NPRE435: Principles of Radiological Imaging

Instructor: Ling-Jian Meng, Professor

Department of Nuclear, Plasma and Radiological Sciences,

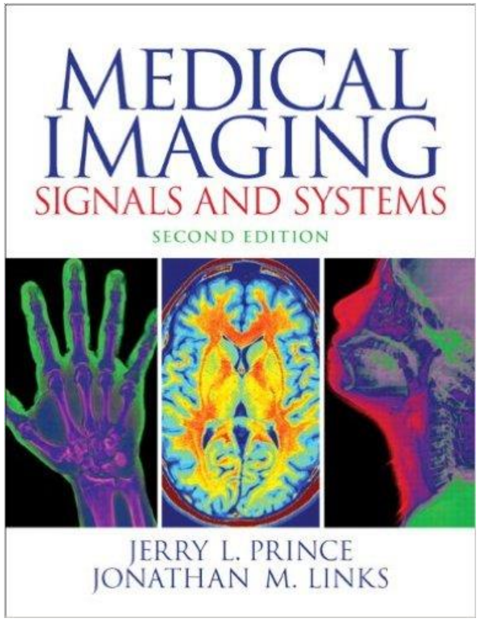
Department of Bioengineering, and

Beckman Institute for Advanced Science and Technology,

University of Illinois at Urbana-Champaign

Course Components

- 37 lectures.
- 1-2 term project(s), TBD.
- 1-2 lab tours:
  - Microscopy Suite (Micro- and Nano-CT) at Beckman Institute.
  - TBD.
- 4 in-class quizzes, one mid-term exam, and one final exam.
- 7 homeworks.



Main textbook

Course website: https://courses.engr.illinois.edu/npre435/

Password: **Radiological#2026**

A Few Remarks about Radiological Sciences

Areas where radiological sciences can make a difference:

- There were close to 20 million new cases of cancer in the year 2022 alongside 9.7 million deaths from cancer. The estimates suggest that approximately one in five men or women develop cancer in a lifetime, whereas around one in nine men and one in 12 women die from it. (American Cancer Society, 2024)

- In 2019, the national patient economic burden was estimated at $21.09 billion, …. These costs are projected to increase, with the total cost of cancer care in the U.S. expected to exceed $245 billion by 2030. (source: American Association for Cancer Research)

- Cardiovascular diseases (CVDs) represent the leading cause of death globally, claiming an estimated 19.8 million lives in 2022. (source: World Health Organization)

- Over 1 in 3 people are affected by neurological conditions, the leading cause of illness and disability worldwide. In 2021, more than 3 billion people worldwide were living with a neurological condition. (source: WHO)

- One study estimated the economic burden of major neurologic diseases to be approximately $800 billion annually in the United States. (source: American Brain Foundation)

Advancing radiological sciences to improve the health and well-being of society …

Lecture Topics

Introduction to Radiological Imaging

Chapter 1: Mathematical Preliminaries for Radiological Imaging

1.1 Signals and systems

1.2 Fourier transform basics and sampling theory

1.3 Analytical image reconstruction methods

1.4 Statistical image reconstruction methods

1.5 Image quality assessment

Chapter 2: Introduction to Physical Principles

2.1 Typical radiation sources for radiological imaging and radiation therapy

2.2 Spatial, spectral, and temporal characteristics of X-ray and gamma-ray emissions

2.2 Interactions of ionizing radiation with matter

Chapter 3: X-ray Radiography and Computed Tomography

3.1 Basic principles, current implementations, and future trends of X-ray generators

3.2 X-ray imaging sensors

3.3 Planar radiography and X-ray computed tomography (CT)

3.4 Neutron and charged-particle transmission CT

Chapter 4: Emission Tomography I: Standard Modalities for Diagnostic Radiology

4.1 The tracer principle in emission tomography and radionuclide therapy

4.2 Gamma-ray imaging sensor technologies

4.3 Single-photon emission computed tomography (SPECT)

4.4 Positron emission tomography (PET)

Lab tour

Chapter 5: Emission Tomography II: Emerging Imaging Technologies

5.1 Positronium lifetime tomography

5.2 Imaging techniques exploring the spatial-spectral-temporal correlations of gamma-ray emissions

5.3 Imaging techniques

Basic Ideas Behind Radiological Imaging:

I: The Ionizing Radiation

Ionizing Radiation

If radiation carries sufficient energy to knock an electron out of its orbital shell around an atom, then it is ionizing radiation. The minimum energy to do this is typically between 2 and 35 eV, depending upon the atom. For example,

Alpha - α - He^{++} - Very short-ranged radiation, a few microns in water

Beta - β^- or e^- - Medium Range, a few hundred microns to a few mm.

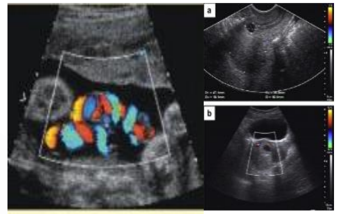
Positron - β^+ - Medium Range, similar

Photon - γ or X-rays – penetrating, a few mm to tens of cm.

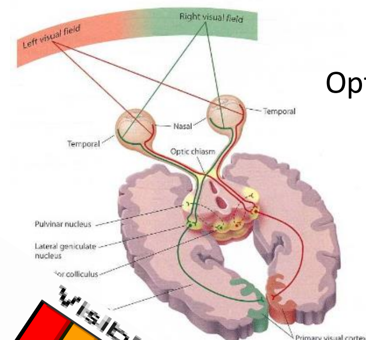
Proton - p^+ - Short range, a few microns.

Neutron - n – Penetrating, energy-dependent, and varies with material.

Imaging Techniques based on the "EM" Radiation



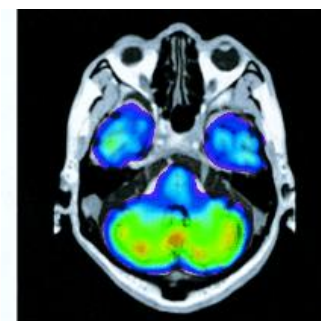
Ultrasound: Mechanical properties

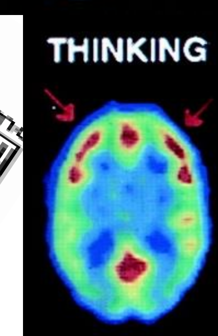


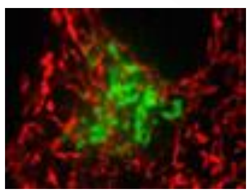
Optical microscopy

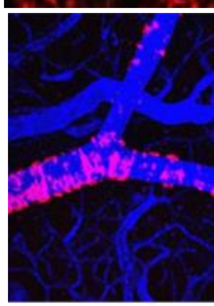
MRI: Essentially proton density, phenotyping, physiological imaging and cell tracking

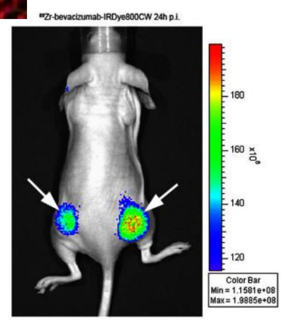
Nuclear imaging: metabolism of molecules, e.g., glucose, antibodies, peptides thymidine …











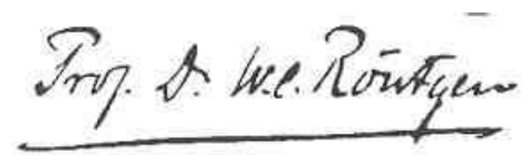
Fluorescence and Bioluminescence imaging: Quantitative imaging of targeted or 'smart' fluorochrome reporters in deep tumors, gene expression, and cell tracking

X-ray: Electron density, Lung, bone, tumor imaging, etc.

