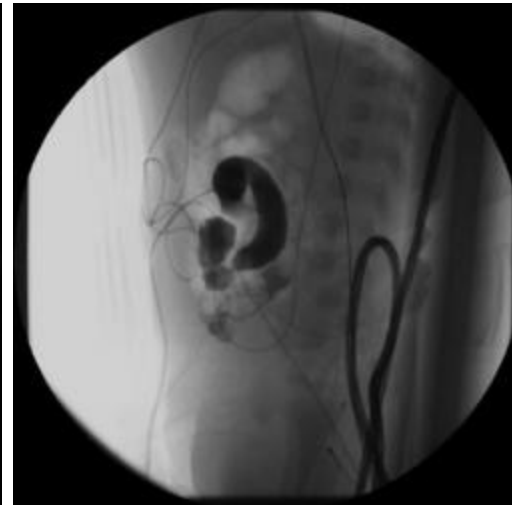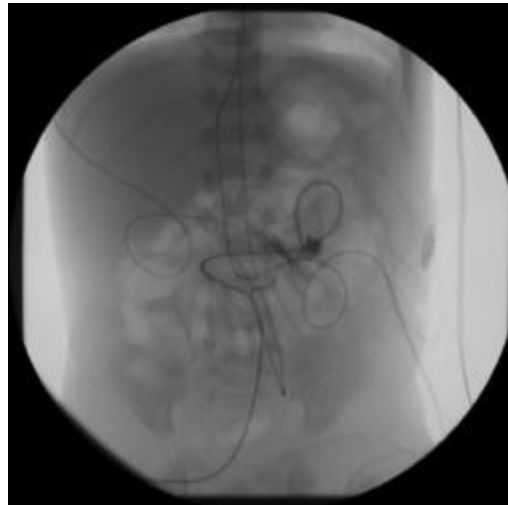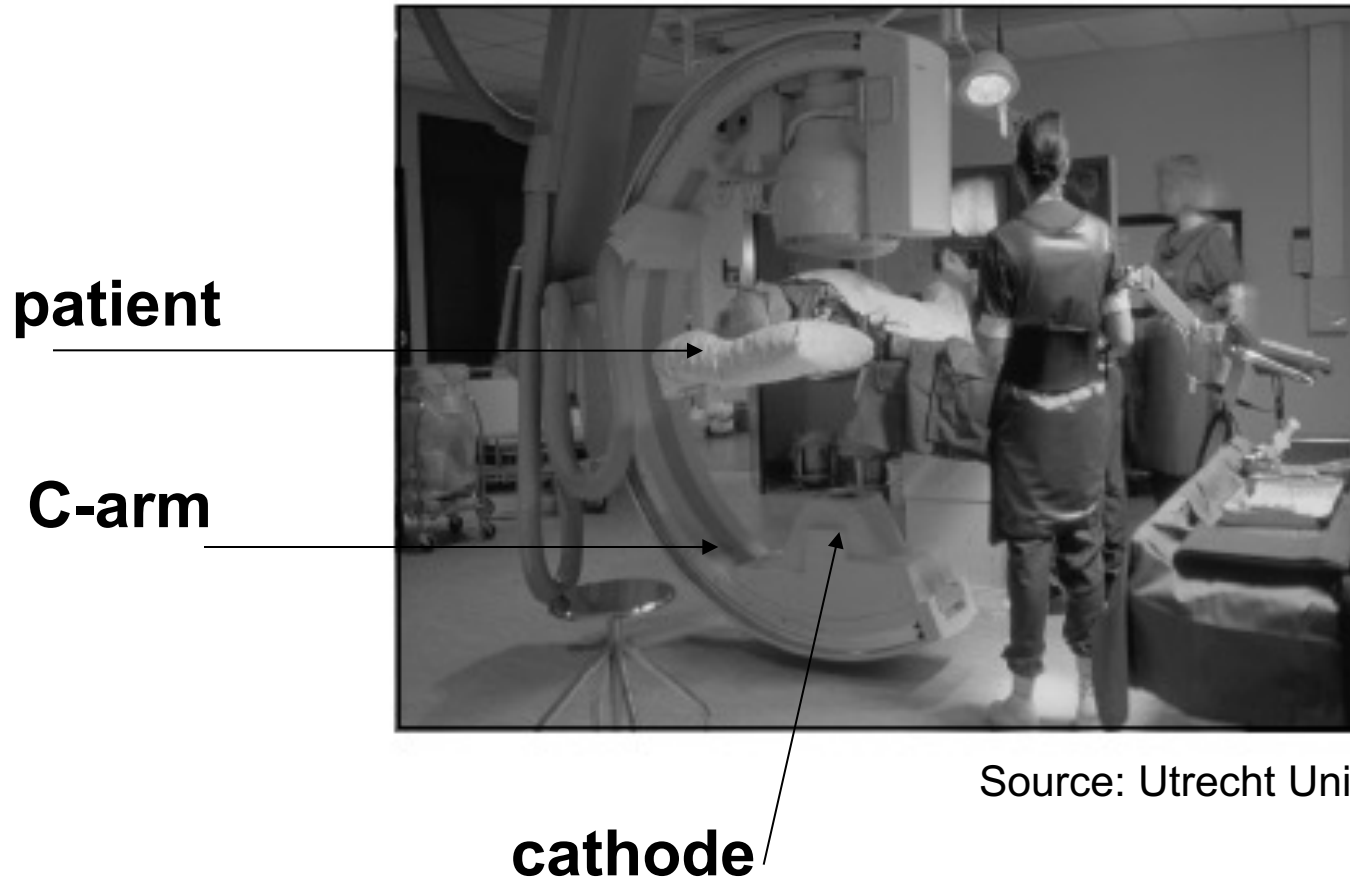
Source: Utrecht University, NL

Computerized Tomography (CT)
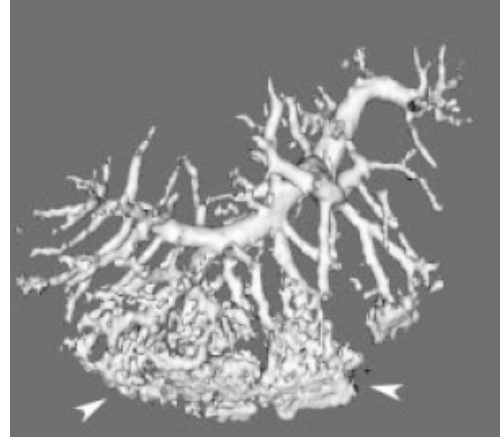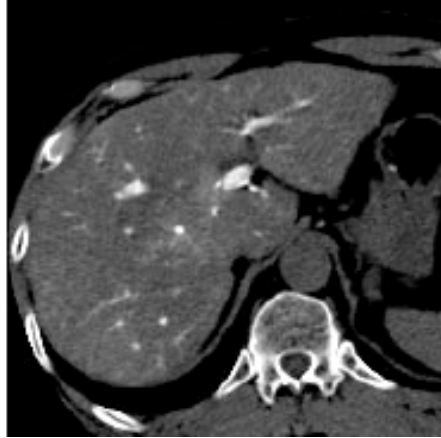
CT

Physics Principles

- Same as X-ray.

CT

Image Formation

- Same as X-ray.

CT

Image Capture

- Generation of a sliced view of body interior ("T")

(cf. tomos = slice in Greek).

- Computational intensive image reconstruction ("C").

Measure = integral attenuation
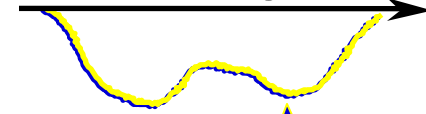
$\mu(x,y)$?
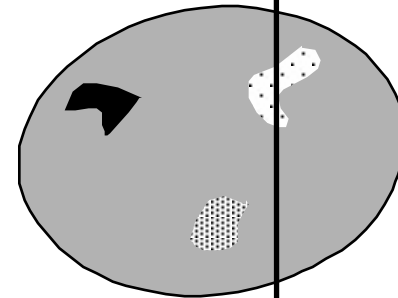
Patient's body

X-ray source

CT

Image Capture

• Translation and rotation of integral measure of absorption.

• Reconstruction: see next lecture
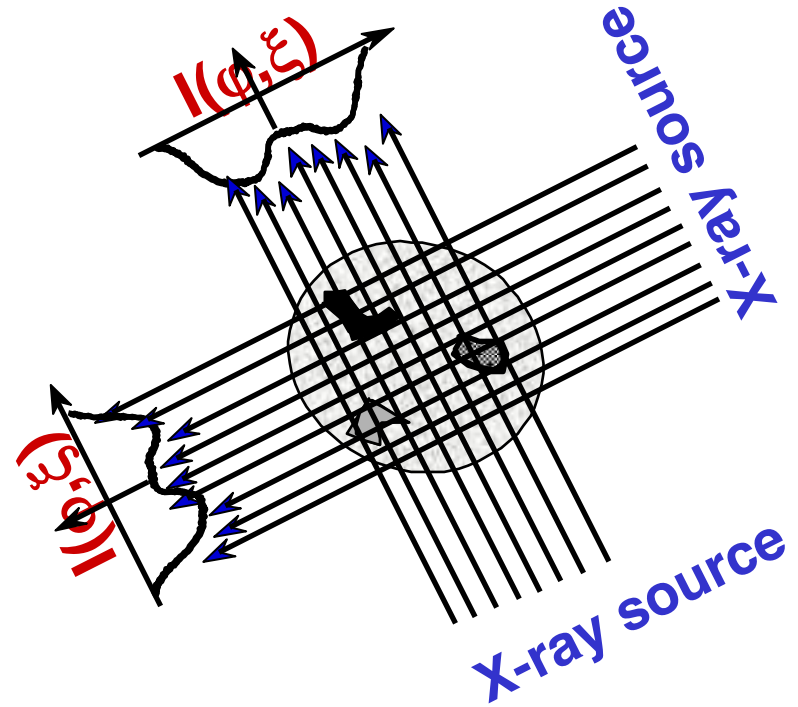
CT

Image Capture: Hounsfield Units

- Relates the linear attenuation coefficient of a local region μ to the linear attenuation coefficient of water, μ_W @ 70 keV (=E_{eff}).
- Based on measurements with the original EMI scanner invented by Hounsfield.

$$HU = 1000 \bullet \frac{\mu - \mu_w}{\mu_w}$$
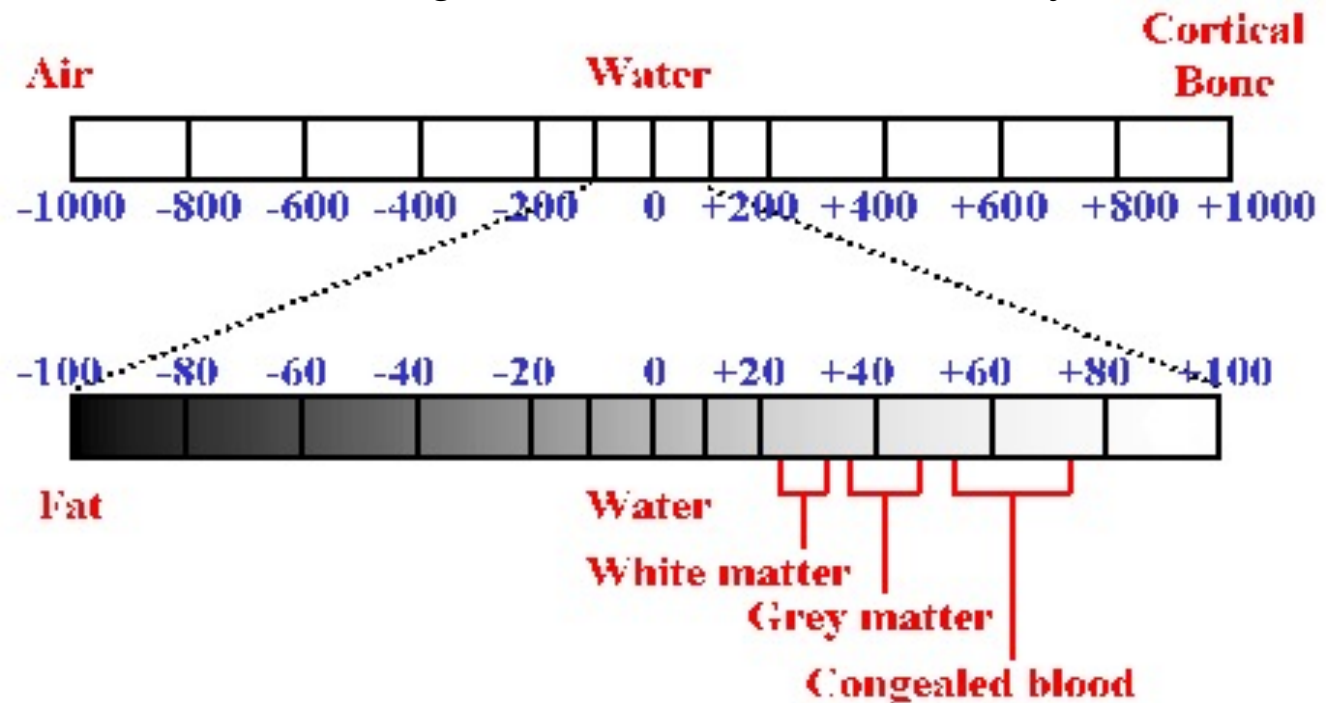
• Assign calibrated values to gray scale of CT images -> allows for thresholding!

CT

System Design

- **1st generation**: Original resolution: 80×80 pixels (ea. 3×3 mm^2), 13mm slice thickness, 5min scan time, 20min reconstruction.

- **2nd generation**: reduced number of view angles $\Rightarrow$ scan time ~30 s.

- **3rd generation**: scan time ~seconds (reduced dose, motion artifacts). Reconstruction time ~seconds.
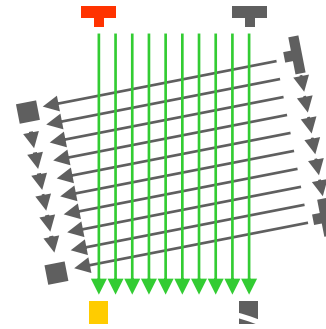
Translation & Rotation
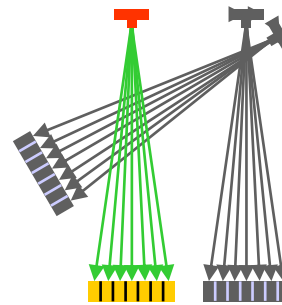
Translation & Rotation
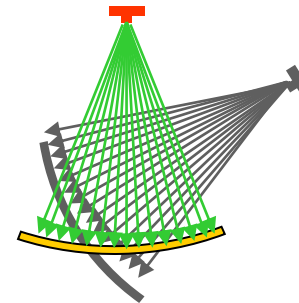
only Rotation

CT

System Design

- **4th generation:** scan time, reconstruction time ~sec.
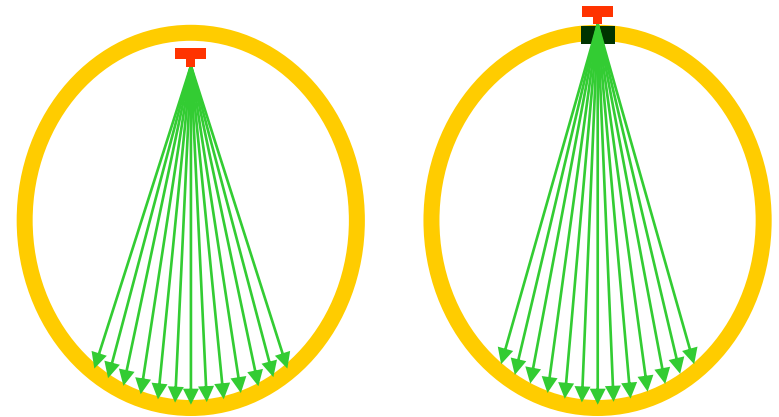
only Rotation of sources

- **Spiral**: Continuous linear motion of patient table during multiple scans. Increased coverage volume per rotation.
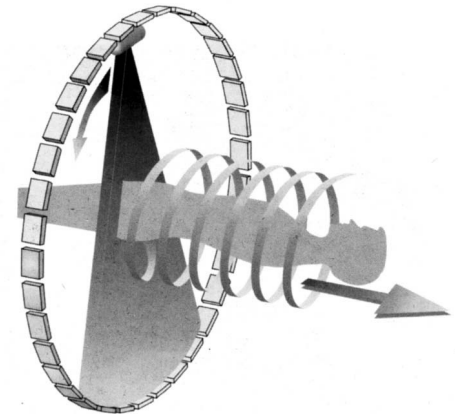
CT
Example: Image quality

1975
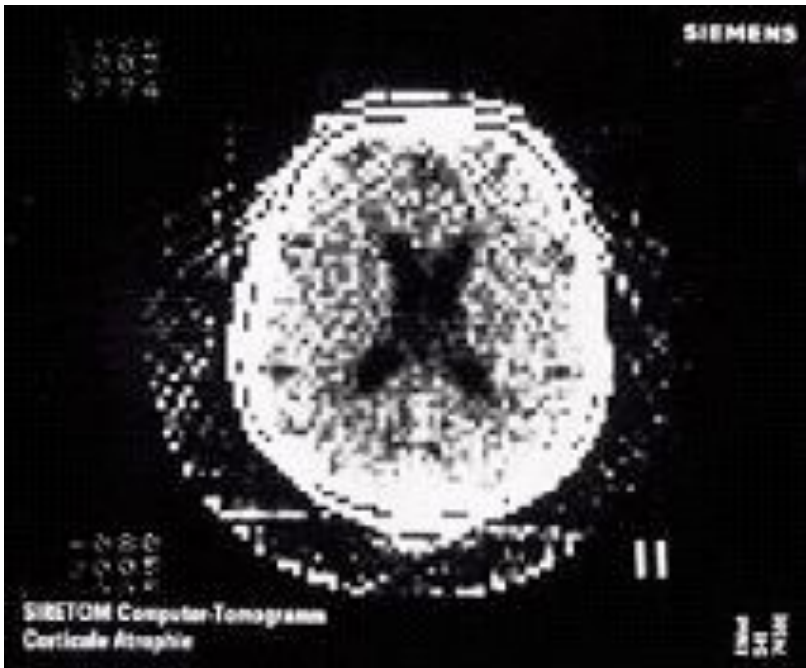
2000

128x128 pixels, 1-4 hours acquisition, 1-5 days computation

512x512pixels, 0.35 sec aquisition, <1sec computation

CT
Example: Lungs
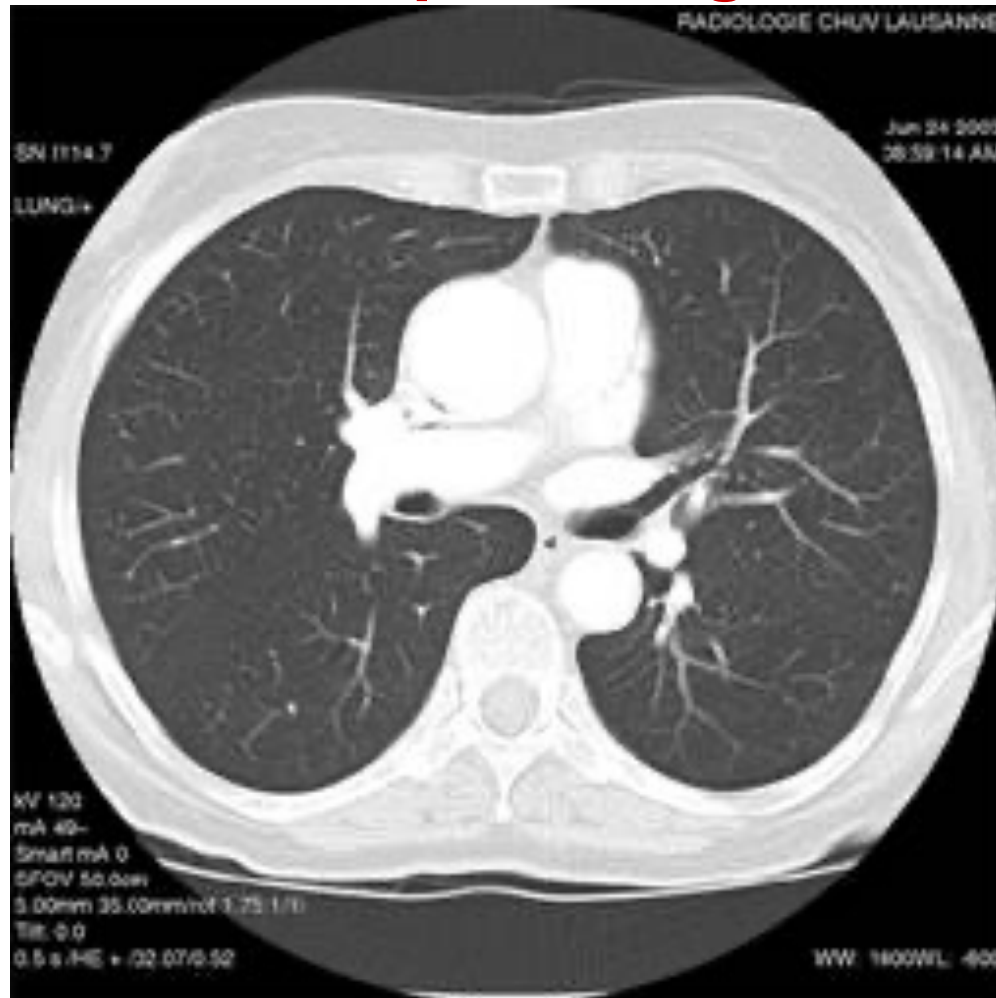
CT

Example: Lungs
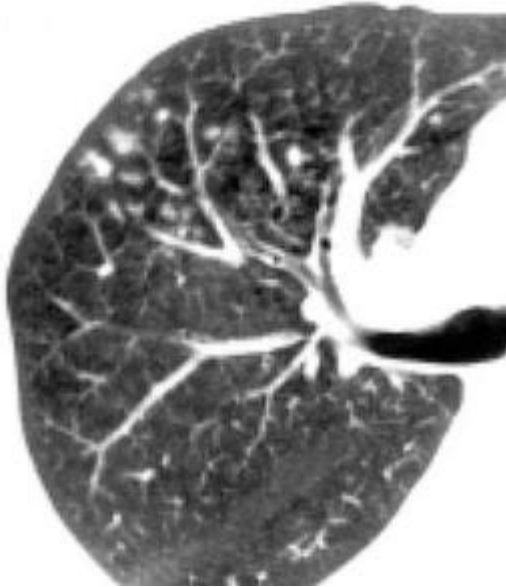
Ex: CT of right lung with active pulmonary tuberculosis: shows centrilobular lesions (nodules or branching linear structures 2-4 mm in diameter) in and around the small airways.