Basic Ideas Behind Radiological Imaging:

II: Planar vs. Tomographic Imaging

Wilhelm Röntgen



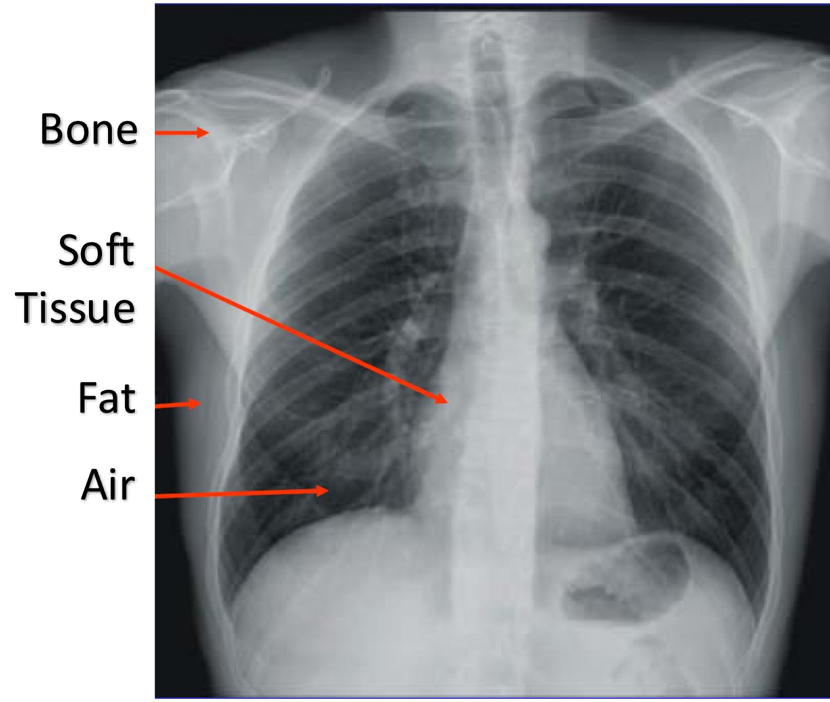
Nov. 1895	– Announces X-ray discovery
Jan. 13, 1896	– Image needle in the patient's hand
	– X-ray used pre-surgically
1901	– Receives first Nobel Prize in Physics for the discovery and use of X-rays.

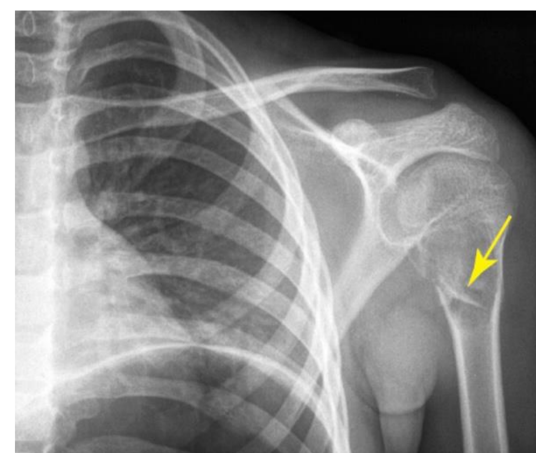
X-ray Planar Radiography

January 1896 - First x-ray made in public

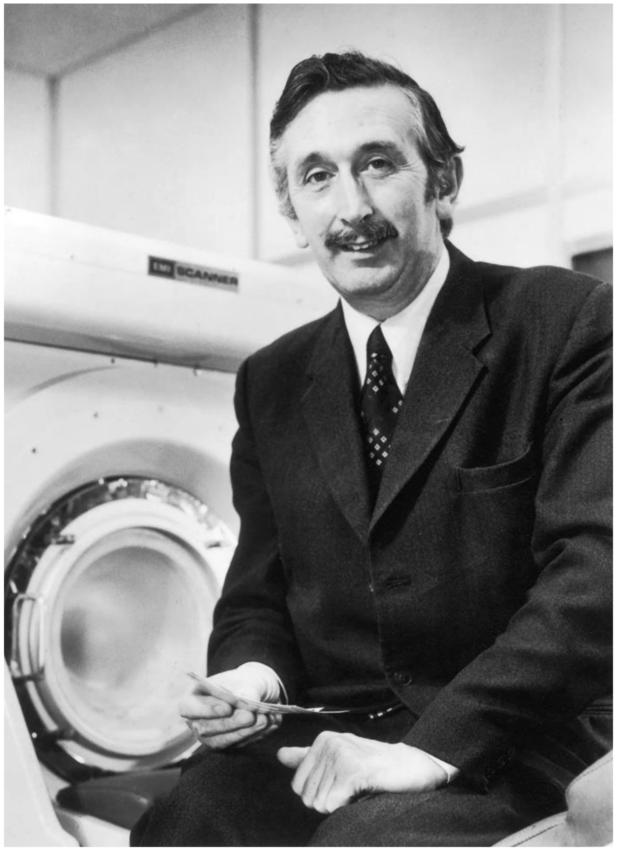
Routine x-ray current technology

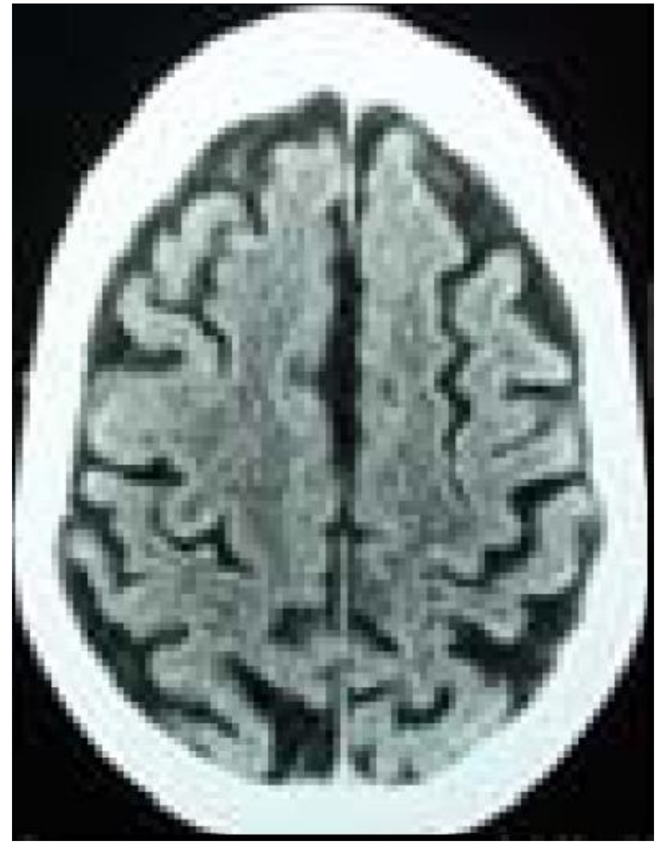
Planar X-ray Radiography





X-ray Computed Tomography (CT)



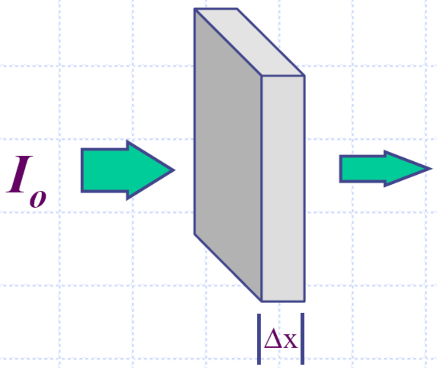


Sir Godfrey Newbold Hounsfield, CBE, FRS, was an English electrical engineer who shared the 1979 Nobel Prize for Physiology or Medicine with Allan McLeod Cormack for his part in developing the diagnostic technique of X-ray computed tomography

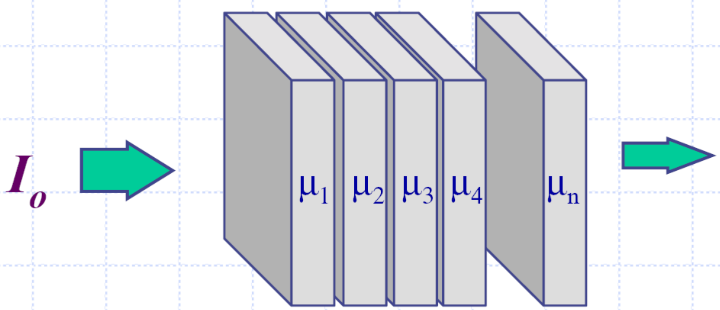
X-ray Planar Radiography

What are we measuring with planar X-ray radiography?