CT
Examples: Abdomen

Diagnosis of appendicitis

CT
Example: Abdomen

Scout CT

TRA CT

Coronal MPR

Source: www.mypacs.net

Virtual endoscopy

CT
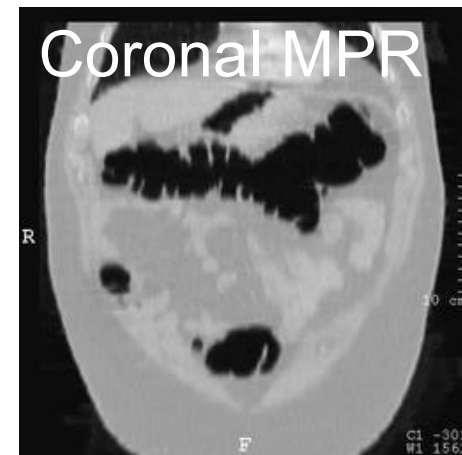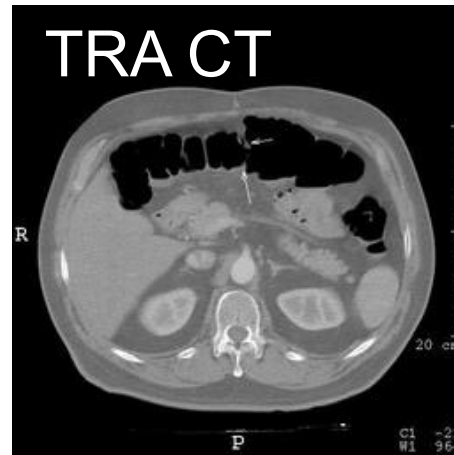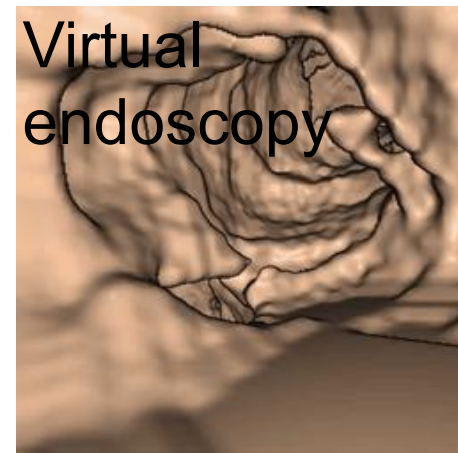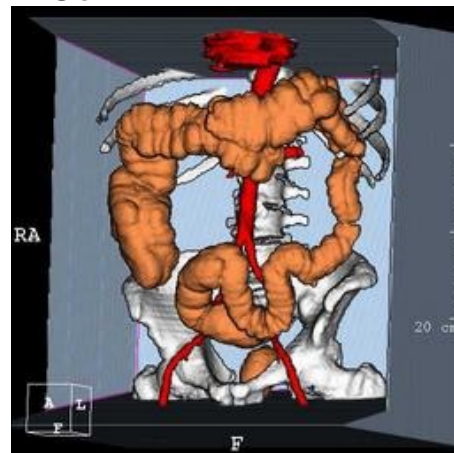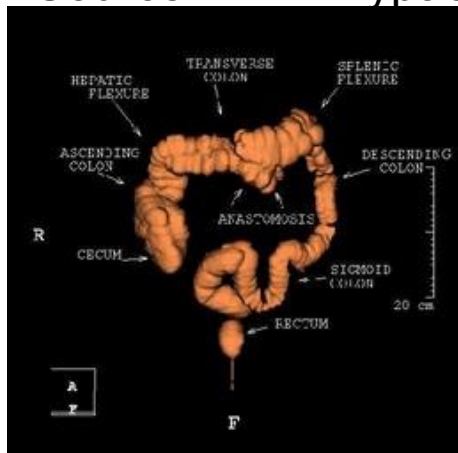
Example: Blood vessels

CT
Example: Blood Vessels

CT

Vitrea©
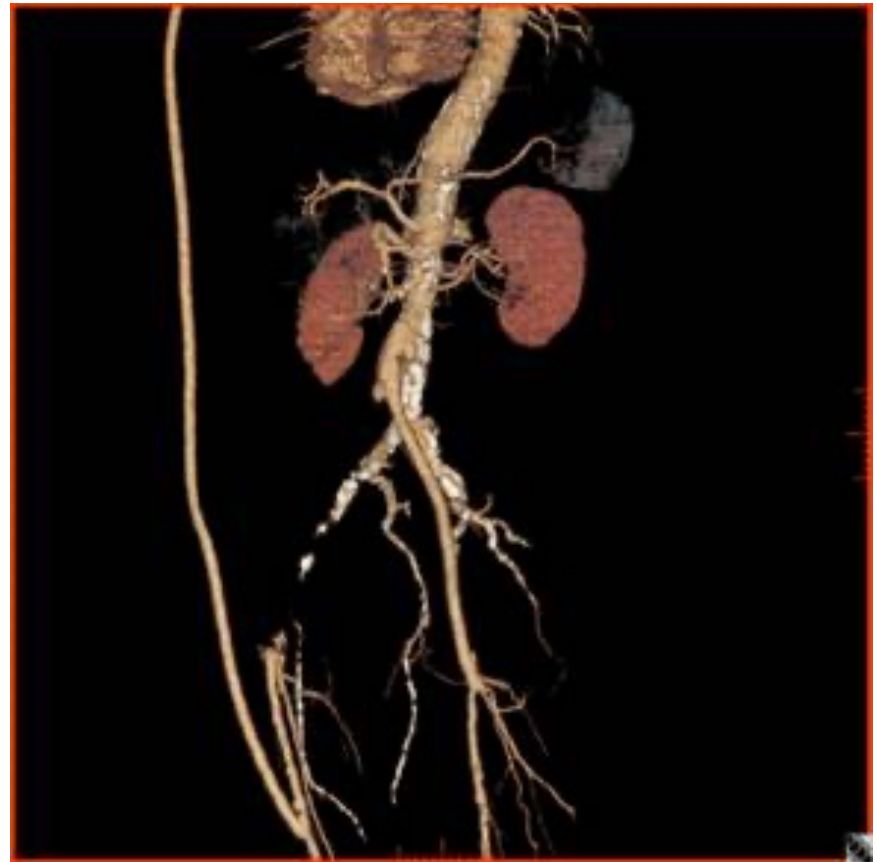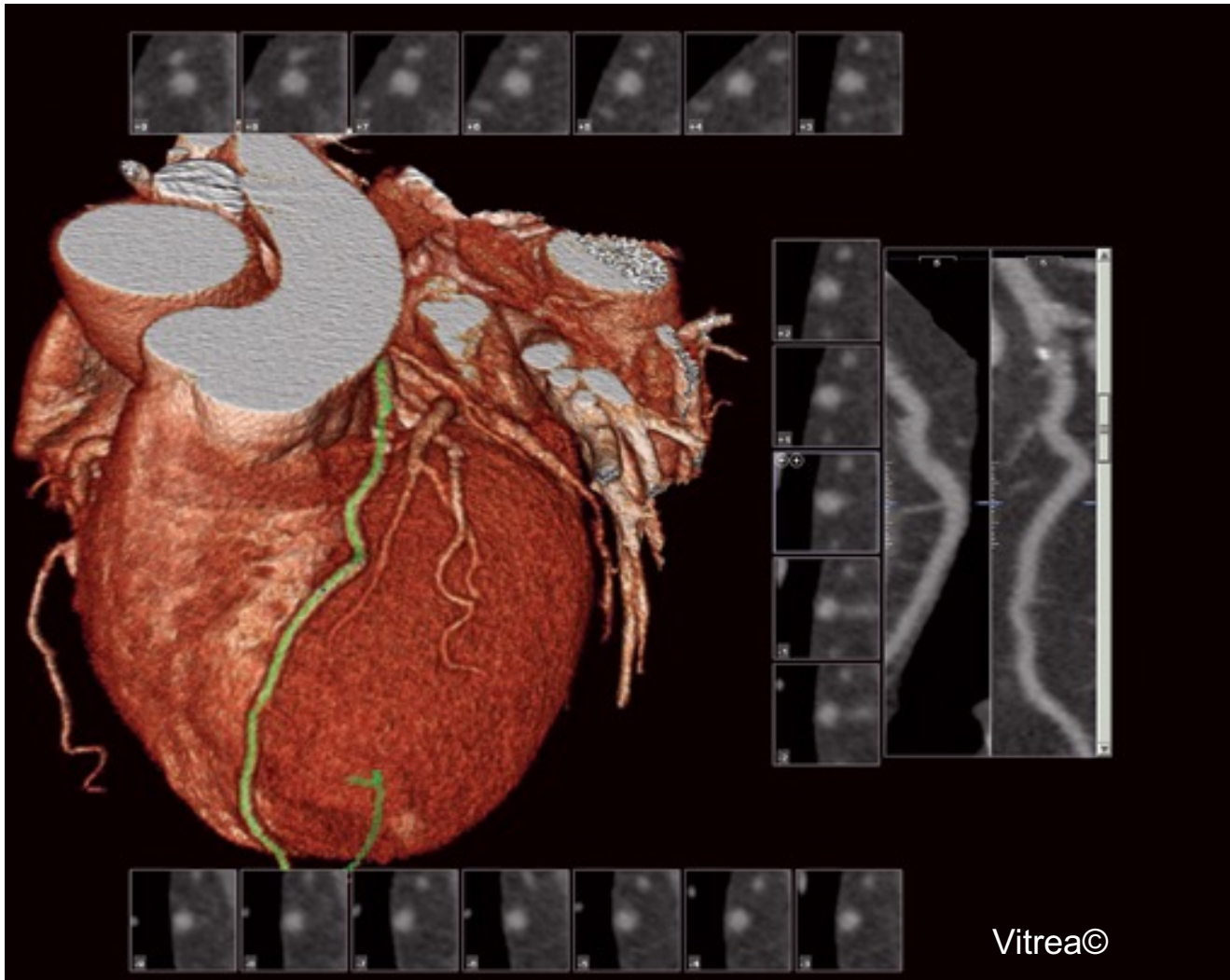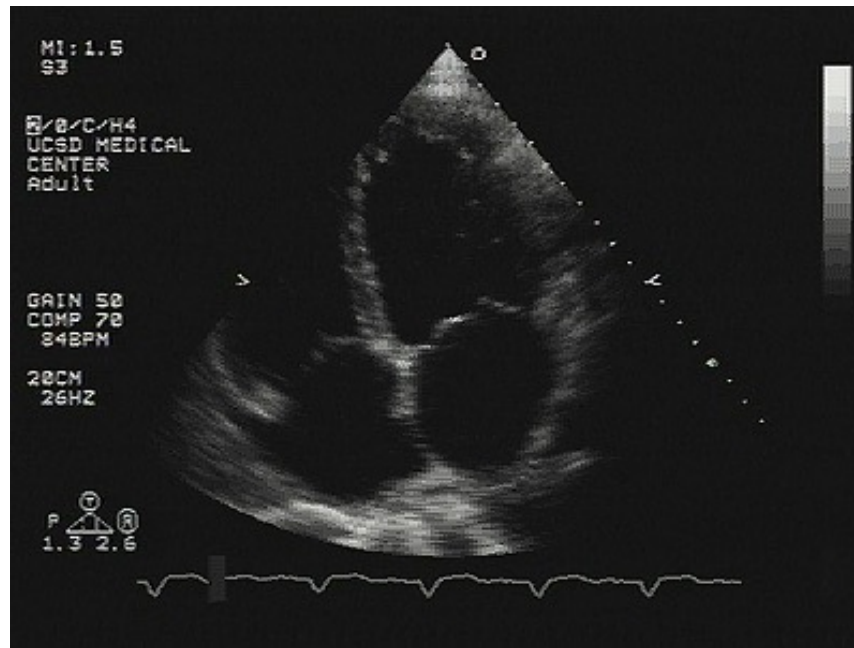
Ultrasound

Ultrasound

Physics Principle

- Traveling pressure waves through a medium.

Ultrasound

Physics Principle

20 Hz   20 kHz   1 MHz   20 MHz

infra-sound   audible sound   ULTRASOUND

Diagnostic Ultrasound

10^1 10^2 10^3 10^4 10^5 10^6 10^7

$f_{light} \sim 10^{15}$ Frequency f (Hz)

$f_{xray} \sim 10^{18}$
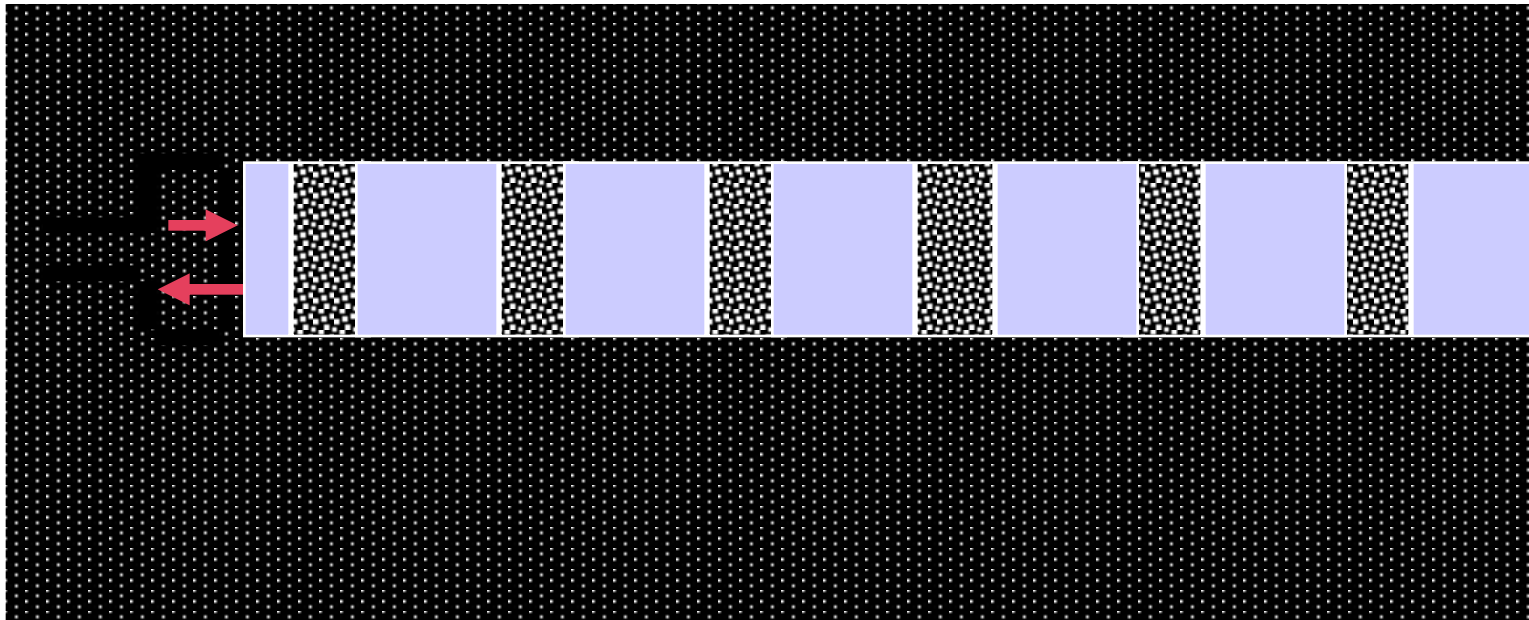
Ultrasound

Image Formation

- Sound waves propagate through the body.

- At each interface, part is reflected, part is transmitted.

- Reflected waves are recorded back.
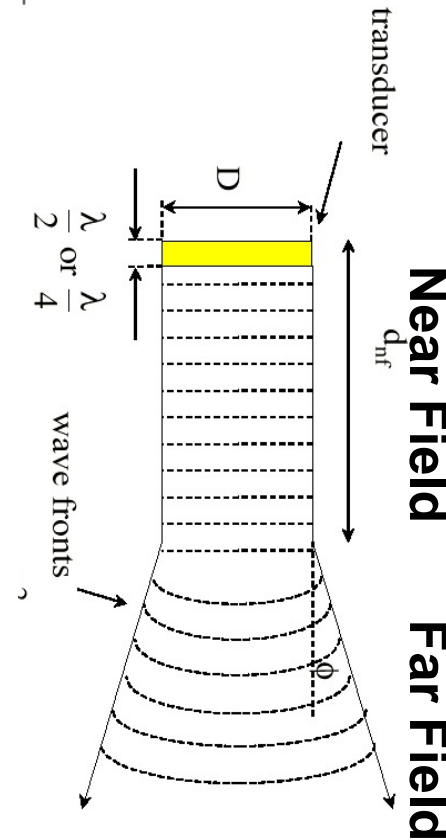
Ultrasound

Image Formation

Ultrasound Pulse

transducer

Echo

Echo

TISSUE

D

$D = c \ \text{Time}/2$

$c = 1.54 \ \text{mm}/\mu s$
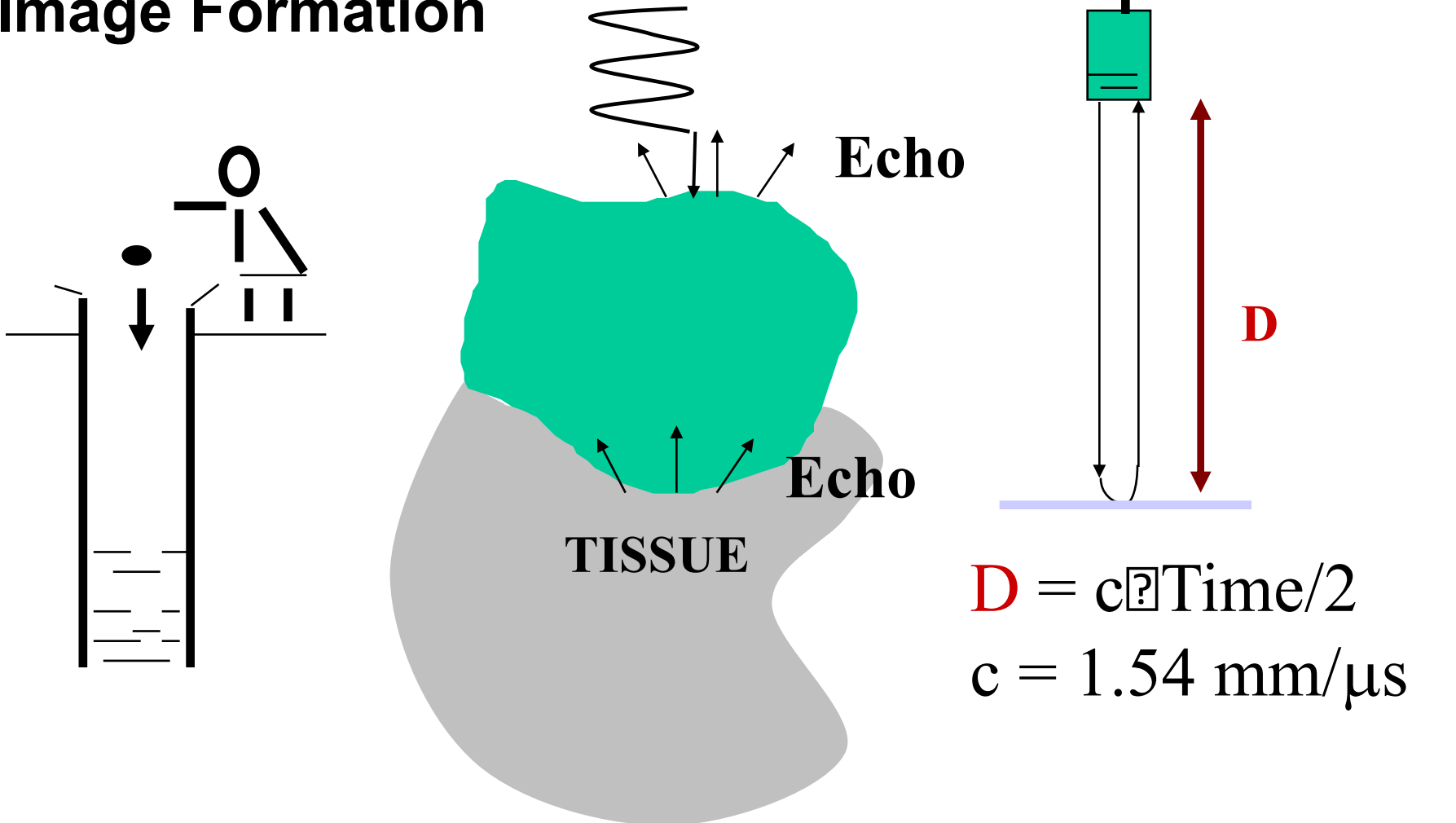
Ultrasound

Image Capture

- **Recorded signals**:
  - Specular reflection, Diffuse scattering, Rayleigh scattering