2 % attenuation change
detectable in film



$$I = I_o e^{-\mu \Delta x}$$

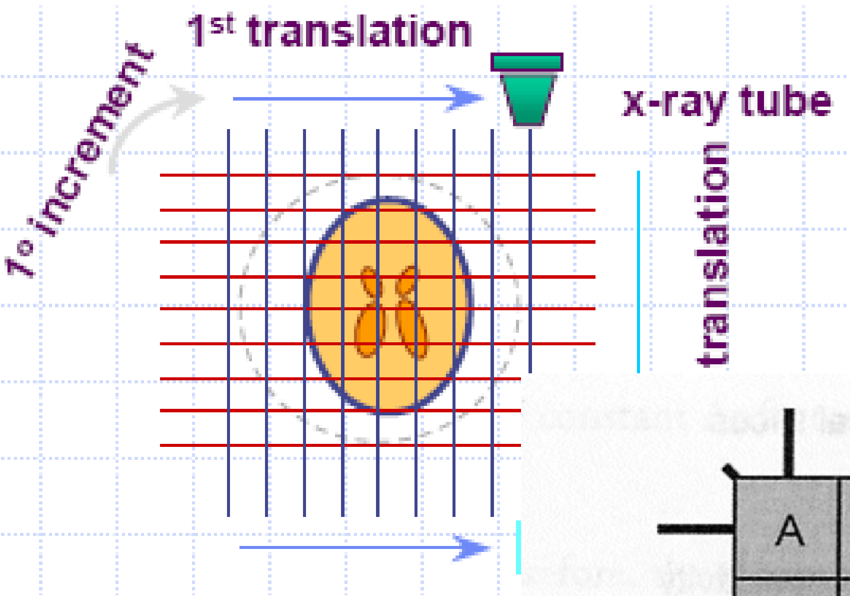


$$I = I_o e^{-\mu_1 \Delta x} e^{-\mu_2 \Delta x} \cdots e^{-}$$

$$= I_o e^{-(\mu_1 + \mu_2 + \cdots + \mu_n)\Delta x}$$

$\Delta x \rightarrow 0,$ $$P = -\ln\left(\frac{I}{I_o}\right) = \int_{-\infty}^{\infty} \mu(x)\,dx$$

X-ray Computed Tomography (CT)



0.2 % attenuation change detectable in CT Images !!

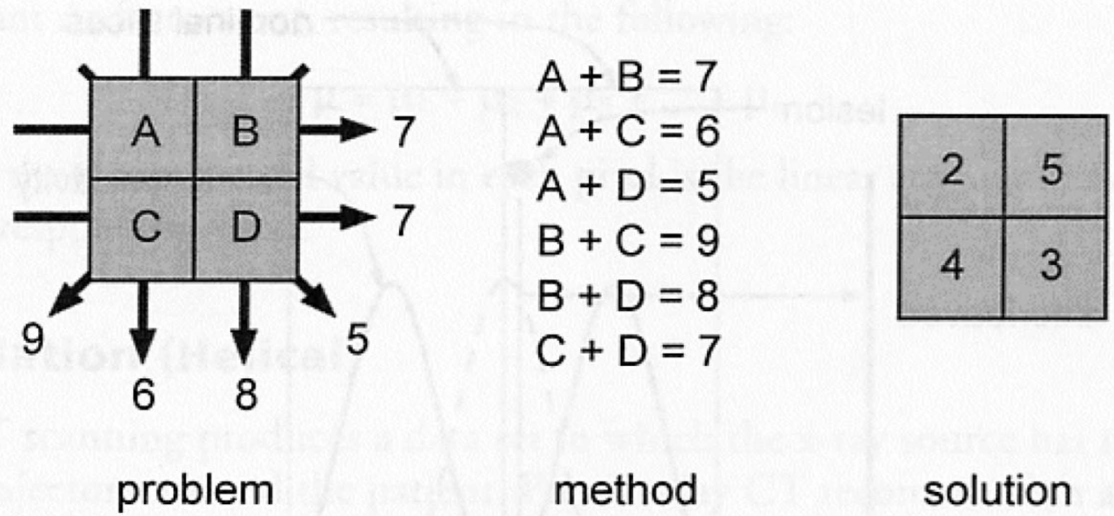
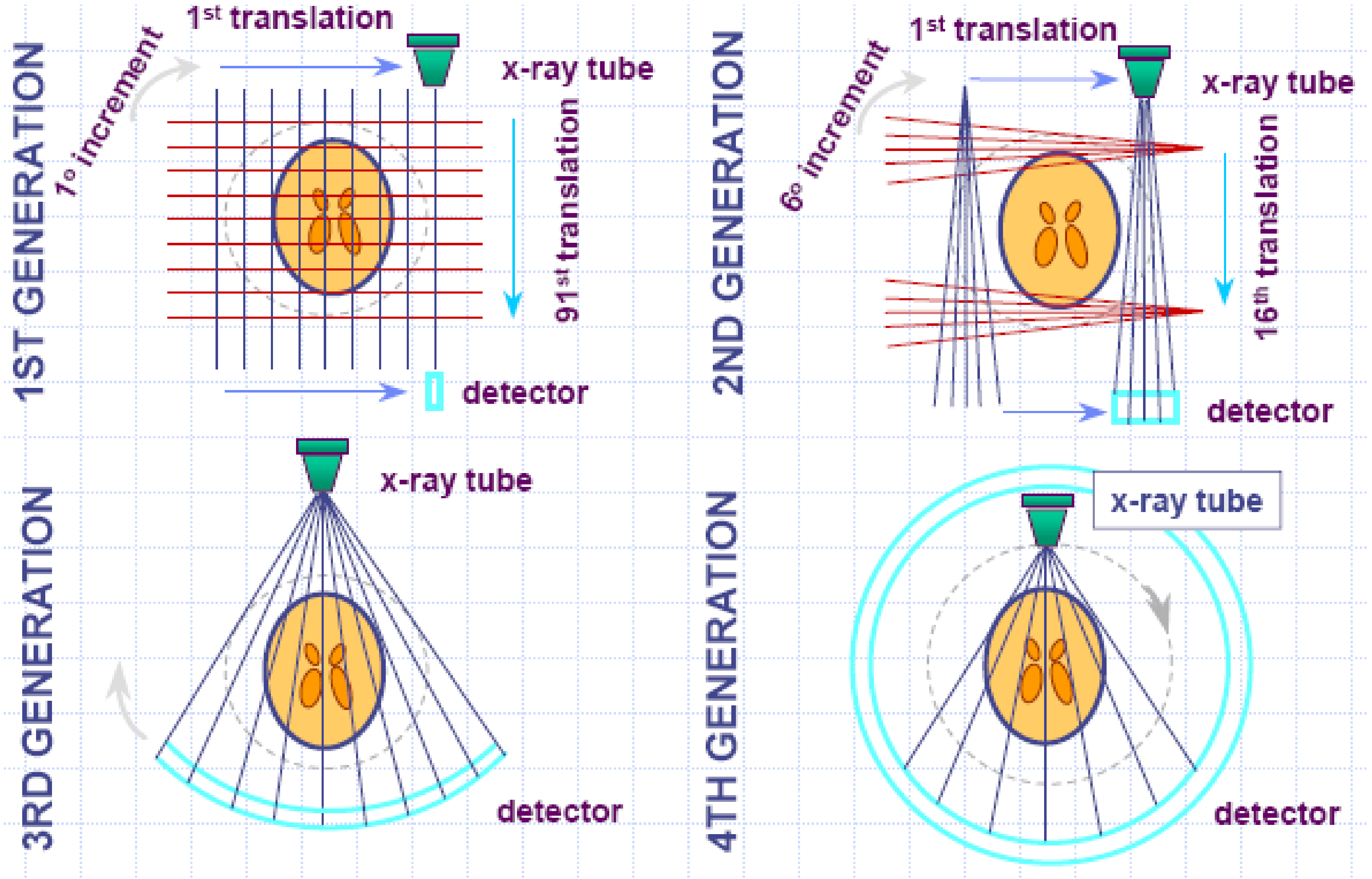