- **Frame rate (FR)** =number of times per second a sweep of the ultrasound beam is performed.
  - The higher the frame rate, the better the temporal resolution.
  - Limited by:
    - Time delay from maximum depth.
    - Speed of sound.
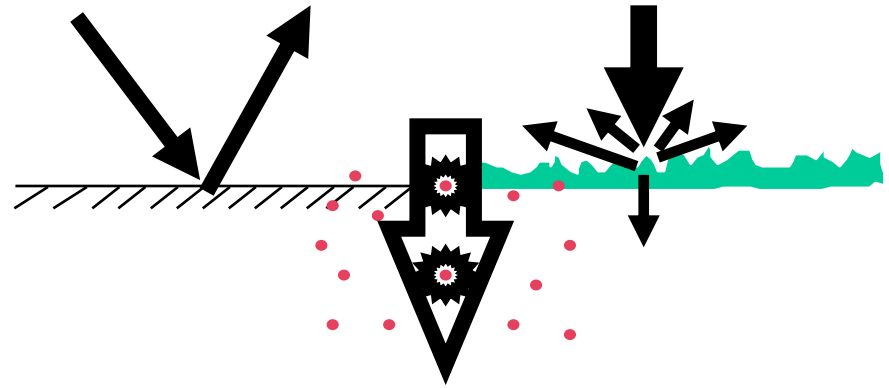
Ultrasound

System Design

Acoustic Insulator

Piezoelectric Element

Transducer

Electric Connector

Backing Material
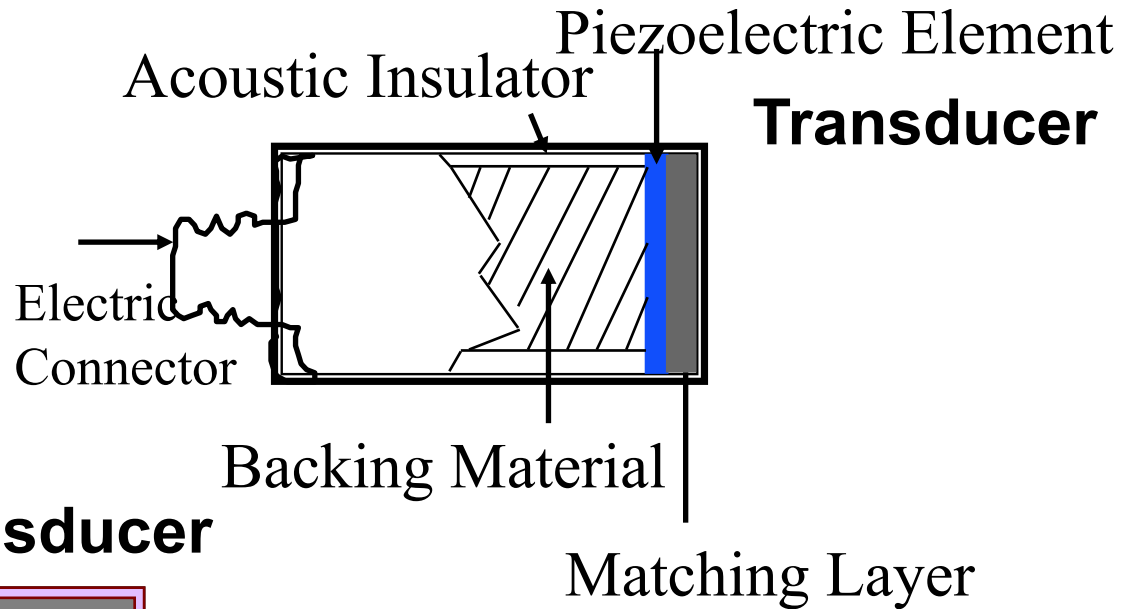
Matching Layer

Phased array transducer
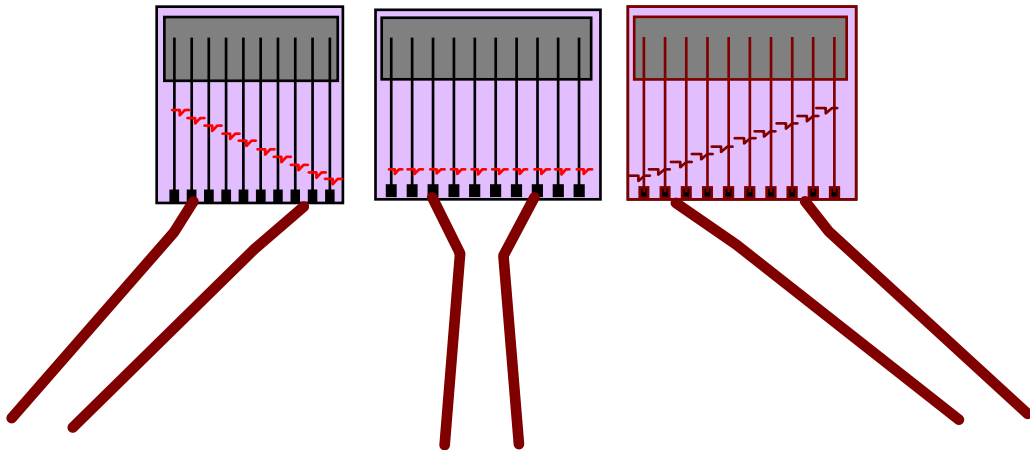
Display
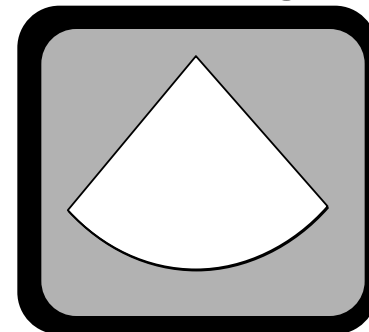
Ultrasound

- **Advantages:**
  - Portable.
  - Inexpensive.
  - Good spatial resolution (<1mm).
  - High temporal resolution.
- **Disadvantages:**
  - Poor image quality.
  - High level of noise.

Ultrasound

Applications

- Obstetric
- Heart
- Gastro-intestinal track (liver, gall bladder, pancreas)
- Urinary track (bladder, kidneys)
- Genital organs (prostate, testicles, ovaries, uterus).
- Blood vessels (Doppler).

Ultrasound

Example: Fetus

Fetus at 9 weeks

– Establish number of fetus.

– Check position of placenta.

– Determine fetal age and development.

– Check for congenital defects.

– Check fetus position.

Ultrasound

Example: Obstetric

1961: First image of fetus

1990: First 3D visualization of fetus

Ultrasound

Example: Heart

- Valve diseases.
- Cardiac function (pumping efficiency).
- Blood clots in cardiac chamber.
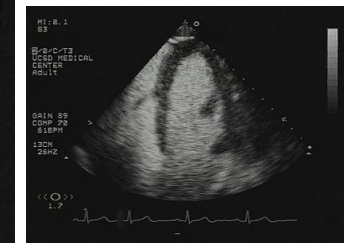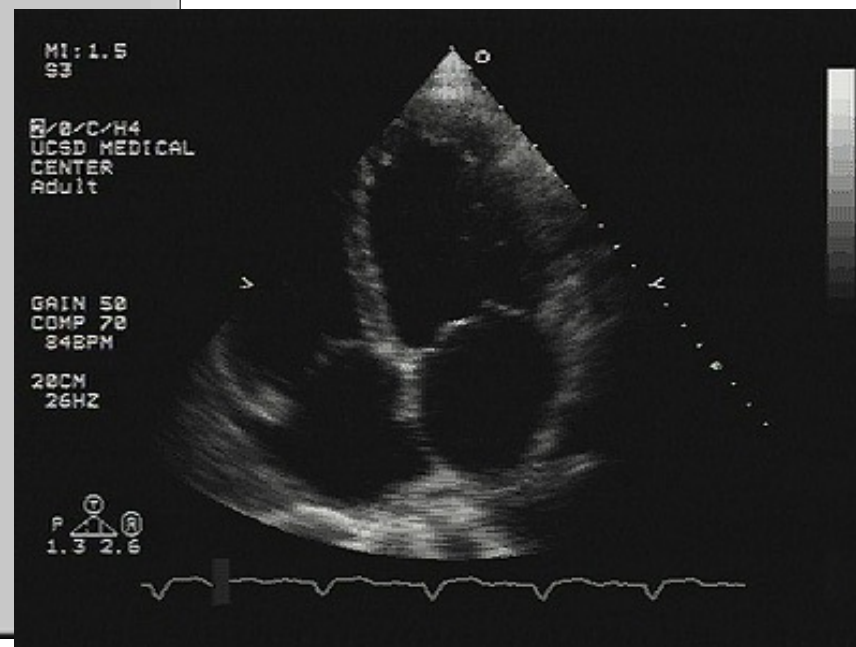
Ultrasound

Example: Heart
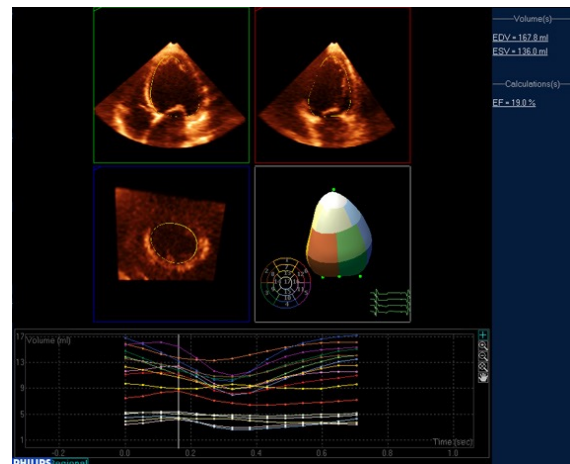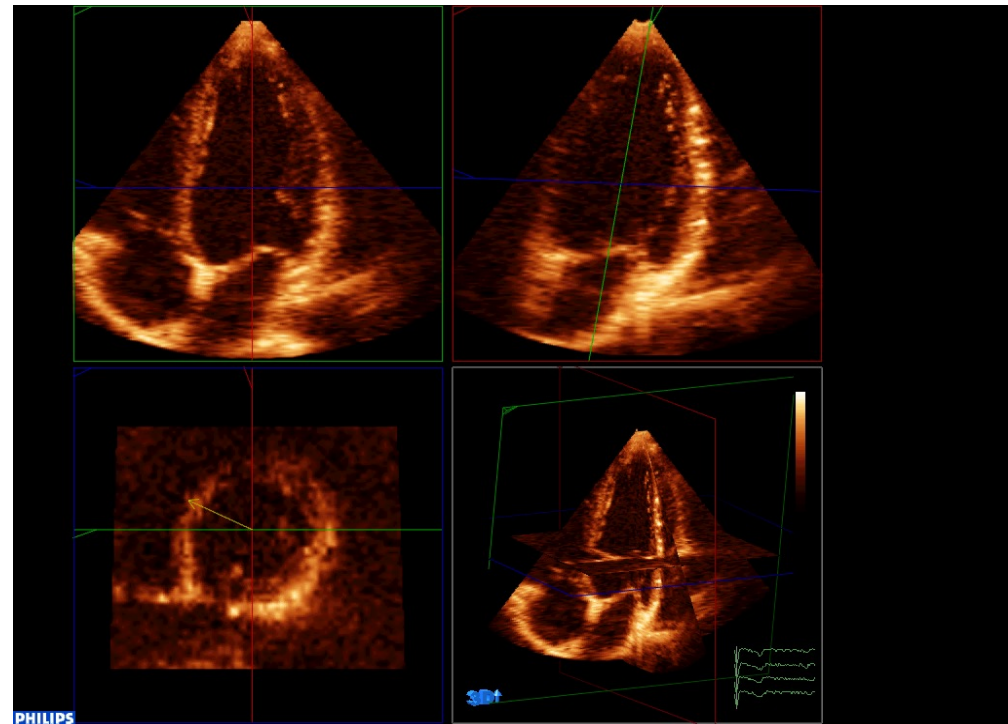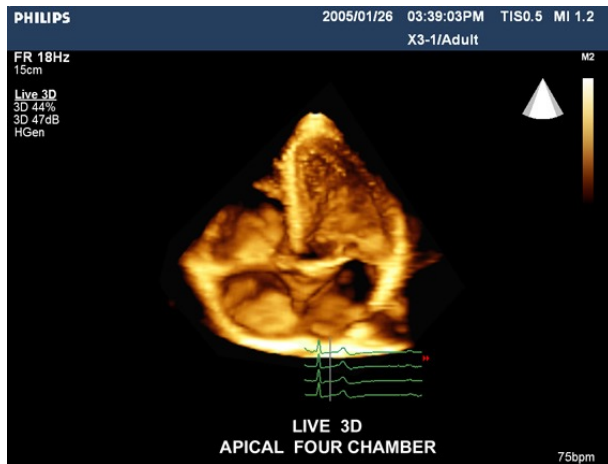
- Real-Time 3D Ultrasound

Ultrasound

- Biopsy guidance.   **Examples: Abdomen**

- Diagnosis of abdominal pains, kidney stones, inflamed appendicitis.

kidney

liver
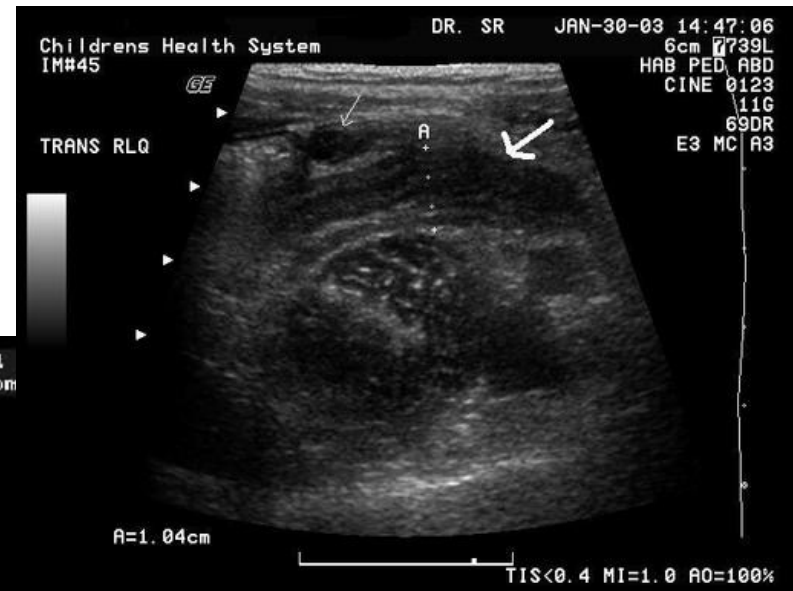
appendicitis

Ultrasound

Example: Blood vessels

- Artery blockage from blood clots.
- Arteriosclerosis (plaques).
- Stent position

CAROTID BIFURCATION

COMMON CAROTID PLAQUE
SonoCT™ IMAGING WITH XRES™ TECHNOLOGY
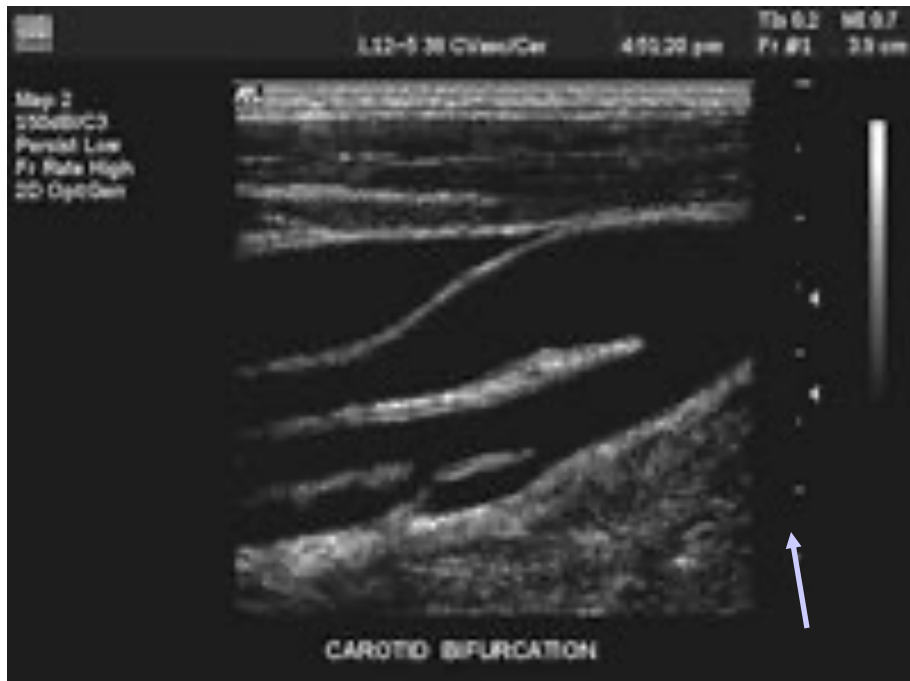
Ultrasound

Example: Blood vessels

- Doppler

Magnetic Resonance Imaging (MRI)

MRI

Physics Principle
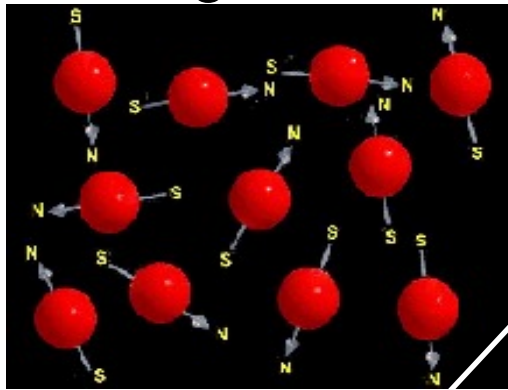
- Nuclei with magnetic dipoles (H).
- Magnetic field $\mathbf{B_0}$ makes nuclei precess along its direction.
- The precession rate is the Larmor frequency.
- $f_L = \gamma\, \mathbf{B_0}$ (43 1.5 = 64 MHz for Hydrogen into a 1.5T magnet).

No magnetic field

Magnetic field

Source: Hielscher, Columbia Univ.
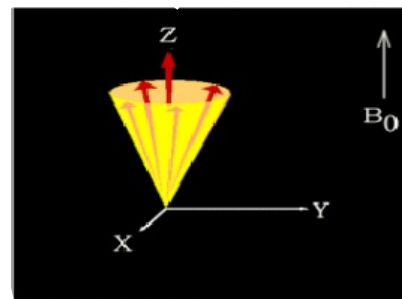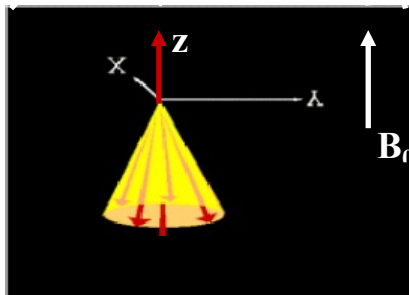
MRI

Image Formation

$$m_z = +1/2$$

$$\Delta E = \gamma B_0$$
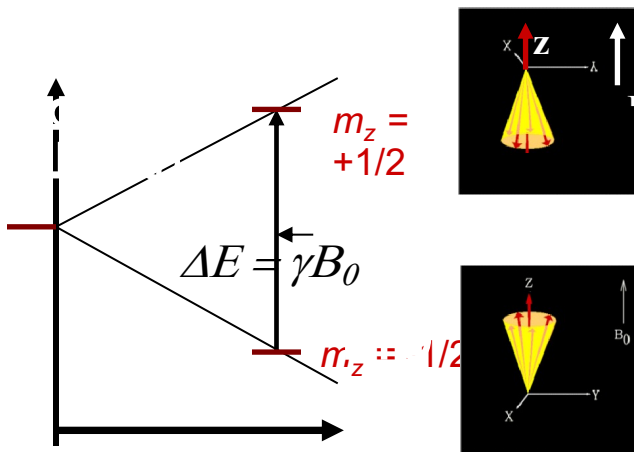
$$m_z = -1/2$$

• For every 1,000,000 nuclei in upper state (mz=+1/2) there are 1,000,001 nuclei in lower state (mz=-1/2).