FIGURE 13-27. The mathematical problem posed by computed tomographic (CT) reconstruction is to calculate image data (the pixel values—A, B, C, and D) from the projection values *(arrows)*. For the simple image of four pixels shown here, algebra can be used to solve for the pixel values. With the six equations shown, using substitution of equations, the solution can be determined as illustrated. For the larger images of clinical CT, algebraic solutions become unfeasible, and filtered backprojection methods are used.

X-ray Computed Tomography (CT)



Examples of X-ray Computed Tomography (CT) Images

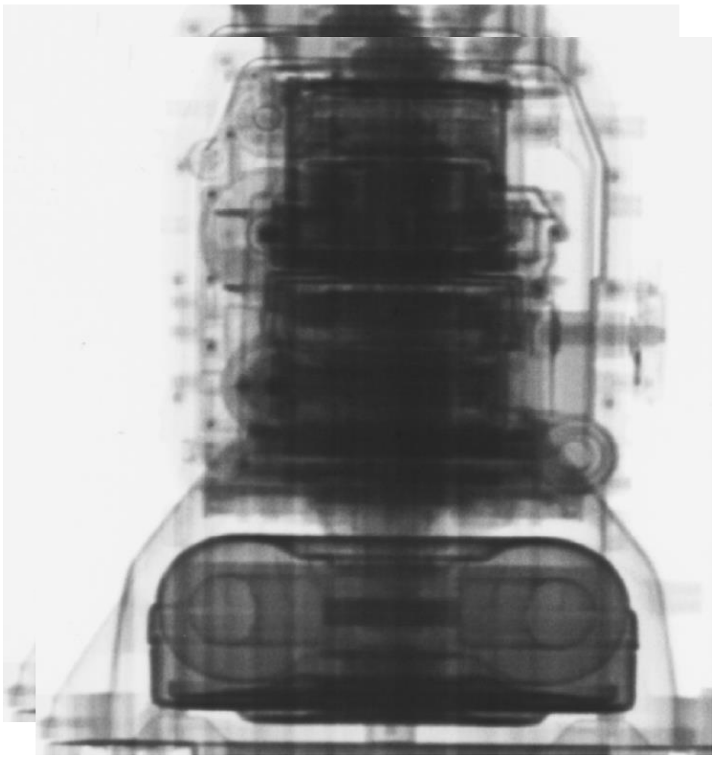
CT images of the human brain

0.2% attenuation change detectable in CT images!

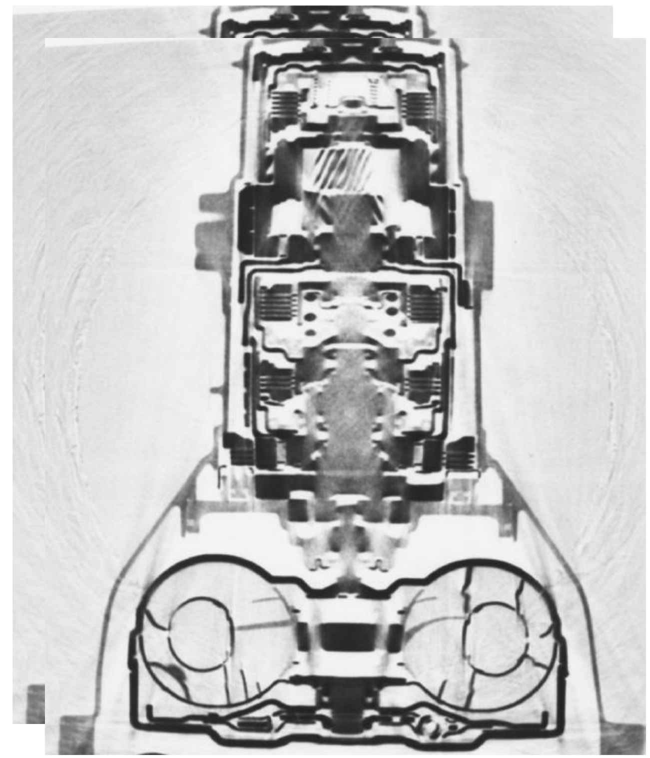
https://www.shutterstock.com/search/head-xray

X-ray Computed Tomography (CT)