• This difference is enough to result in macroscopic net magnetization of material.

• Nuclei with magnetic dipole moment μ, and angular momentum **S**.

• Net magnetization **M** = density of μ.

• Tip **M** away from **B$_0$** ⇨ Precession at frequency γB_0, producing a measurable RF magnetic field.

B$_0$

Z

J or μ or **M**

Y

|B$_0$| γ t

X
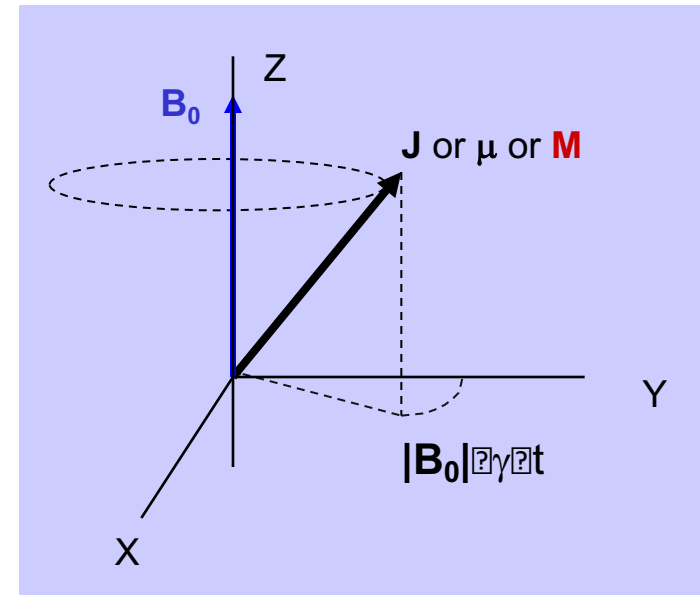
MRI

Image Capture

- As the magnetization precesses it creates its own RF magnetic field.
- This field is much smaller than the exciting RF field.
- It can be detected with a standard radio receiver (e.g. RF coils used to tip M away from B_0)
- The resulting signal from precession is called the Free Induction Decay or FID.
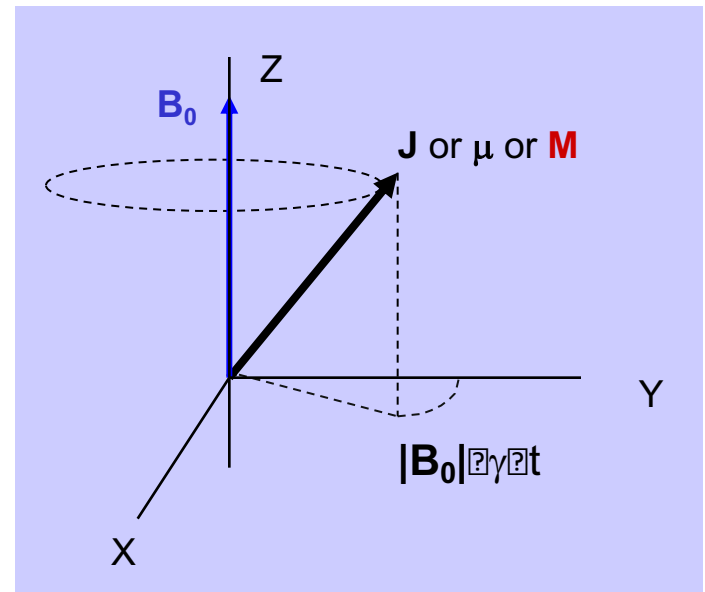
MRI

System Design

- ## Main Magnet

  – High, constant, Uniform Field, B_0.

- ## Gradient Coils

  – Produce pulsed, linear gradients in this field: G_x, G_y, & G_z

  – <u>spatial localization</u>

- ## RF coils

  – Transmitter: B_1 Excites NMR signal to generate Free Induction Decay (FID).

  – Receiver: Senses FID.

Résultante M_0

B_0

f_0
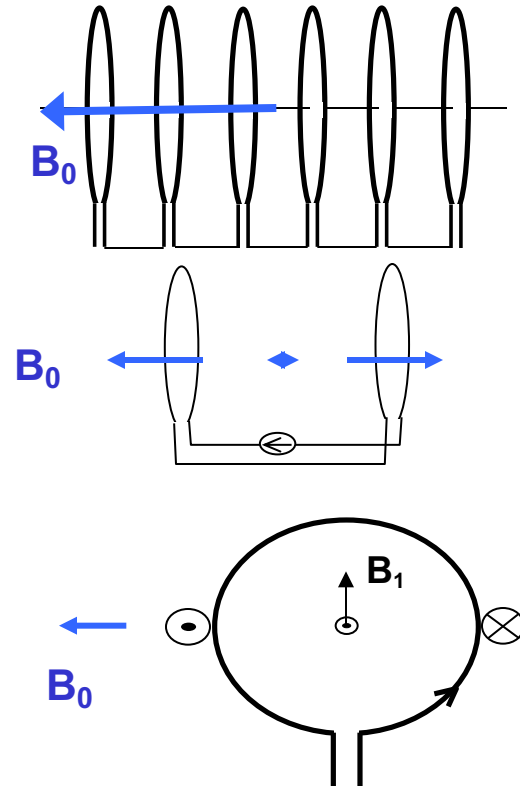
Retour de l'aimantation à son état d'équilibre:

B_0

M_0

Z

Y

X
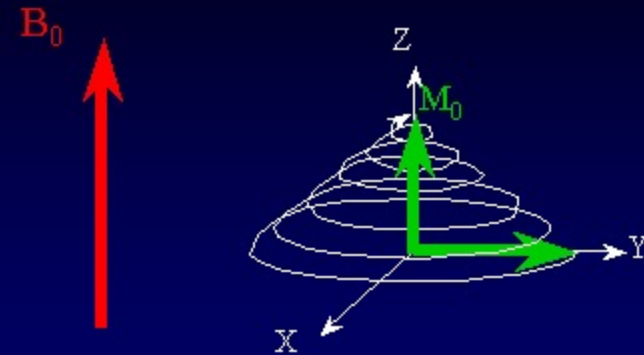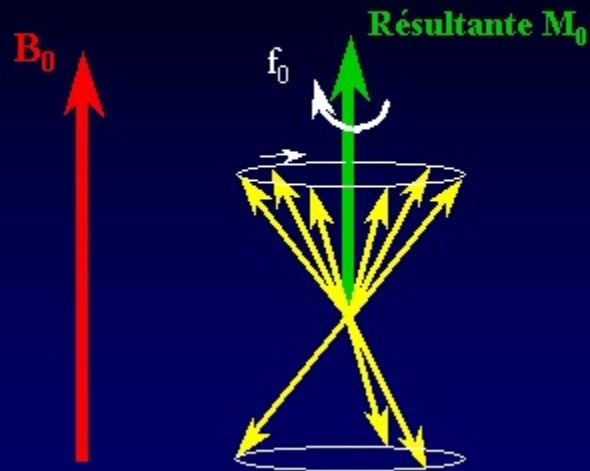
Enregistrement d'un courant dans la bobine de réception:

B_0

Z

f_0

M_{XY}

Y

X
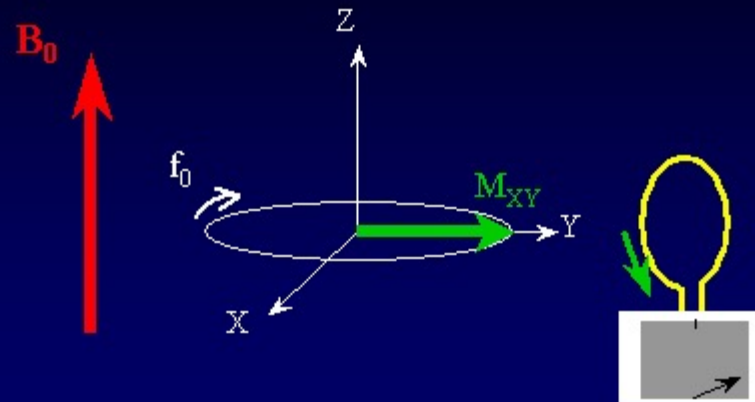
MRI

System Design
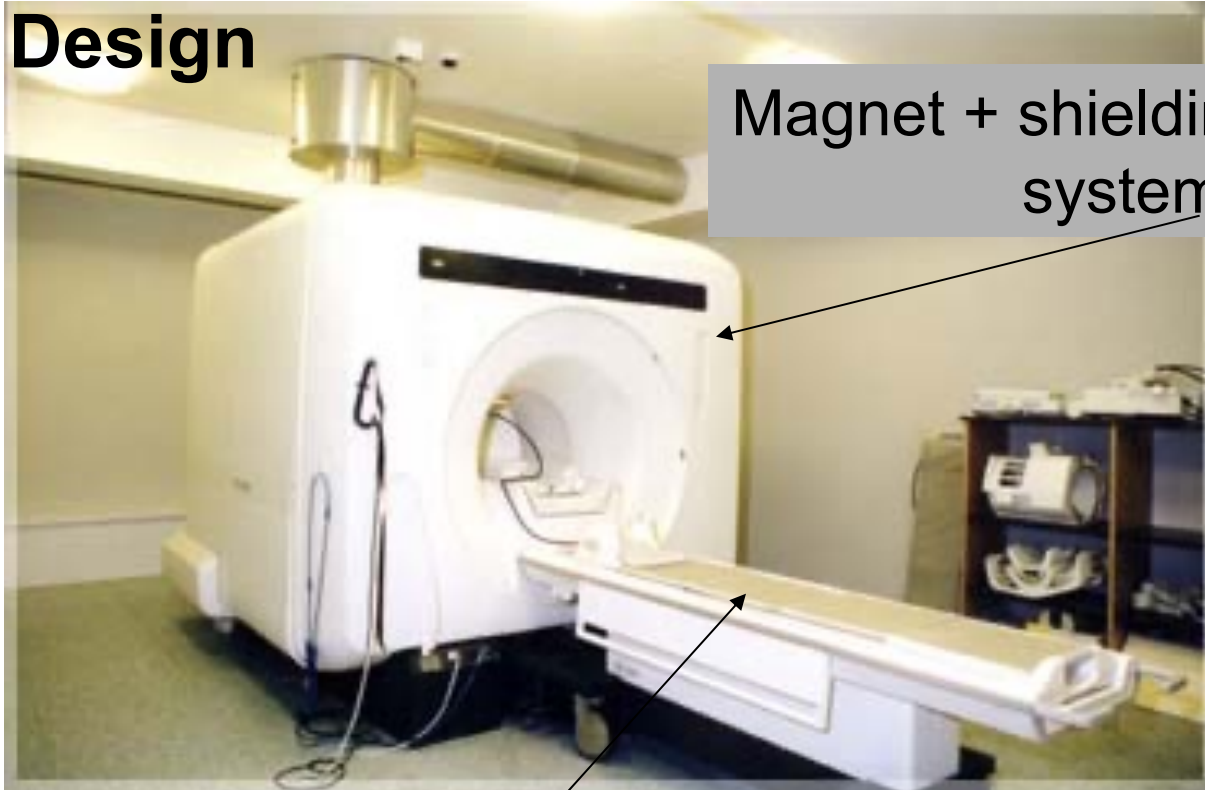
Magnet + shielding + cooling systems

gantry

MRI

- **Advantages:**
  - High image quality.
  - Good spatial resolution (~1mm).
  - Almost all tissues.
  - Can provide information on both anatomy and function.
- **Disadvantages:**
  - Very expensive scanners.
  - Some patients cannot be imaged (pacemaker, claustrophobia).

MRI

Applications

- Brain (Multiple sclerosis, Alzheimer's disease, epilepsy, tumors)
- Spine
- Muscles, tendons.
- Blood vessels: angiography (strokes, aneurism)
- Heart
- Soft tissues

MRI

Example: Heart

- CINE MRI
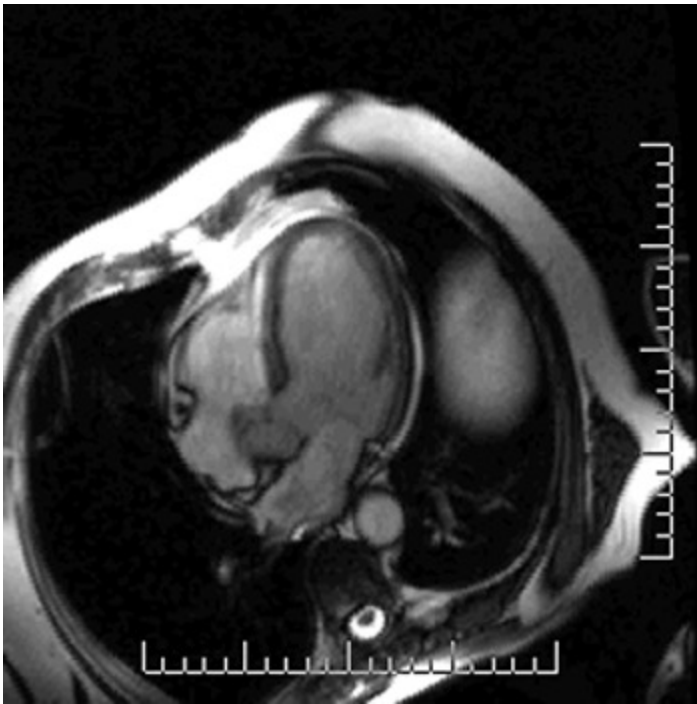
Courtesy of Robert R. Edelman
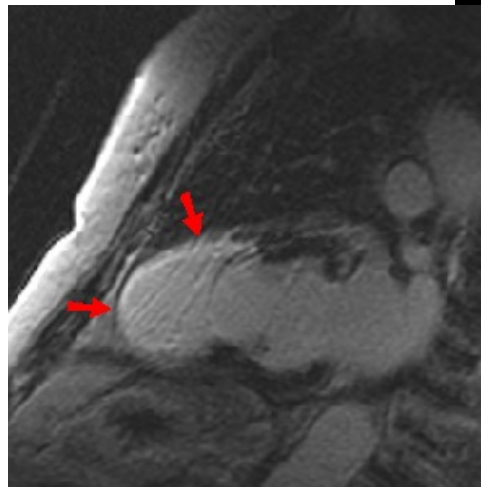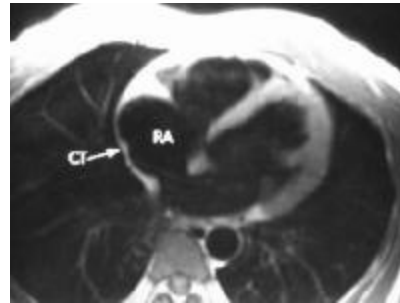
MRI

Example: Heart
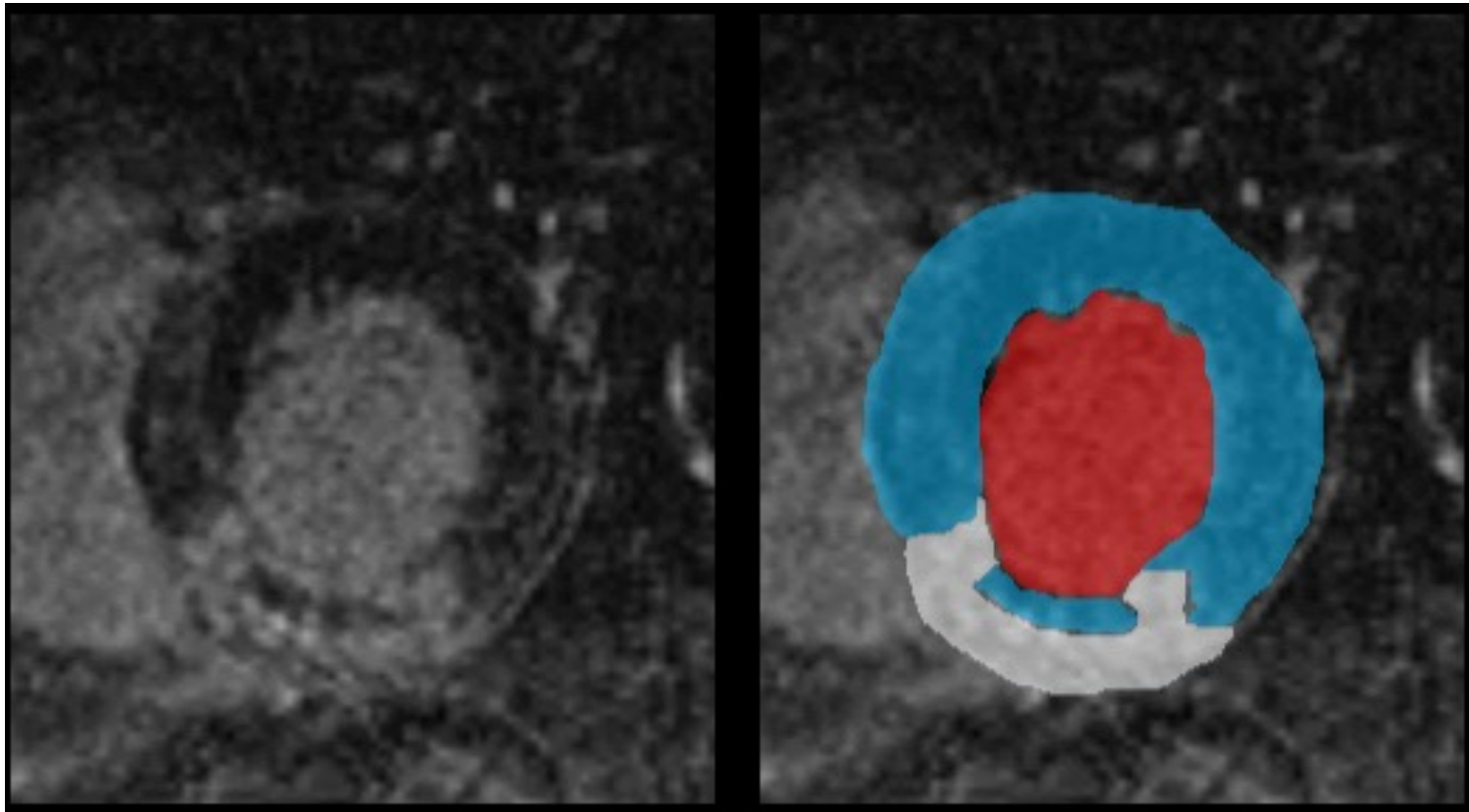
MRI for myocardial perfusion

MRI

Example: Blood vessels
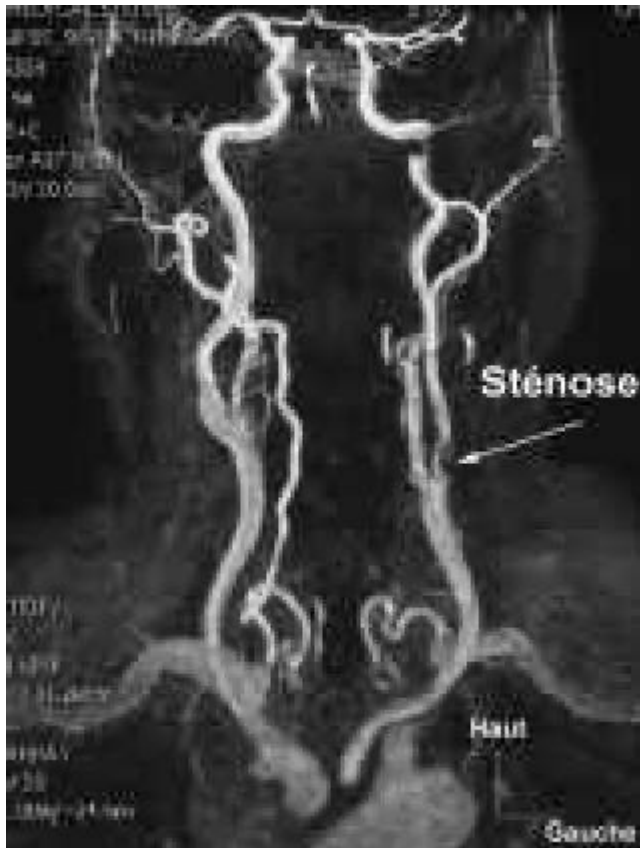
Magnetic Resonance Angiography
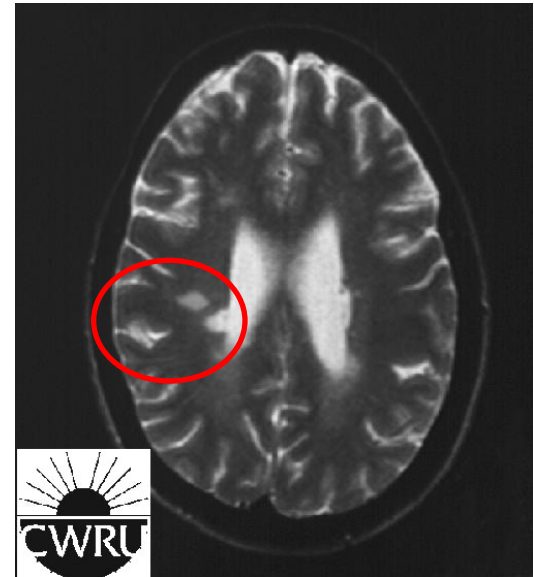
MRI

Example: Blood vessels

Aorta

MRI
Example: Brain

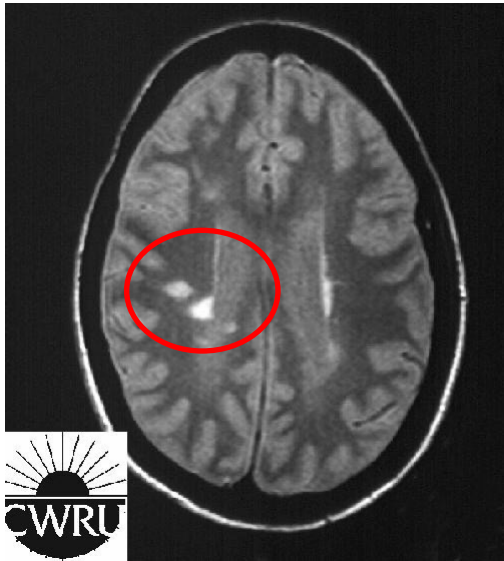SAGITTAL   AXIAL   CORONAL

CEA SHFJ ORSAY / TELECOM PARIS
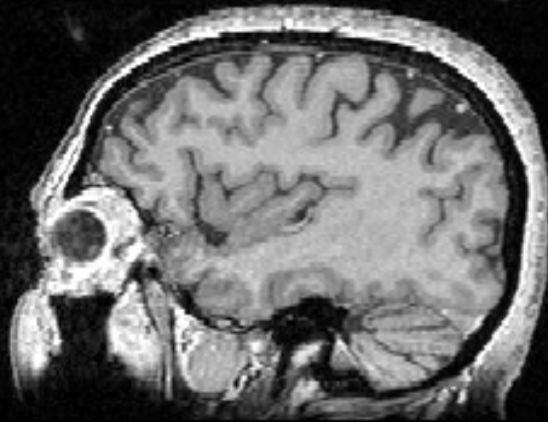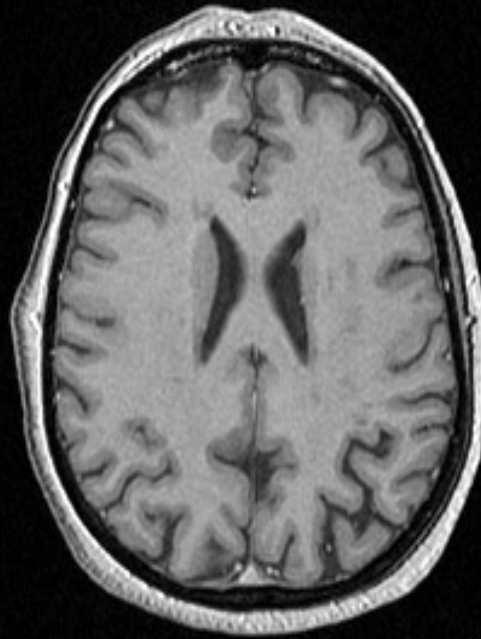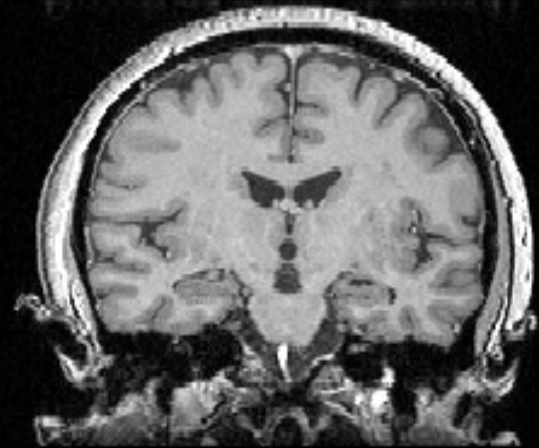
MRI

Example: Brain

- Diagnosis of Alzheimer's and Parkinson's disease.
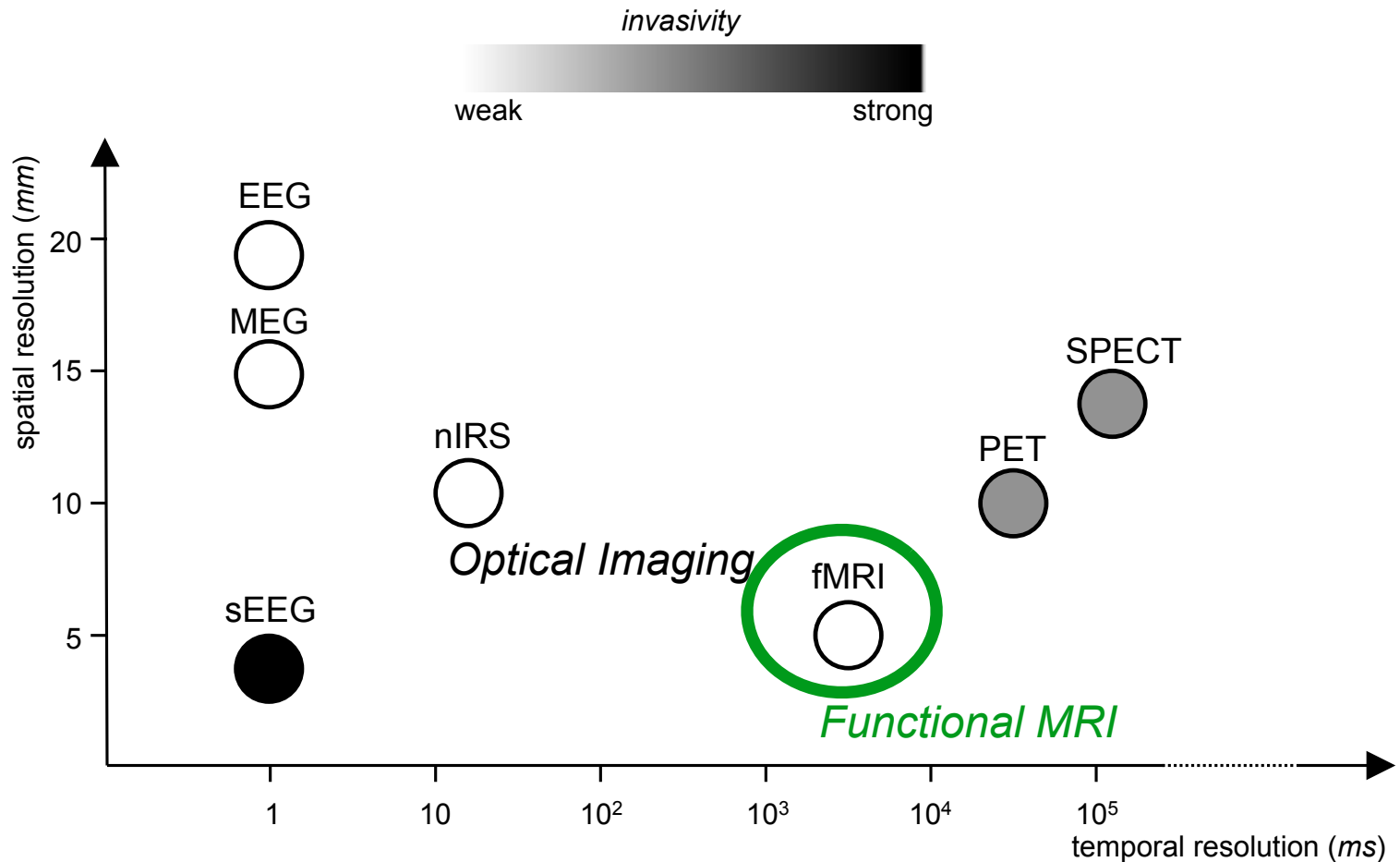
MRI
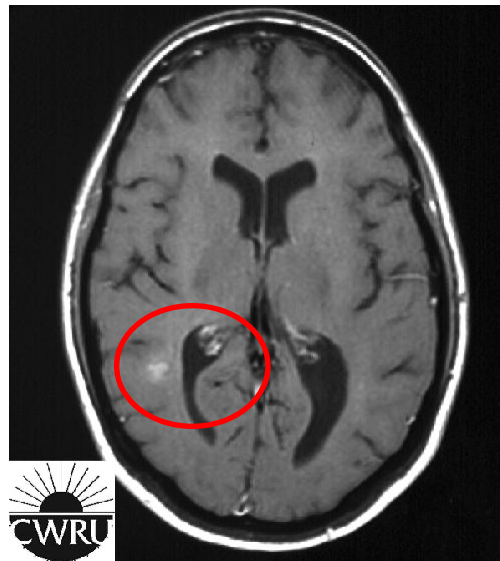
Example: Blood vessels

MR Angiography
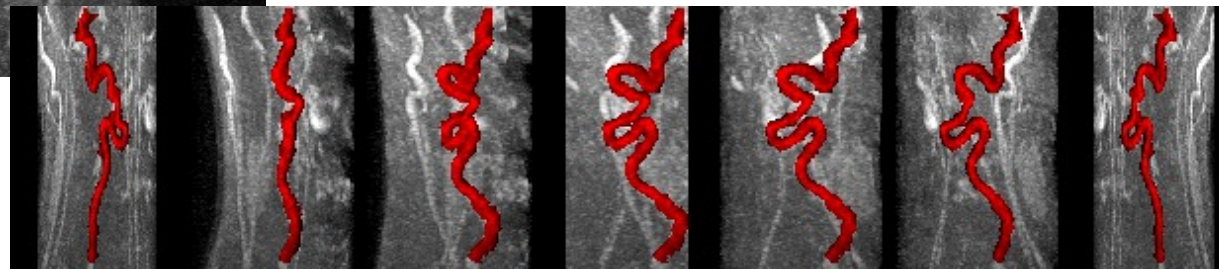
fMRI

Functional neuroimaging modalities

neuro

capillar

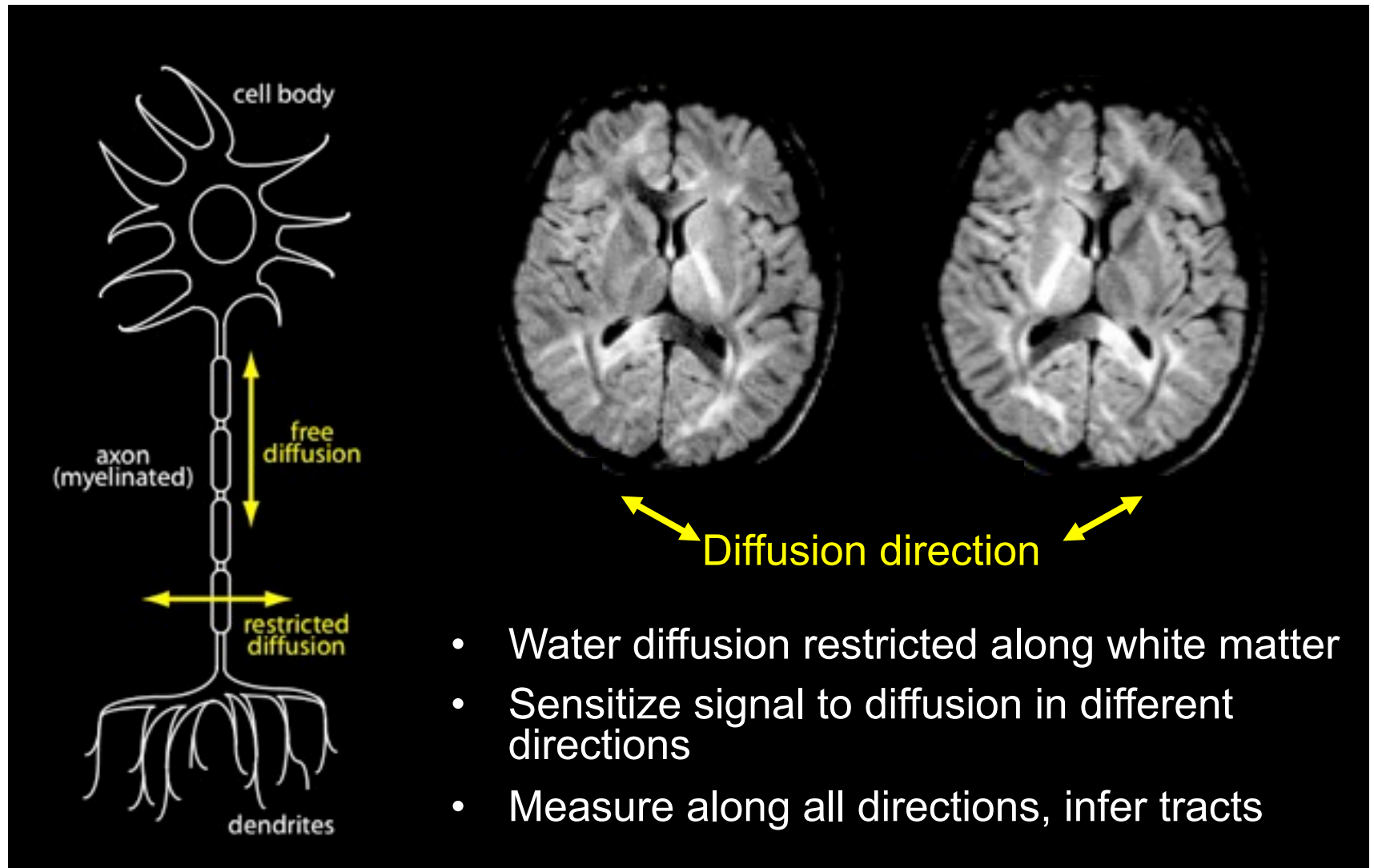HbO$_2$ HbO$_2$ dHb HbO$_2$ HbO$_2$ HbO$_2$ HbO$_2$
dHb HbO$_2$ HbO$_2$ HbO$_2$ dHb dHb dHb
HbO$_2$ dHb dHb HbO$_2$ HbO$_2$ HbO$_2$ HbO$_2$
HbO$_2$ HbO$_2$ HbO$_2$ HbO$_2$ dHb HbO$_2$ dHb HbO$_2$
HbO$_2$ HbO$_2$
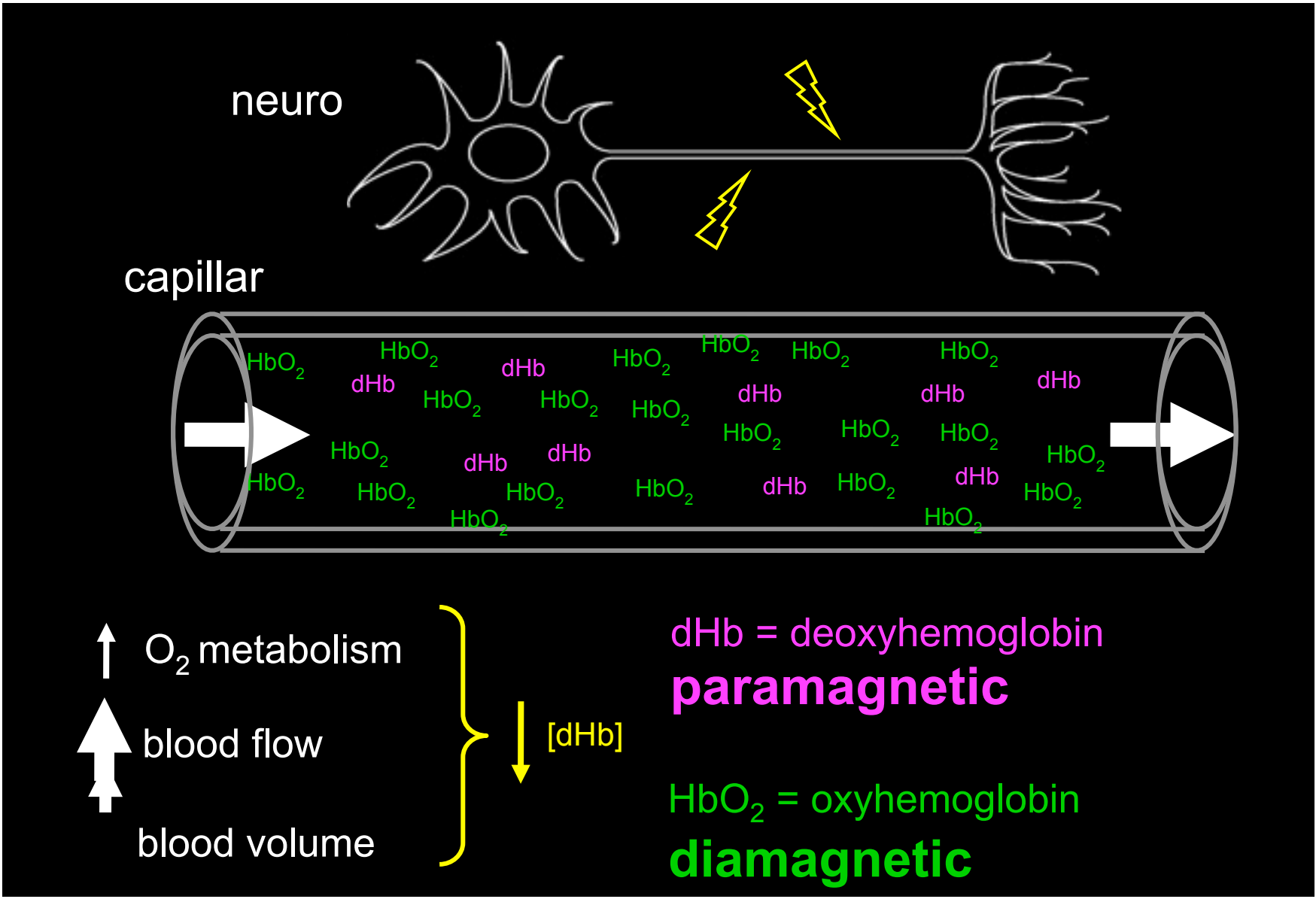
↑ O$_2$ metabolism

↑ blood flow

blood volume

↓ [dHb]
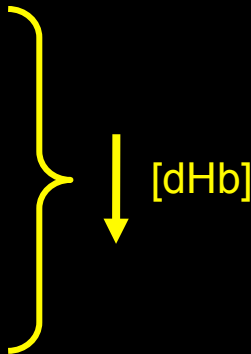
dHb = deoxyhemoglobin
paramagnetic

HbO$_2$ = oxyhemoglobin
diamagnetic

Diffusion MRI

Diffusion direction

- Water diffusion restricted along white matter
- Sensitize signal to diffusion in different directions
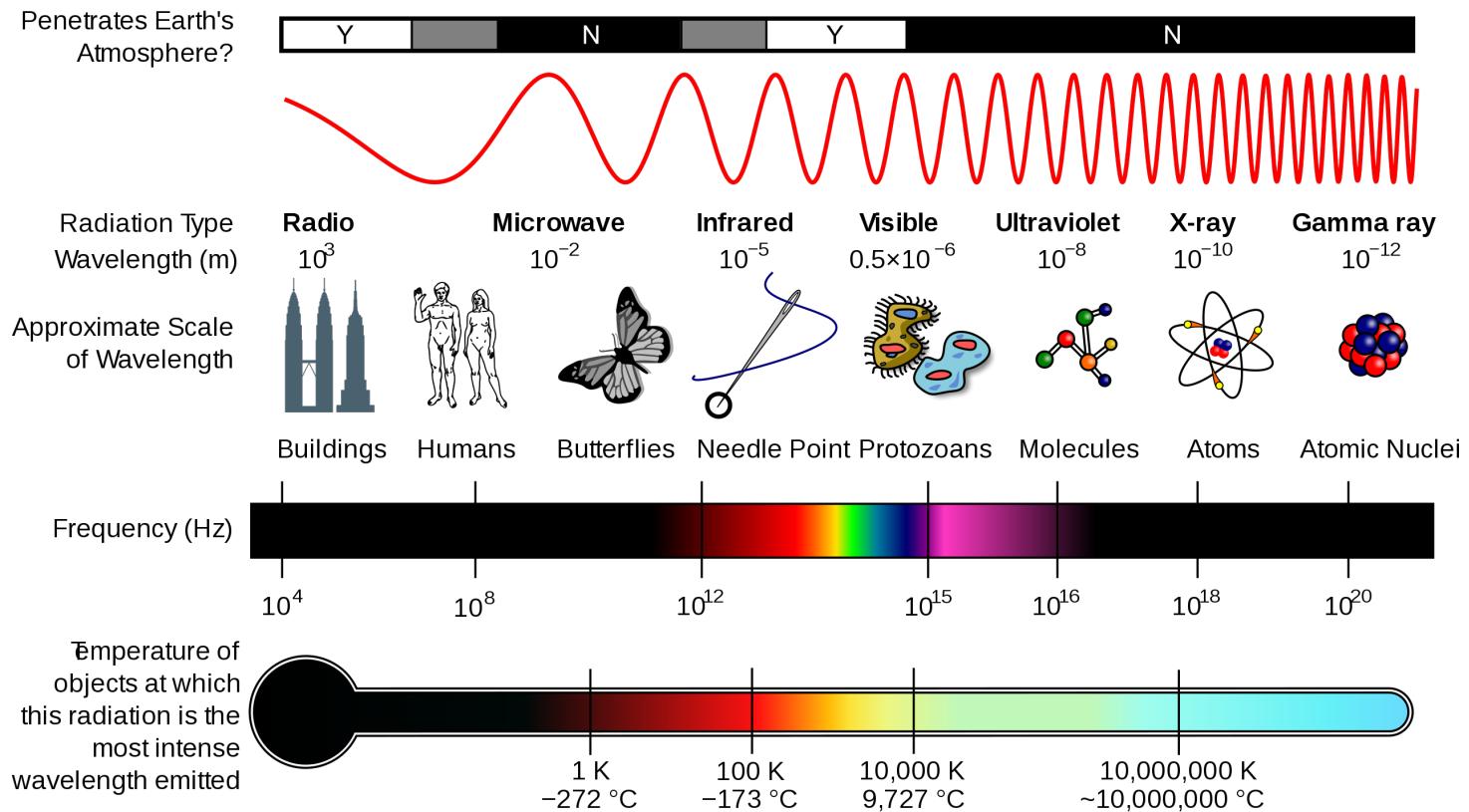- Measure along all directions, infer tracts

Nuclear Imaging (SPECT, TEP)
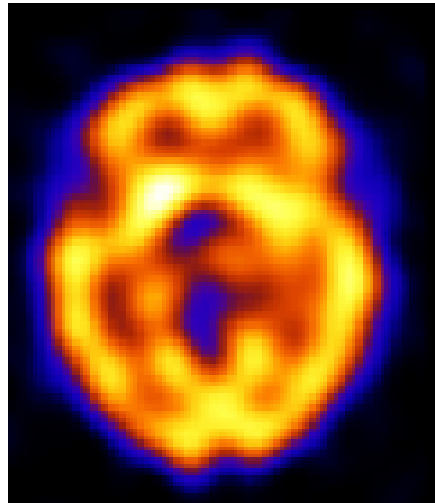
Electromagnetic spectrum

Source: Wikipedia

Nuclear Imaging

Physics Principle

Nuclear imaging is the use of radioactive materials for imaging structures and function inside the body.