Planar X-Ray



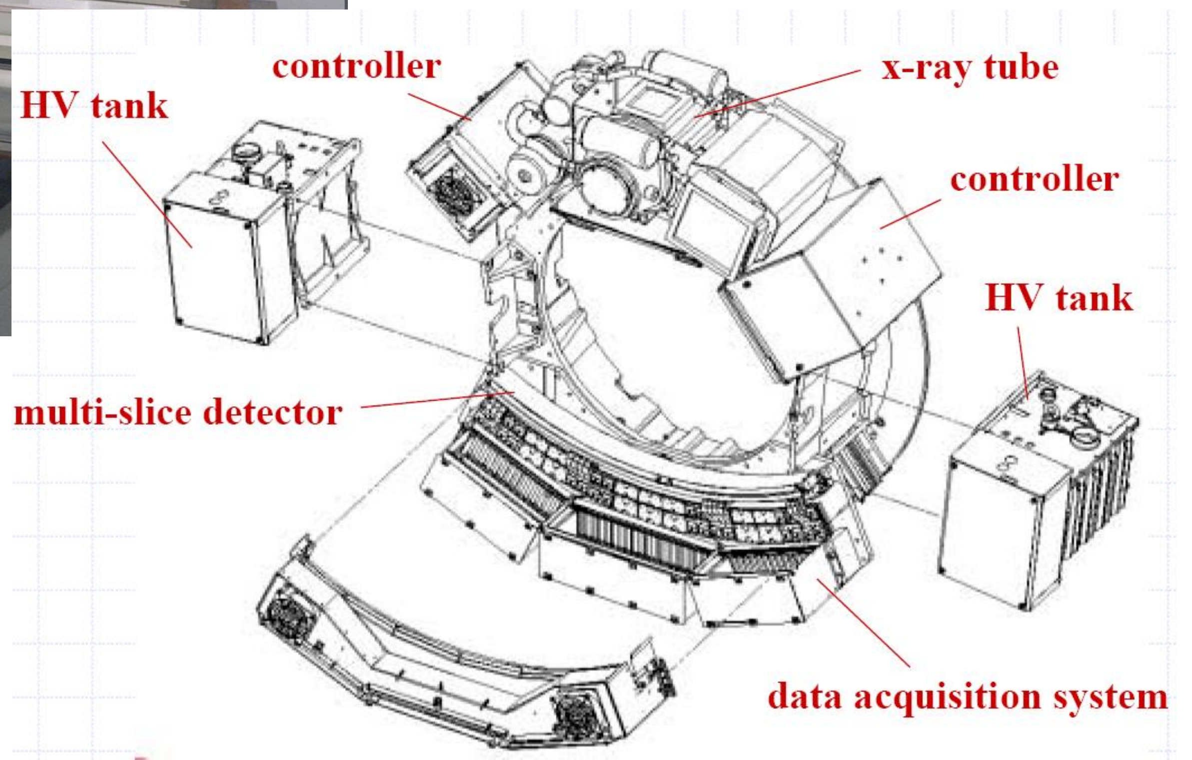
Computed Tomography



Separates Objects on Different Planes

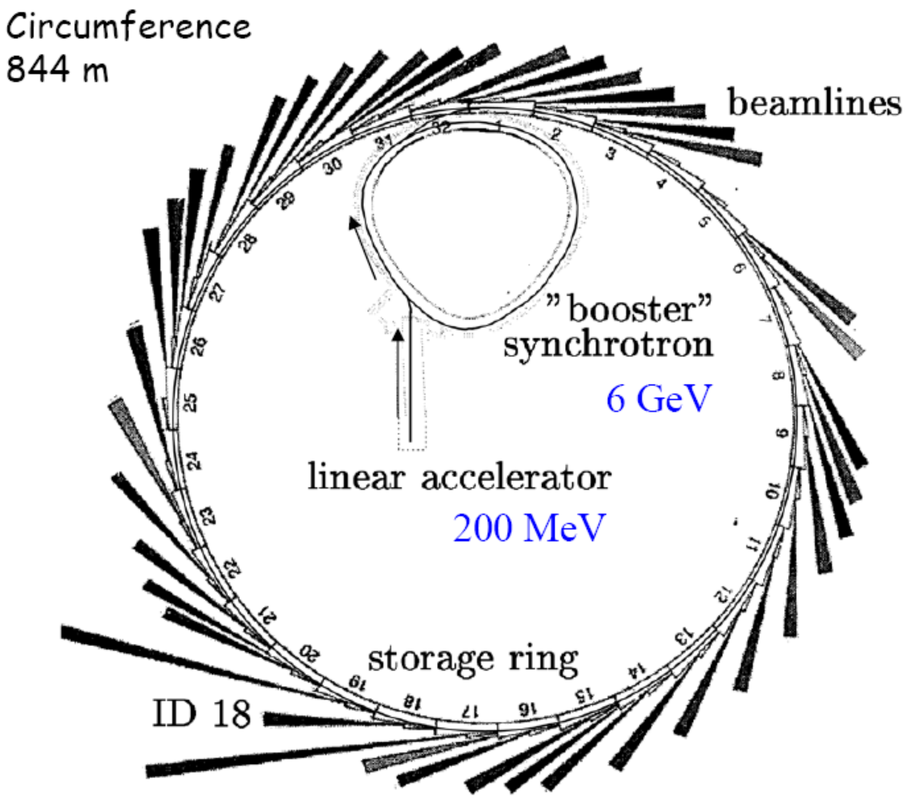
Images courtesy of Robert McGee, Ford Motor Company

Modern X-ray Computed Tomography (CT)

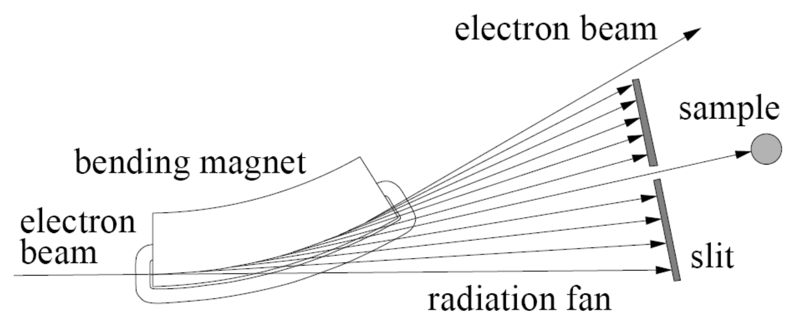


Sources of Electromagnetic Radiation – Synchrotron Radiation

European Synchrotron Radiation Facility

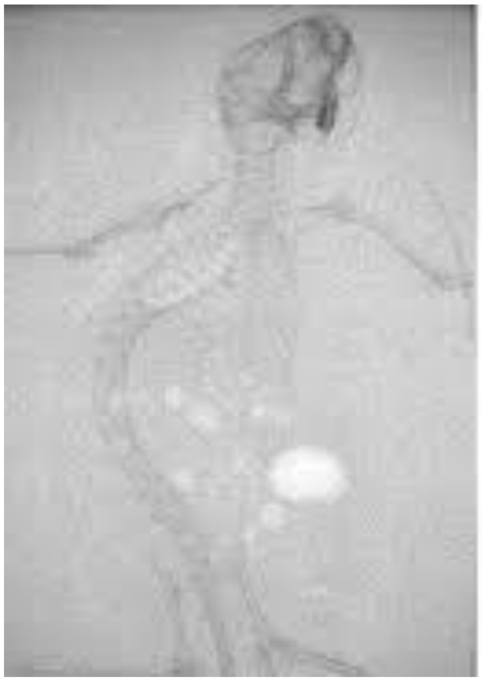


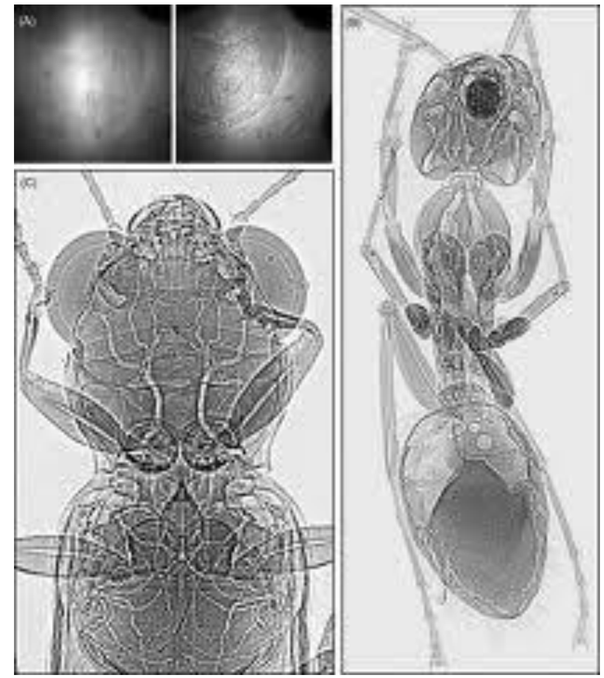
Advanced Photon Source (APS)



From http://www-hasylab.desy.de/science/groups/schneider_group/misc/RR-Lecture-1.pdf

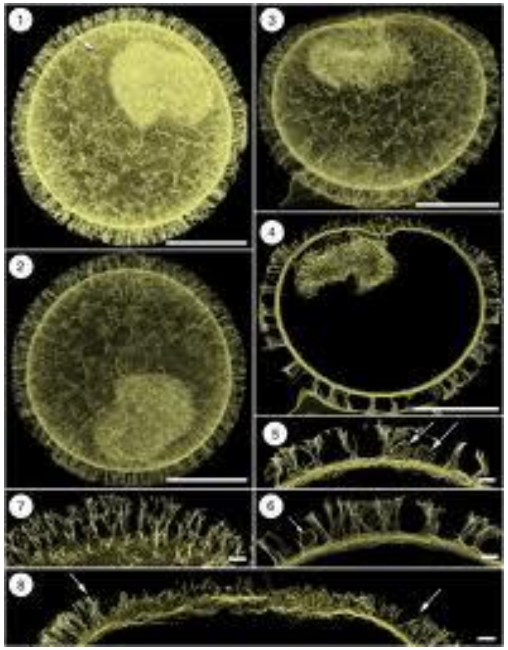
Other Interesting X-ray Imaging Techniques

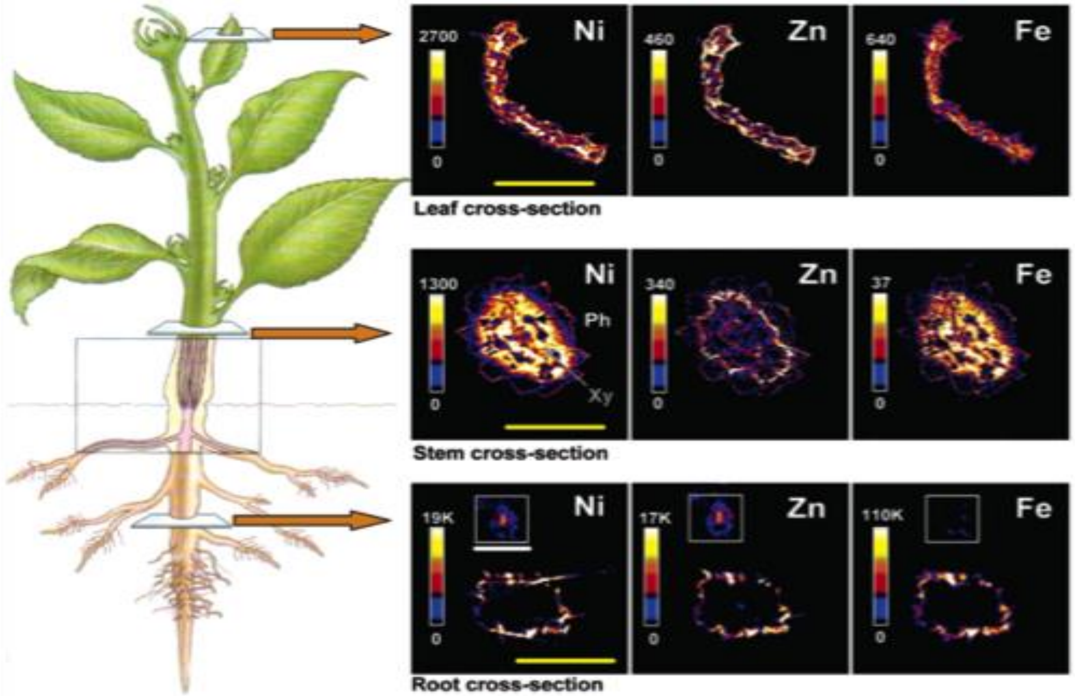




X-ray phase contrast imaging

Other Interesting X-ray Imaging Techniques



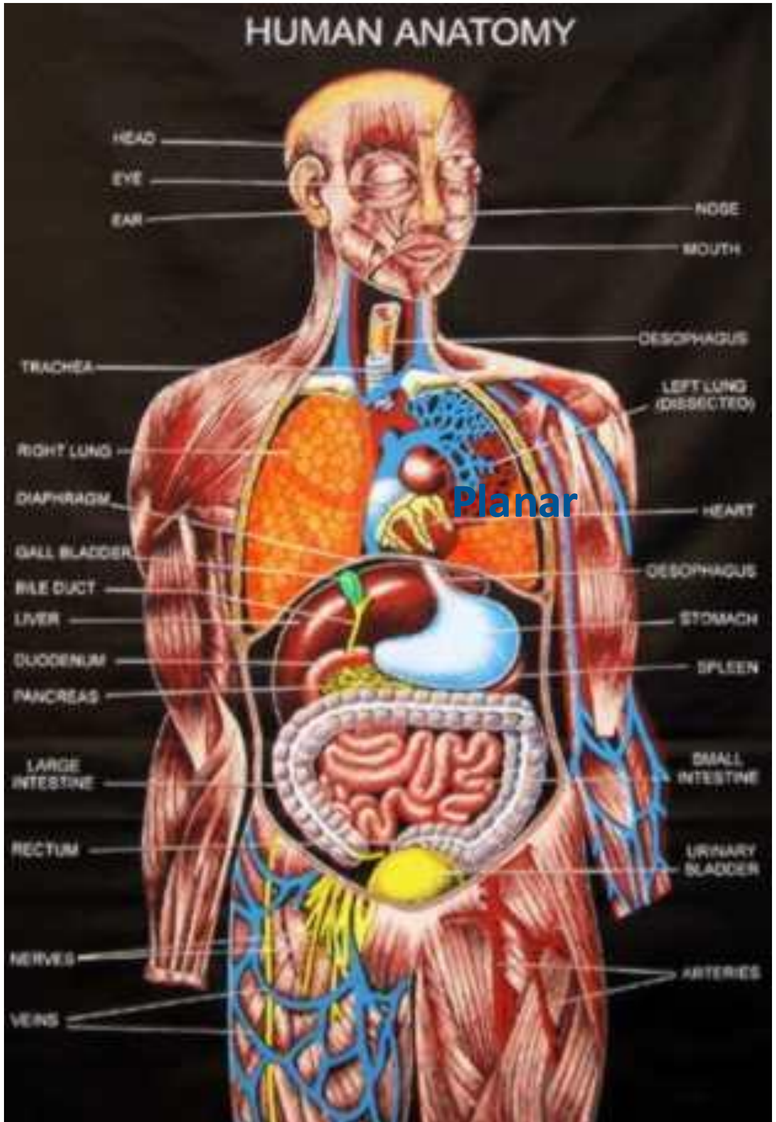


X-ray fluorescence Computed Tomography (XFCT)

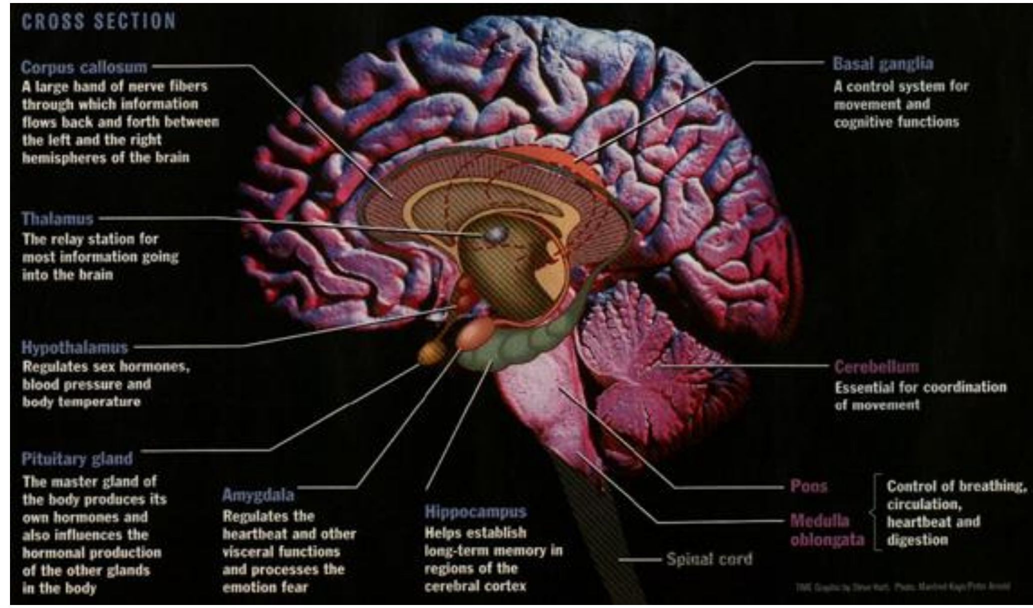
Basic Ideas Behind Radiological Imaging:

III: Structural Imaging vs. Functional Imaging

What Can We See With X-ray CT?