Stability of Atomic Nuclei

- *ground state:* most stable.
- *metastable state:* nucleus is unstable, has long lifetime before transforming to another state.
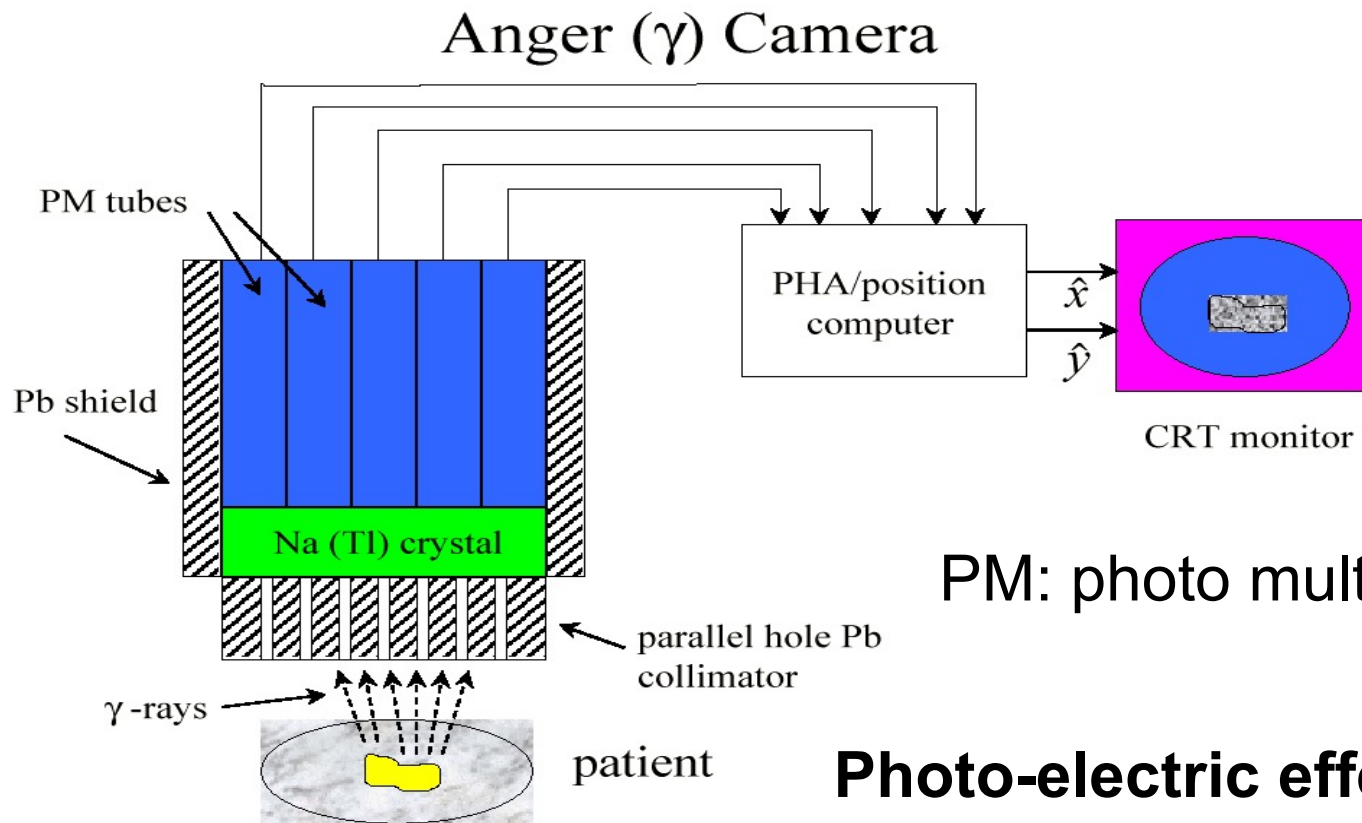- *excited state:* nucleus very unstable, exists in this state for small time period before transforming.

radioactive decay { excited state → ground state ----→ radiation (α, β, or γ)
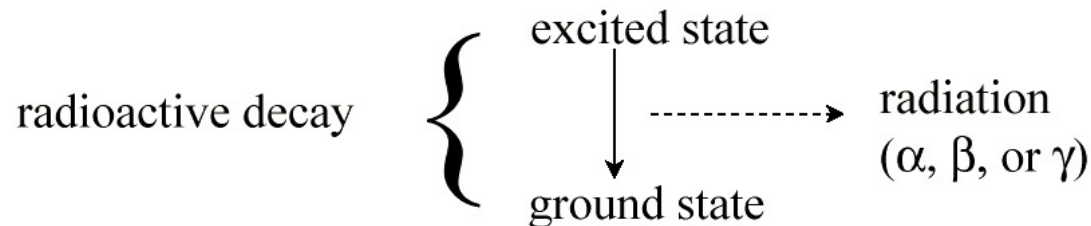
Nuclear Imaging

	Energy (in keV)	Half-life (in hours)
Technétium ^{99m}Tc	140	6
Iode ^{123}I	159	13
Thallium ^{201}Tl	75 et 135	73
Xénon ^{133}Xe	81	127
Indium ^{111}In	173 et 247	67

Nuclear Imaging

System Design

Anger (γ) Camera

PM tubes

Pb shield

Na (Tl) crystal

parallel hole Pb collimator

γ-rays

patient

PHA/position computer

$\hat{x}$

$\hat{y}$

CRT monitor

PM: photo multiplier

Photo-electric effect

+ Compton (undesirable)

Nuclear Imaging

SPECT (single photon emission computerized tomography)

• Several projections

• Reconstruction (as for CT, see next lecture)

• Attenuation correction

Nuclear Imaging

PET (positron emission tomography)

• In unstable nucleus, (more protons than neutrons) proton converts to neutron under emission of positron.

• Positron travels limited distance in tissue.

• Positron can combine with electron of nearby atom and emits two 511 keV X-ray photons (γ rays) that travel in opposite directions.

	^{15}O	^{13}N	^{11}C	^{18}F
Half-life (in min)	2	10	20	110

Nuclear Imaging

Positron annihilation

Positron Ring Detector

...

coincidence detector → reconstruction computer
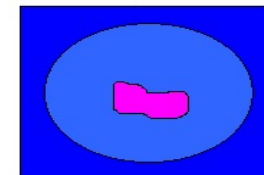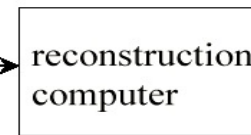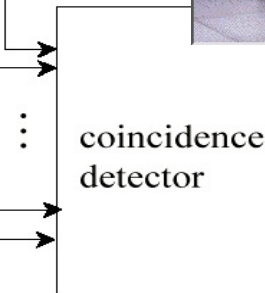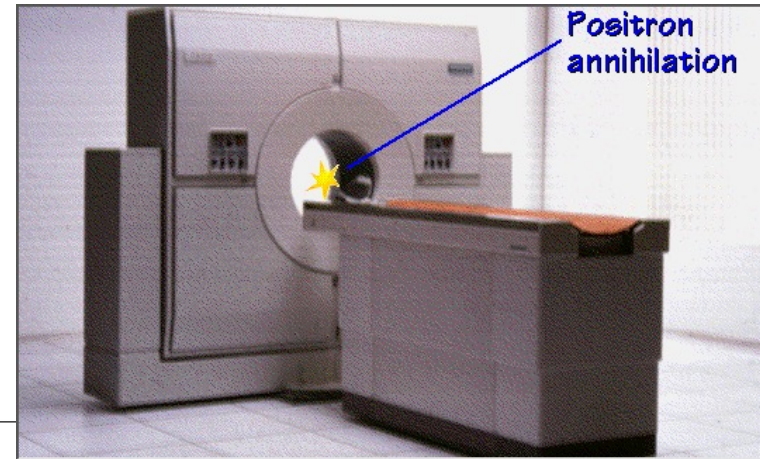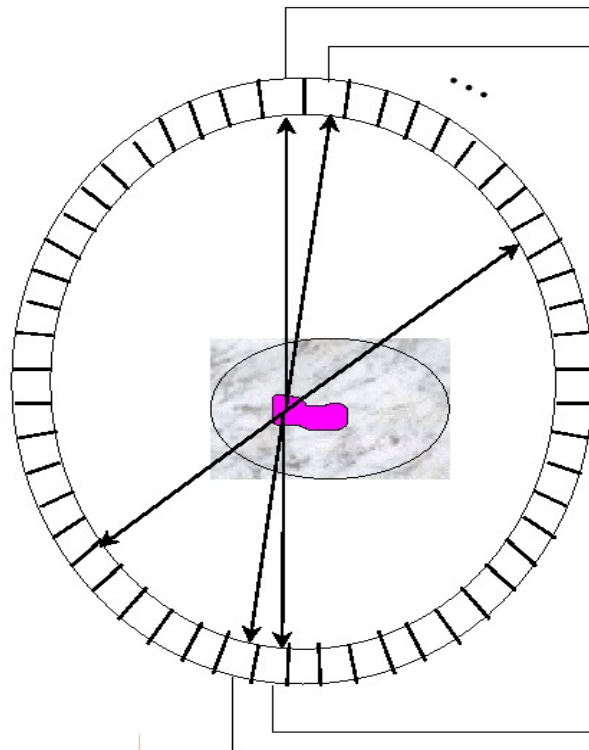
(see next lecture)

CRT monitor

Nuclear Imaging

- **Advantages**
  - Functional imaging: metabolism, immunology, function, flux (not an anatomical imaging technique!).

- **Disadvantages**
  - Poor spatial resolution (a few mm).
  - High level of noise.
  - Expensive hardware.
  - Need of cyclotron.

Nuclear Imaging

Applications

- Heart
- Lungs
- Kidneys
- Bladder
- Gastro-intestinal Track
- Endocrine system (hormones)
- Immune system (white blood cells)
- Tumors (ex: FDG)

Nuclear Imaging

New developments

- Detection using semi-conductors
- Combined machines:
  - PET/CT
  - PET/MRI

Nuclear Imaging
Whole Body
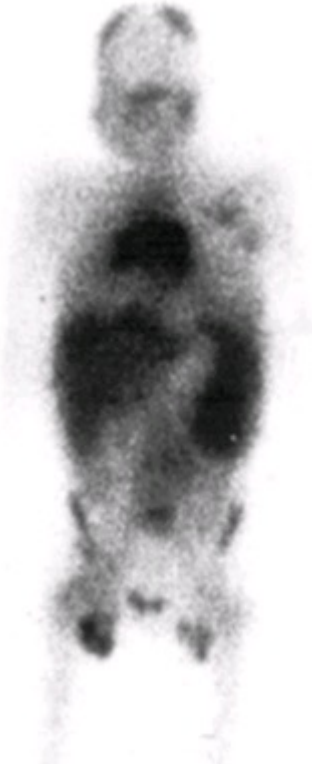
Figure 1. Whole-body gallium-67 scan showing lymphoma in the chest, the spleen, the abdomen, and the groin. The chest and spleen sites were known before the scan. The abdominal and groin uptakes were detected only by the scan.
Source: http://www.nucmednet.com/galymph.htm
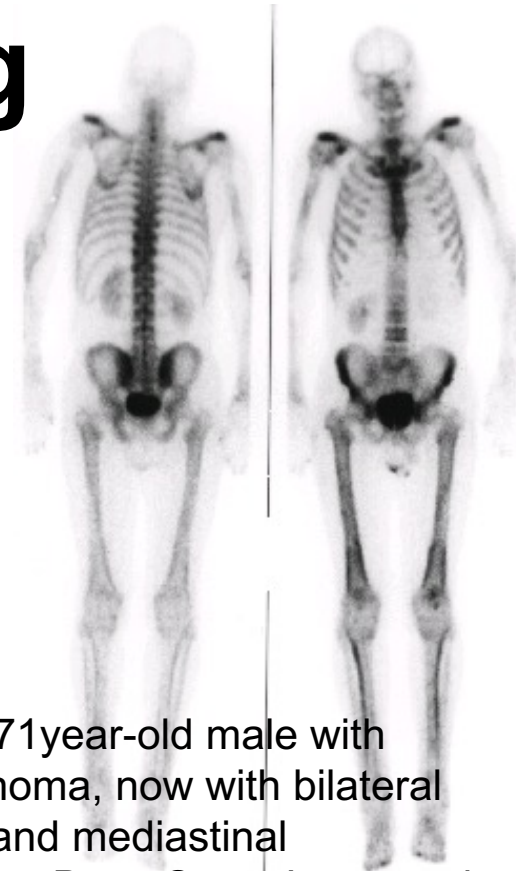
Clinical History: A 71year-old male with history of lung carcinoma, now with bilateral pulmonary nodules and mediastinal adenopathy.**Findings:** Bone Scan: Increased radiopharmaceutical uptake along cortical margins of the bilateral femurs and tibias. No evidence of bony metastases.

Diagnosis: Hypertrophic osteoarthropathy

http://www.uhrad.com/spectarc.htm

Nuclear Imaging
Example: Lung

SPECT scan for lung perfusion (pulmonary embolism)
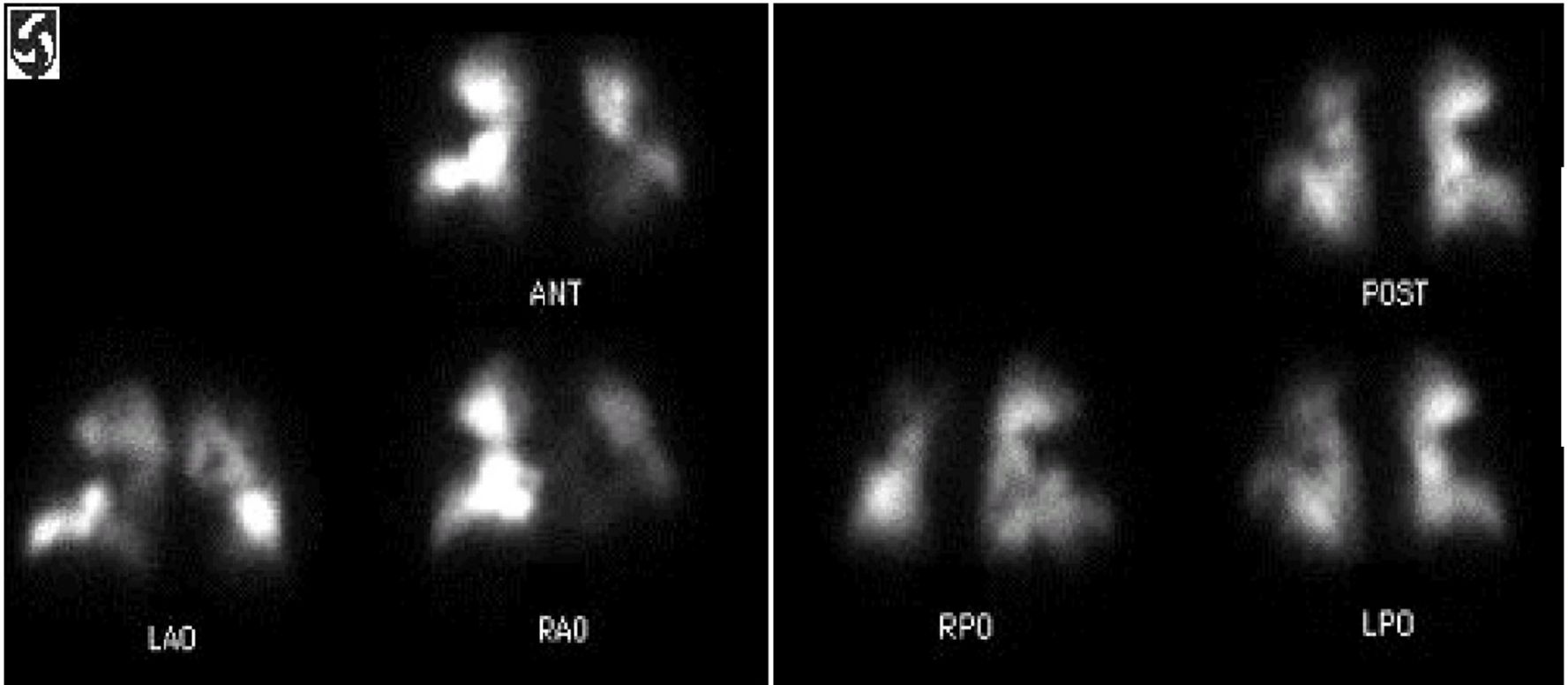
Source: Brigham & women's Hospital