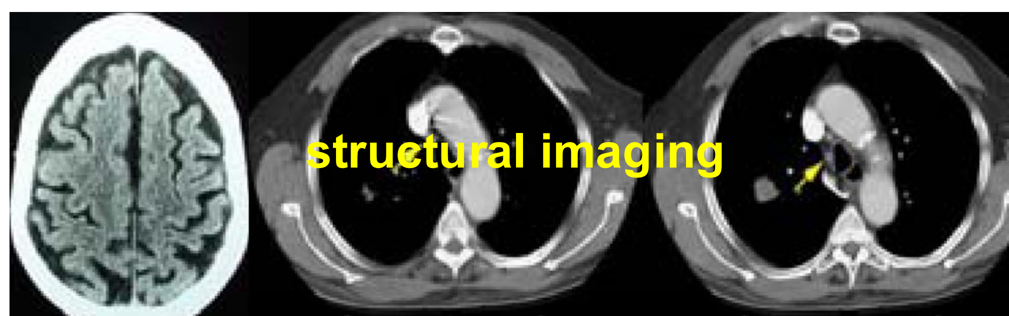


http://fanz.dvrlists.com/about-human-anatomy/



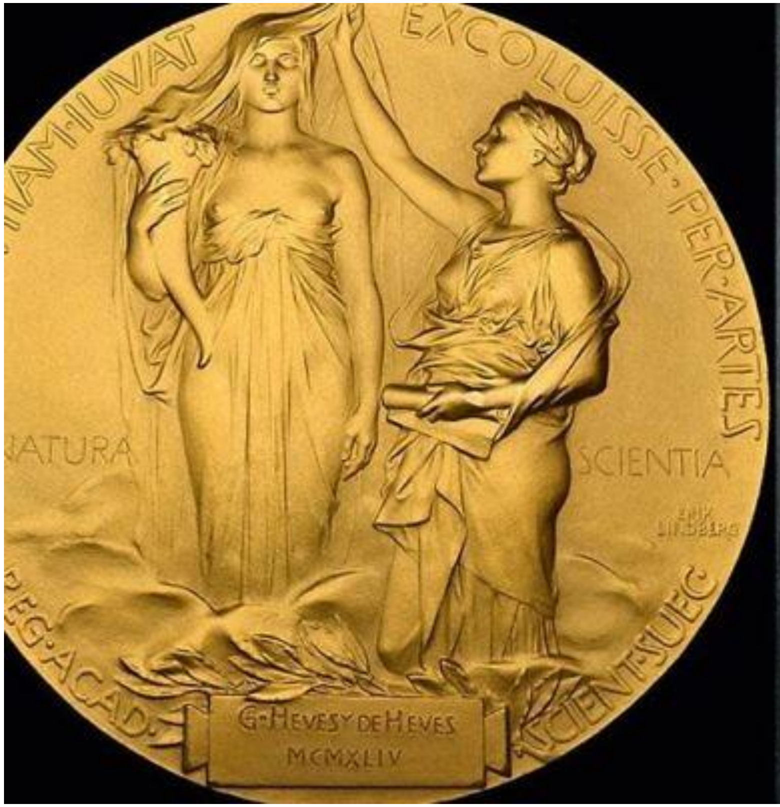
interior of the brain

http://www.indiana.edu/~busey/Q301/BrainStructure.html



The Tracer Principle

George de Hevesy, who received the Nobel Prize in Chemistry in 1943.

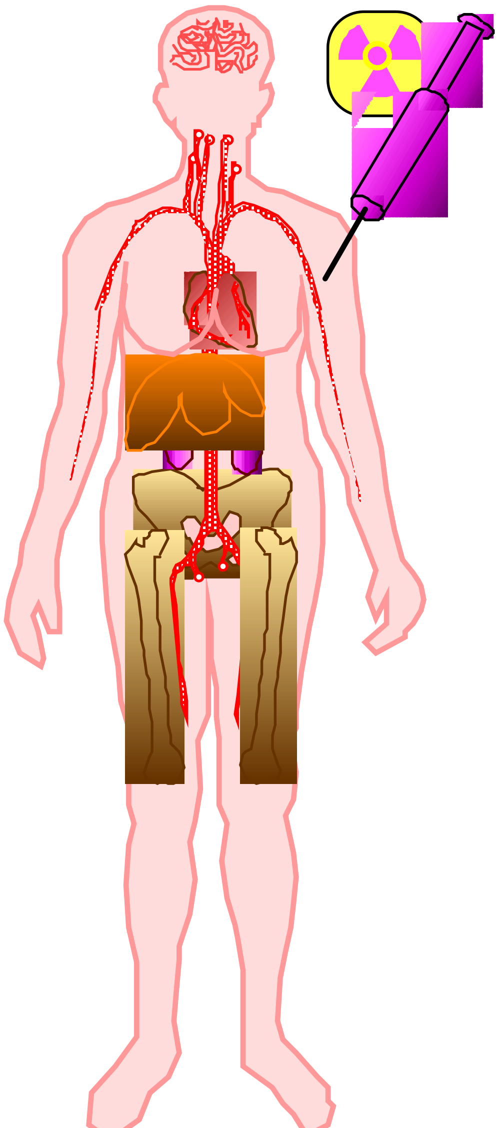


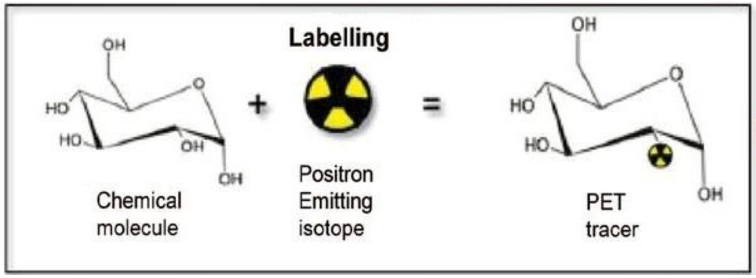
What is the Tracer Principle?

What is the tracer principle?

- Appropriately chosen radioactive compounds participate in an organism's physiological processes in the same way as non-radioactive materials.
- These compounds can be detected through the detection of their radiation signatures, such as gamma rays.

Emission Tomography



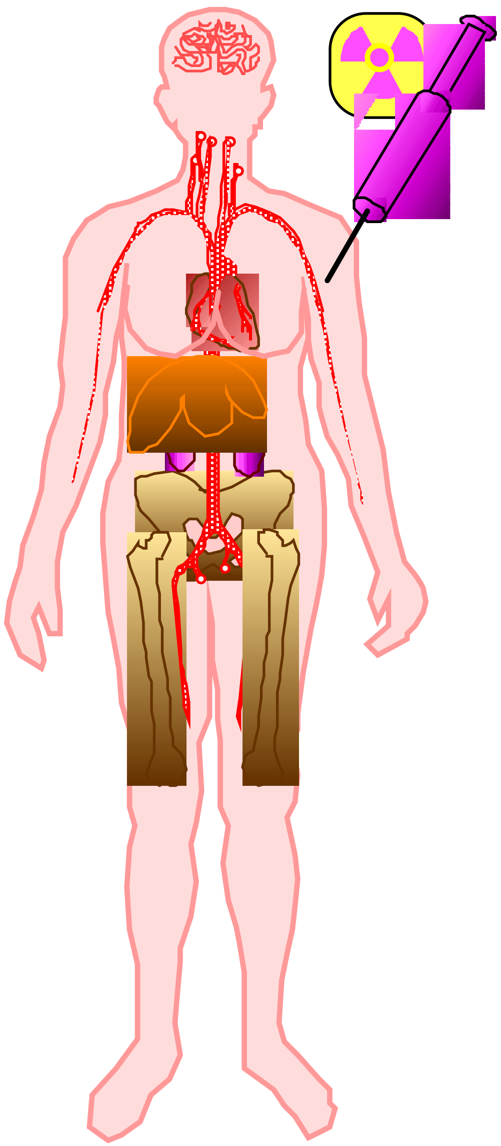


- Drug is labeled with radioisotopes that emit gamma rays.
- Drug localizes in patient according to metabolic properties of that drug.
- Trace (pico-molar) quantities of drug are sufficient.
- Radiation dose fairly small (<1 rem).