Nuclear Imaging

Example: Heart

- Perfusion Imaging

Stress exams

Abnormal blood flow

Normal blood flow

Stress

Rest
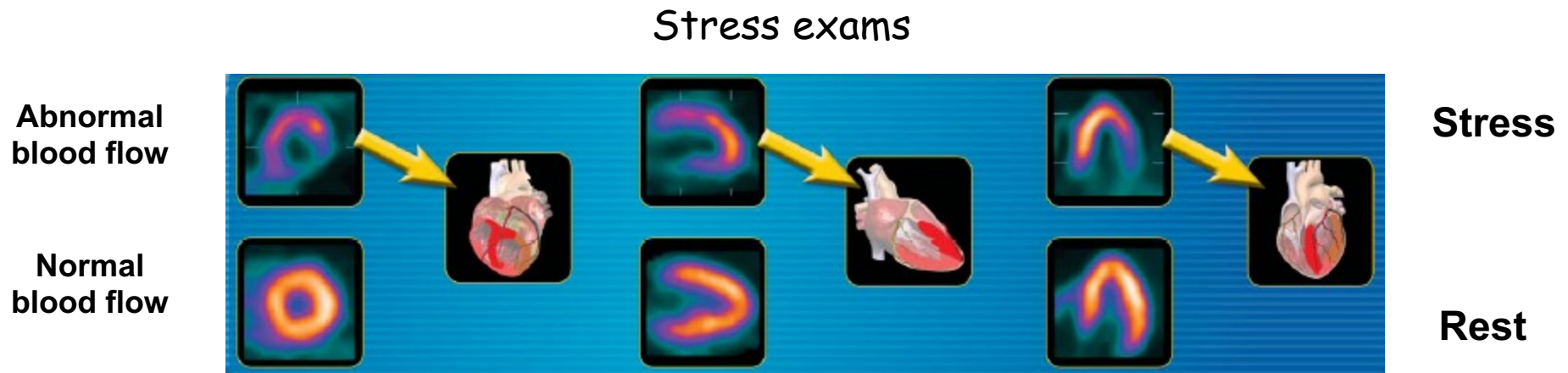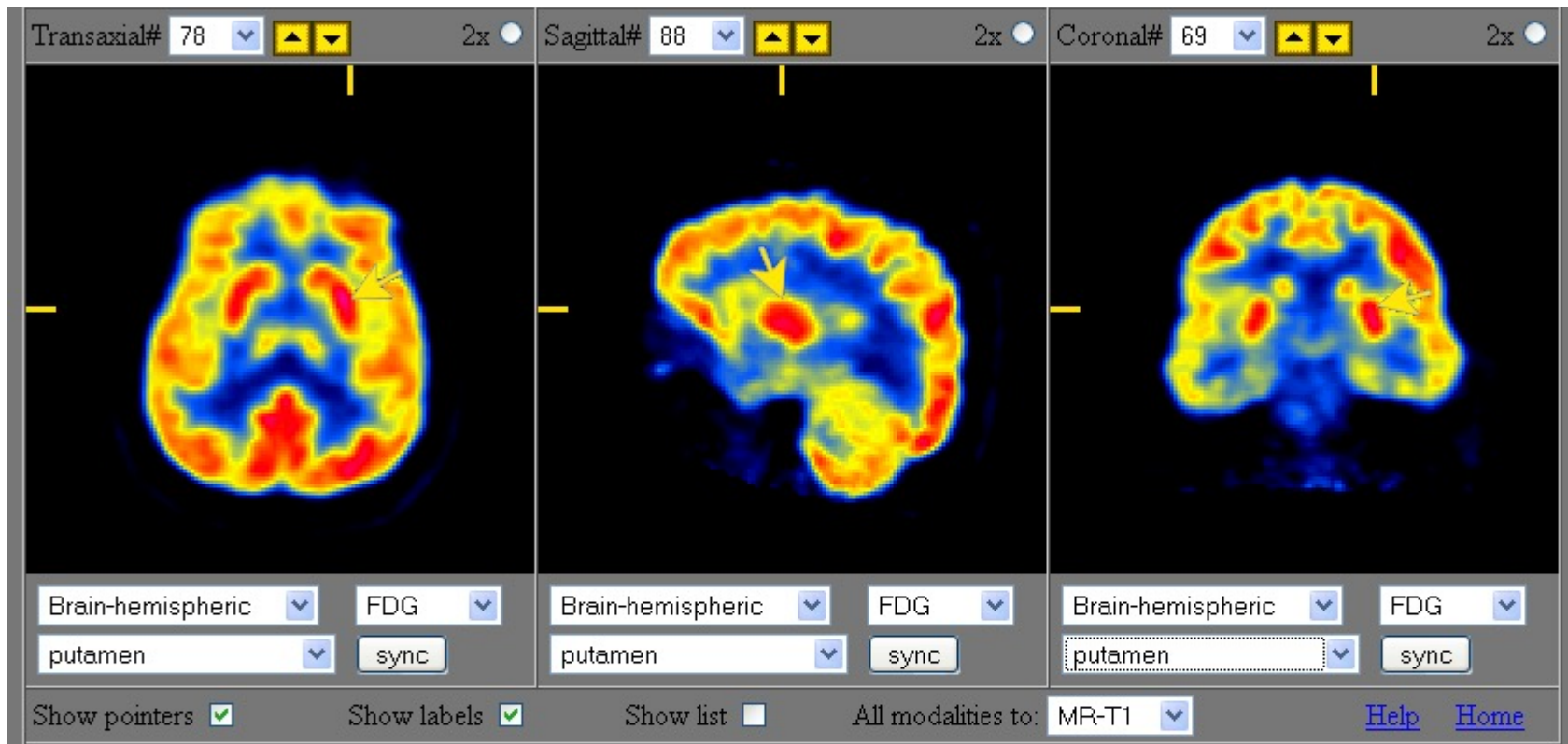
Nuclear Imaging

Example: Brain

Nuclear Imaging
Example: Brain

Source: www.med.harvard.edu/AANLIB
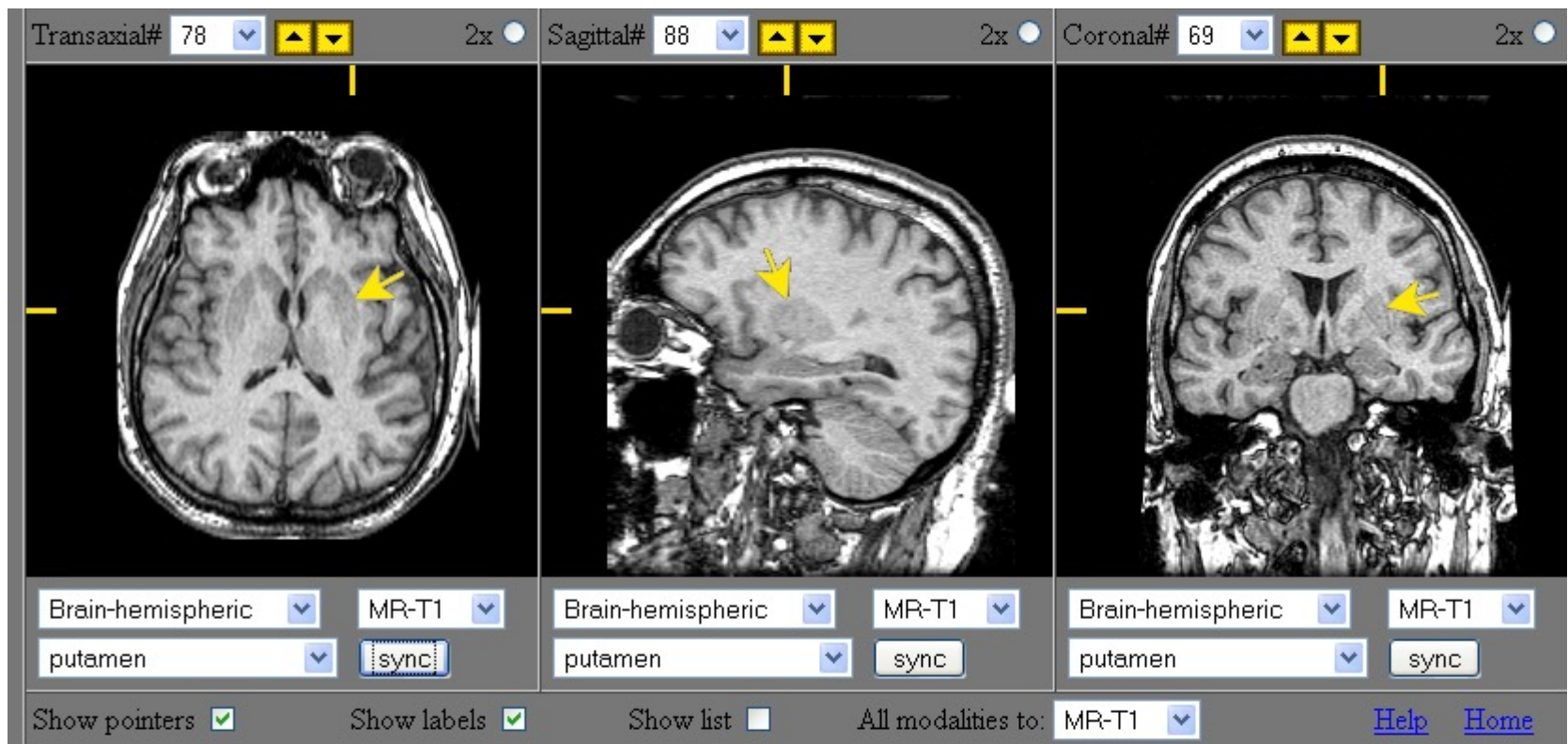
Nuclear Imaging

Example: Brain
PET with FDG tracer for diagnosis of brain tumor
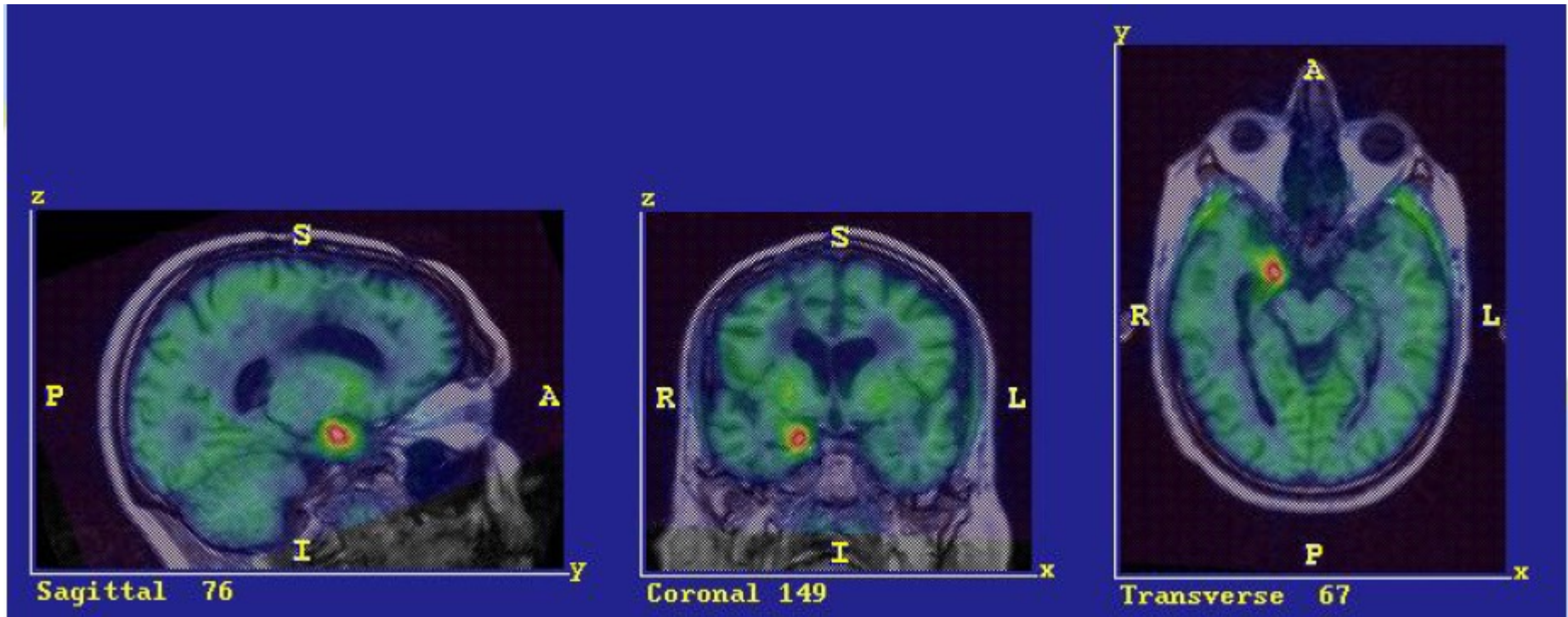
Source: V. Cunningham, GlaxoSmithKline.

Nuclear Imaging

Example: Brain

PET for in-vivo testing of new drugs

[^{11}C]-R-rolipram   MRI

Source: V. Cunningham, GlaxoSmithKline.
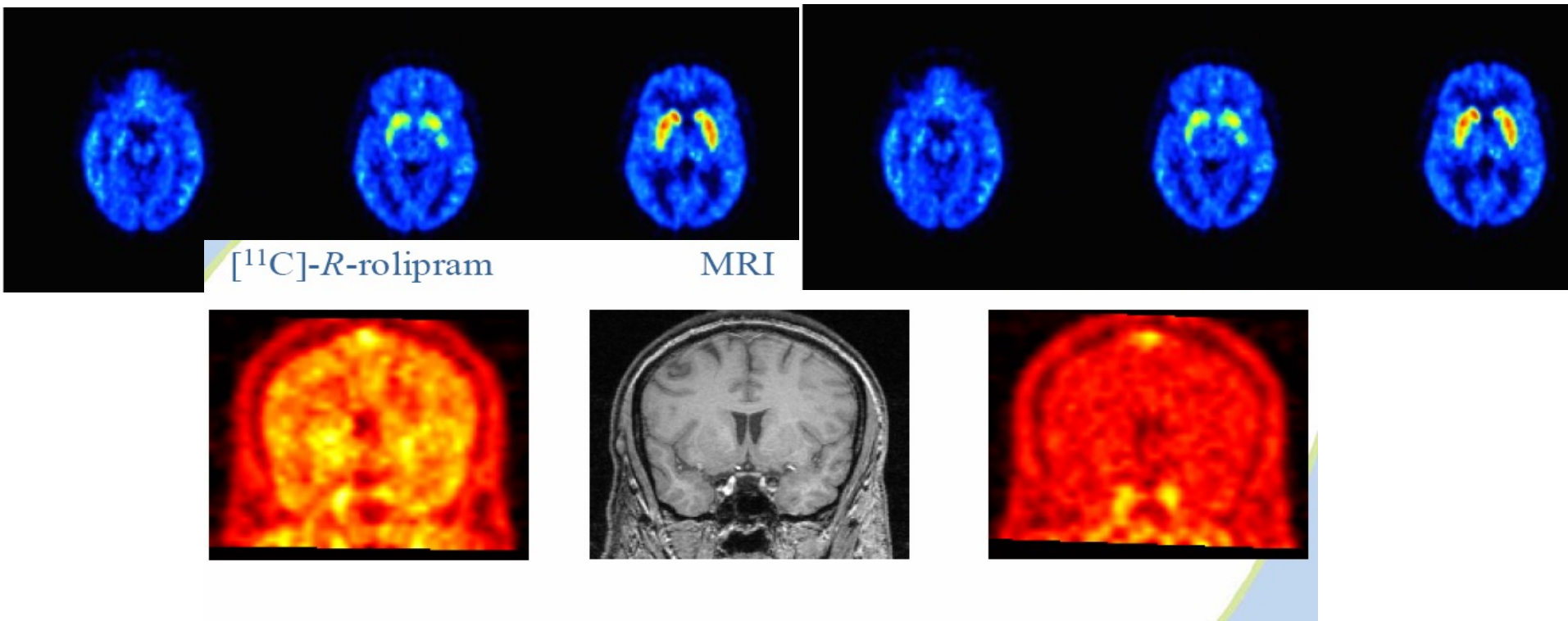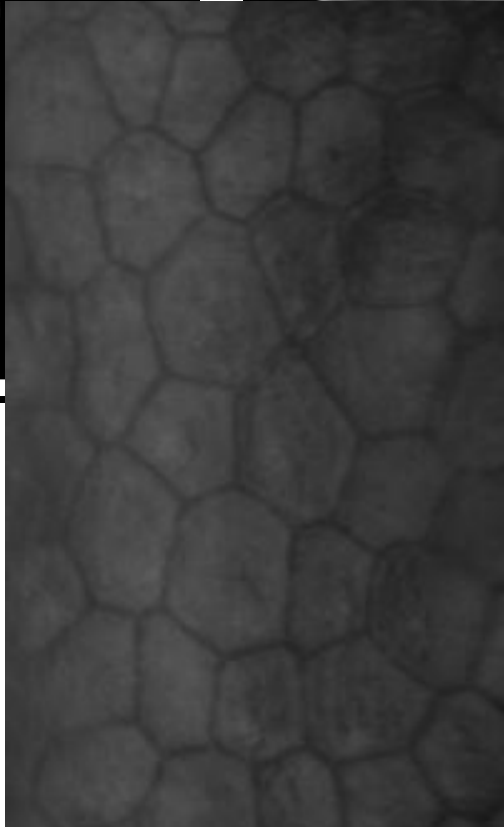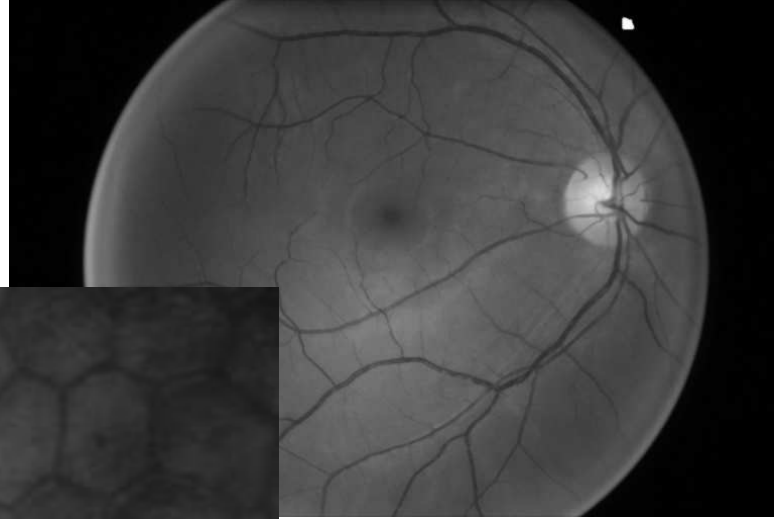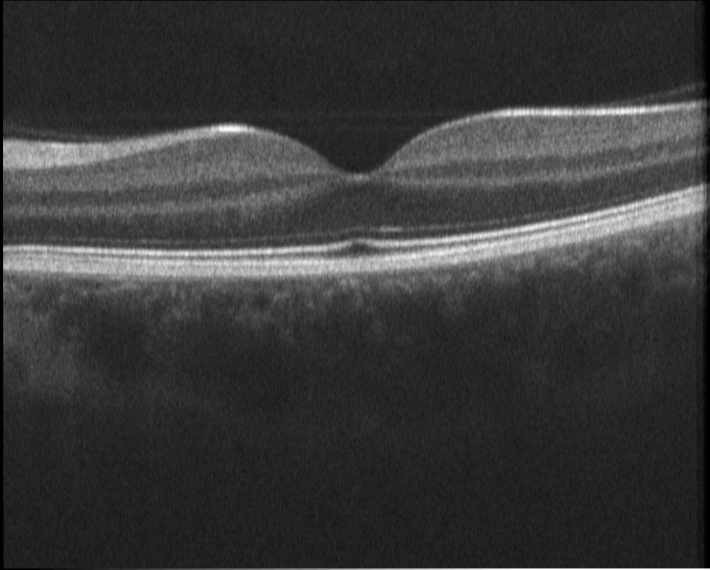
Optical imaging

Research in Medical Imaging: a few examples

Registration of MRI and PET abdomen images
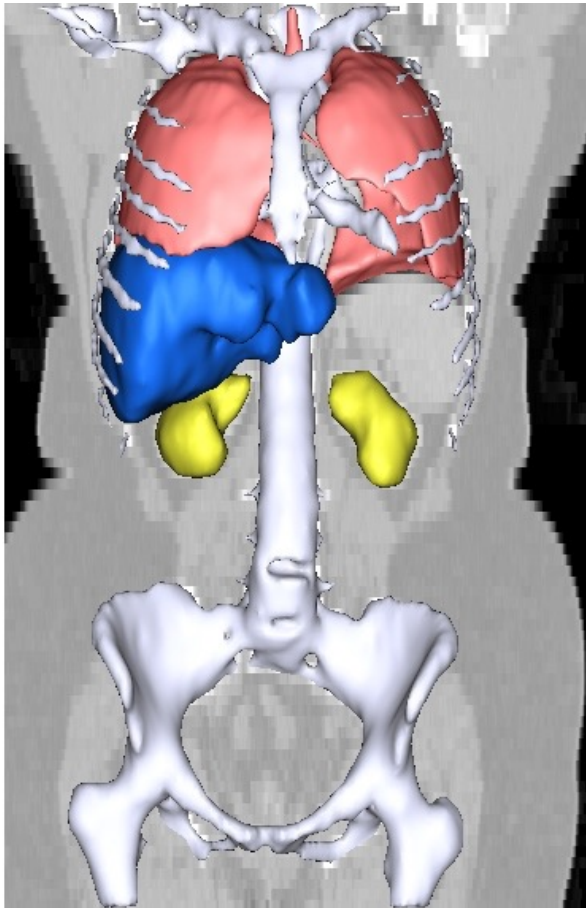
Segmentation of cortical brain structures
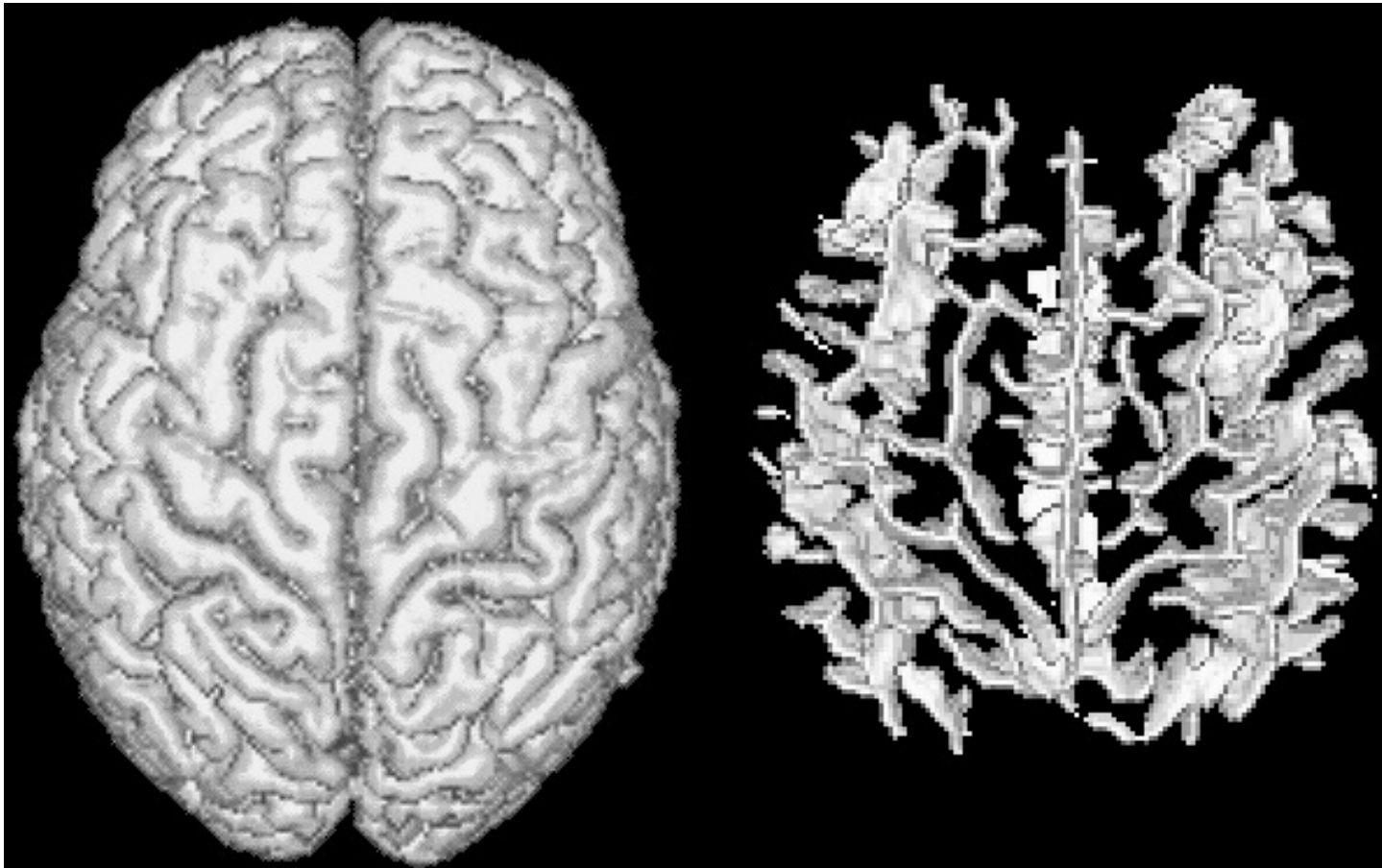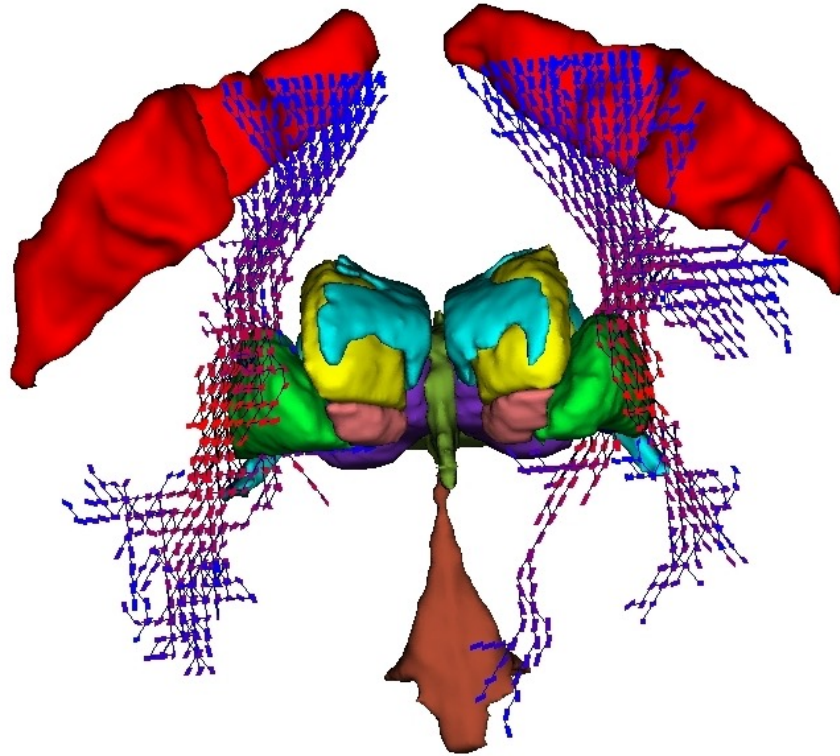
Segmentation of sub-cortical structures

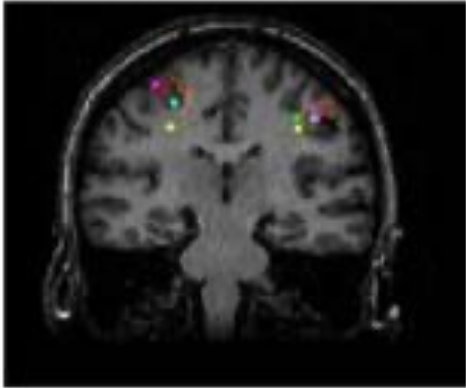Lateral ventricles

Third ventricle

Caudate nucleus

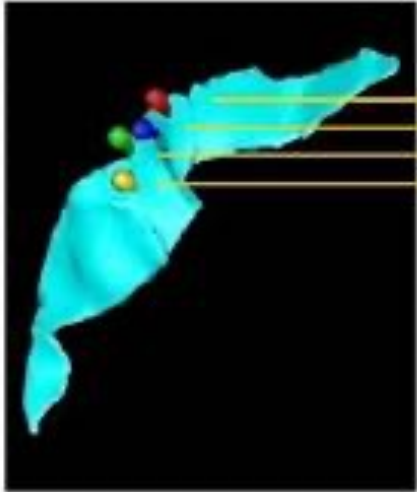Thalamus
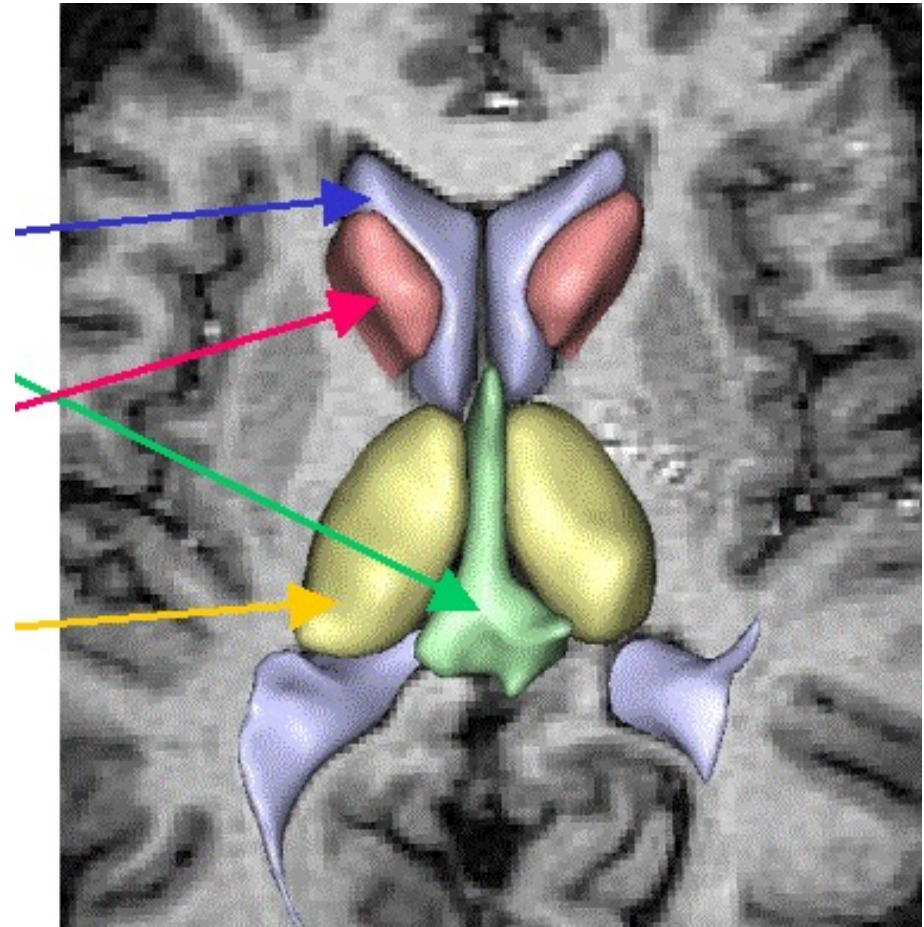
Segmentation of sub-cortical structures and tumors
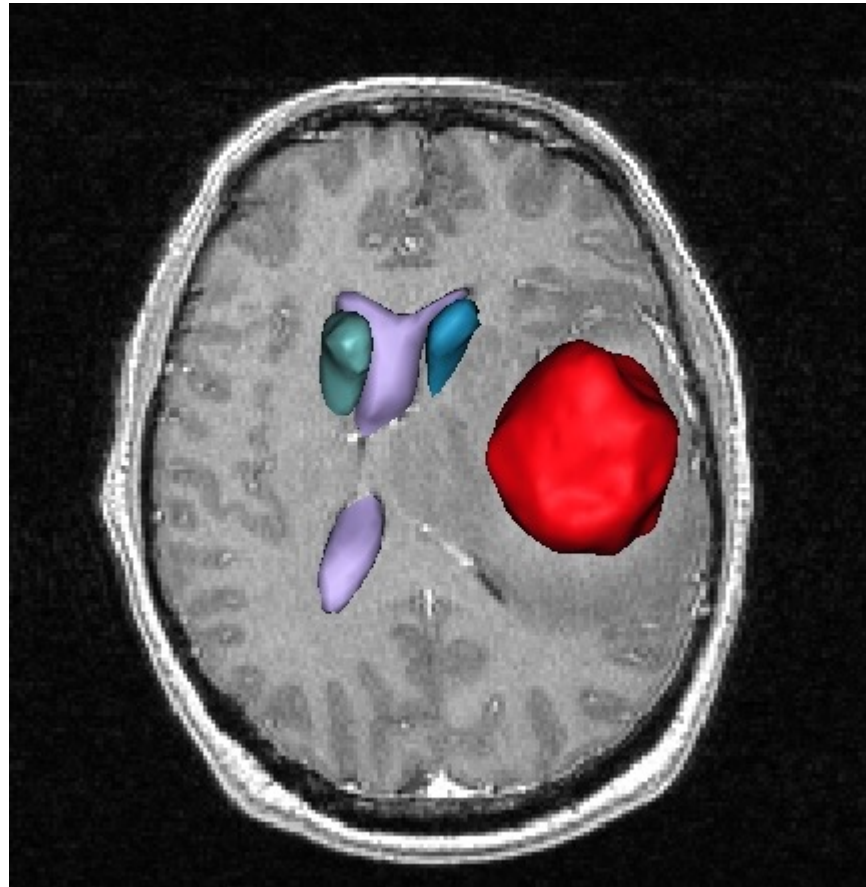
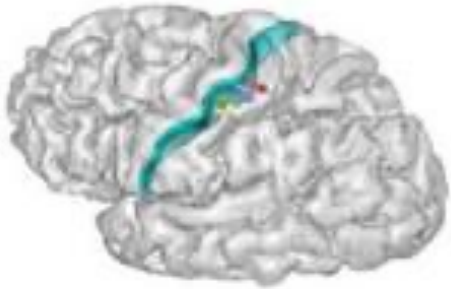# Diffusion Tensor MRI for Brain White Matter Fibers

Functional Brain MRI

Distance entre doigt ~ 0.9 cm
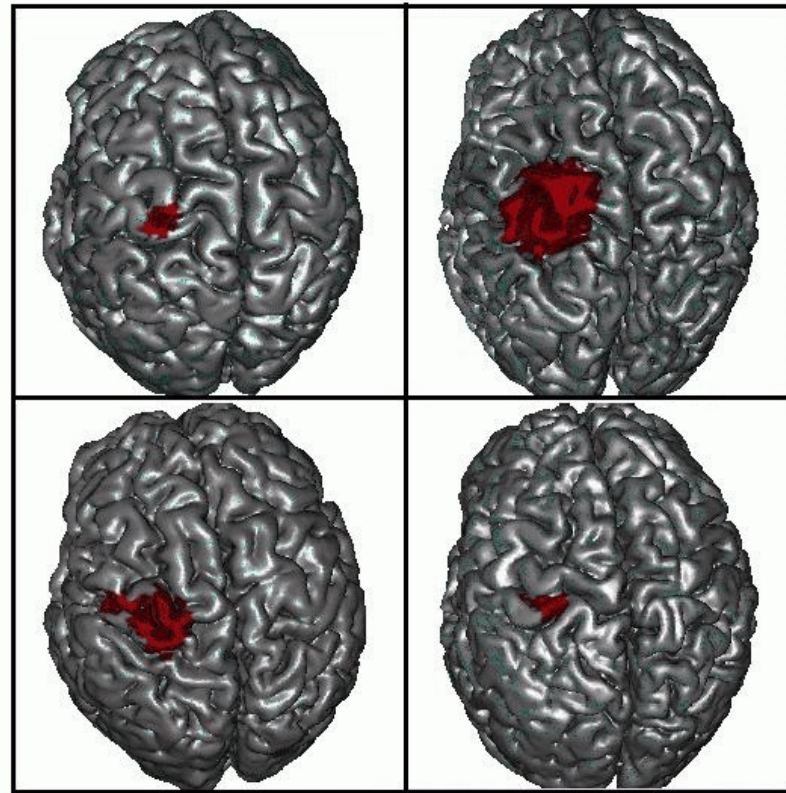Distance I - V ~ 1.5 cm

Motor control of fingers

petit doigt
majeur
index
pouce
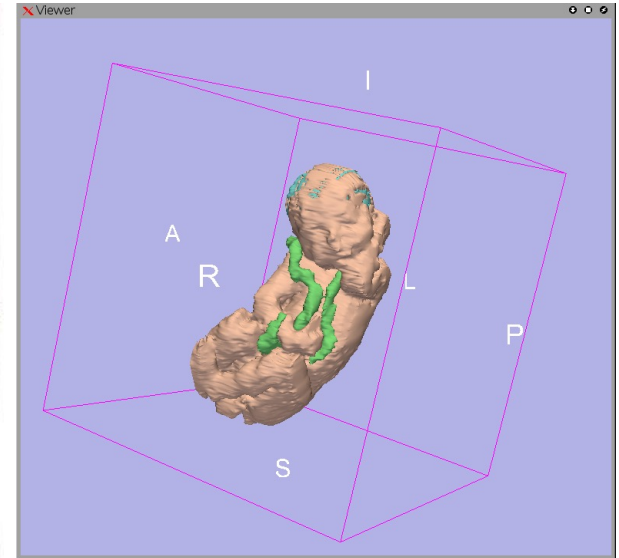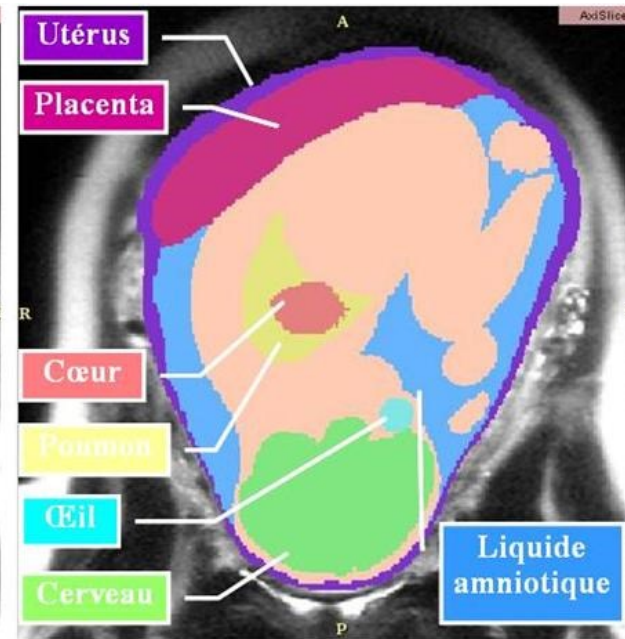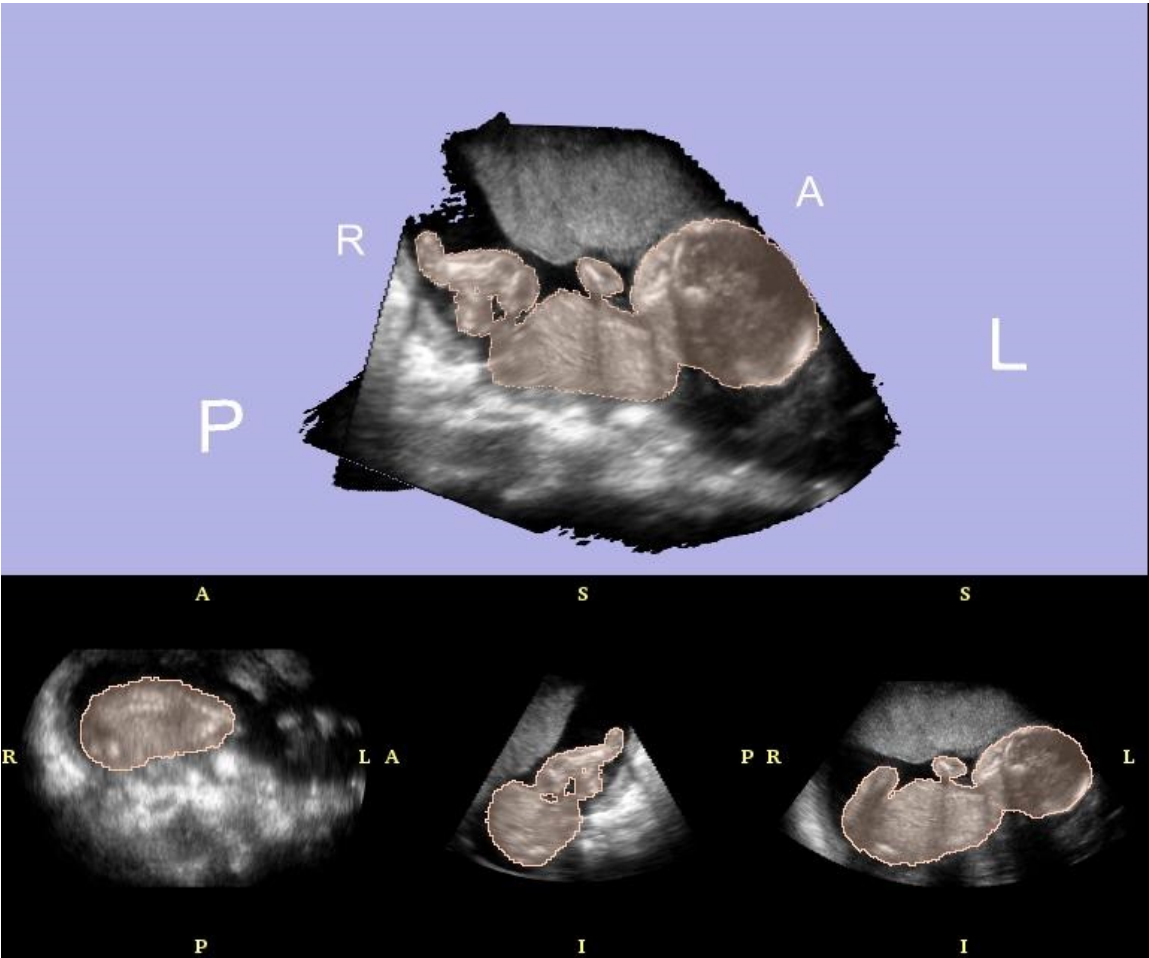
Functional MRI
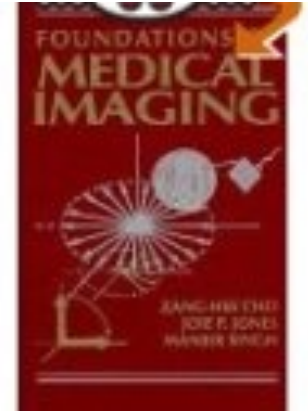

# Motor control of right hand

Fetal Imaging

Fetal Imaging

Books

•**Foundation of Medical Imaging**, Z.H. Cho, J.P. Jones, M. Singh, John Wiley &Sons, Inc., New York 1993, ISBN 0-471-54573-2.

•**Principles of Medical Imaging**, K.K. Shung, M.B. Smith, B. Tsui, Academic Press, San Diego 1992, ISBN 0-12-640970-6.

•**The Essential Physics of Medical Imaging (2nd Edition)** ,Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholdt Jr., John M. Boone, Lippincott Williams & Wilkins; 2nd edition, ISBN 0683301187.
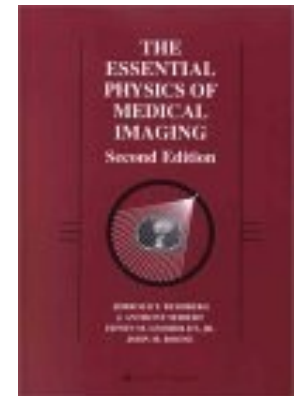
•**Image Reconstruction in Radiology**, J.A. Parker, CRS Press, Boca Raton, FL 1990, ISBN 0-8493-0150-5/90.

•**Principles of Magnetic Resonance Imaging,** Zhi-Pei Liang, P.C. Lauterbur IEEE Press, New York, NY 2000, ISBN 0-7803-4723-4.