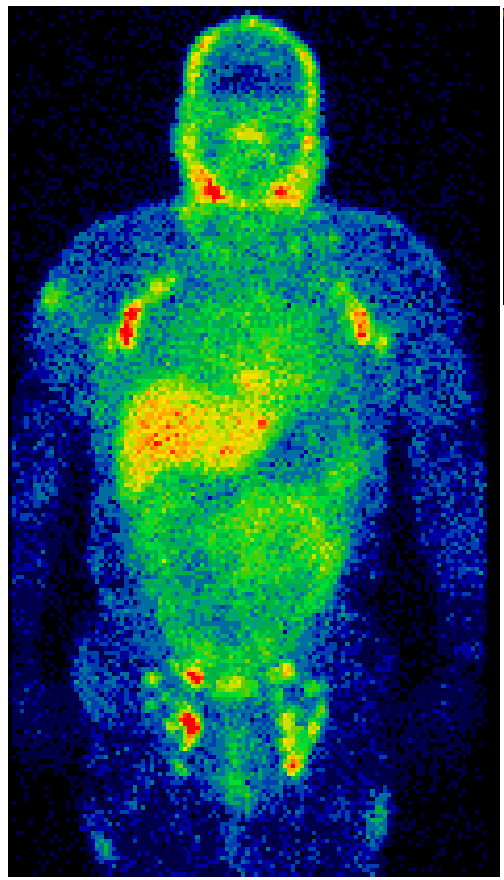
Drug Distributes in Body

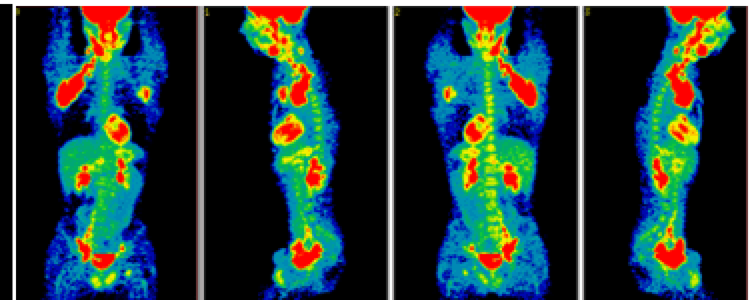
Above illustration from Dr. William Moses

Emission Tomography



Above illustration from Dr. William Moses



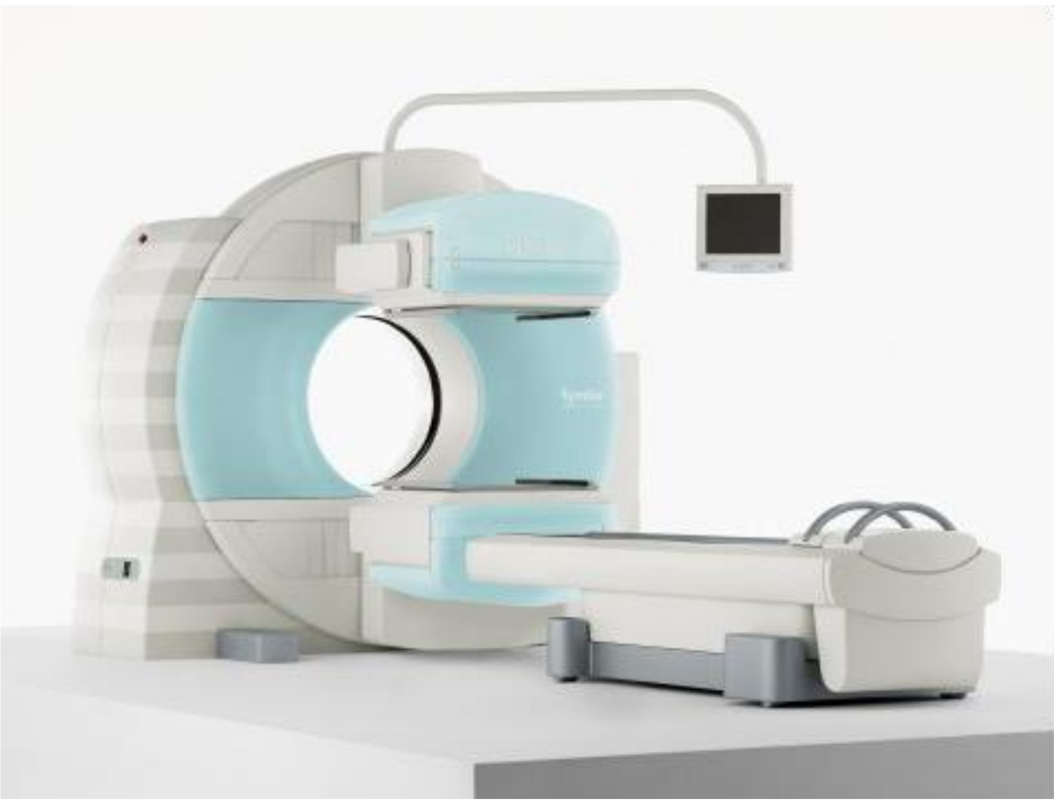


(Left and above) Typical emission tomography images

Is there anything that we do not like??

http://imaging.cancer.gov/patientsandproviders/cancerimaging/nuclearimaging

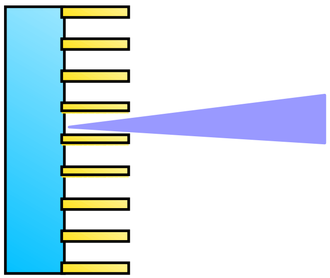
Single Photon Emission Computed Tomography (SPECT)



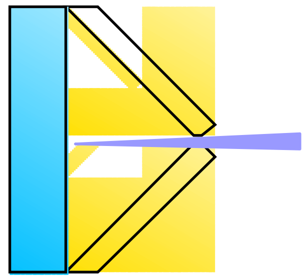
Siemens Symbia SPECT/CT

Philips Precedence SPECT/CT

Single Photon Emission Computed Tomography (SPECT)



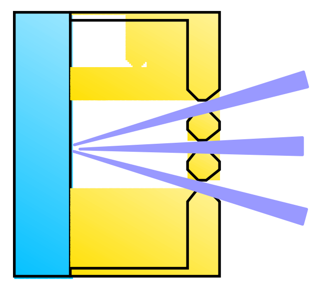
Collimator



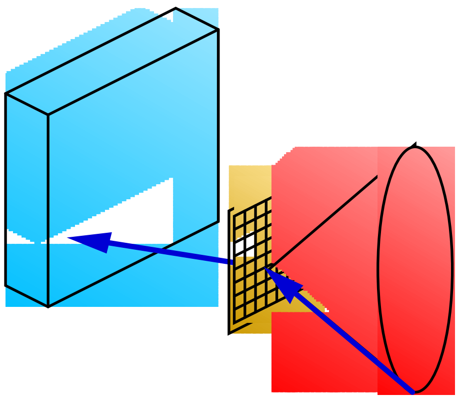
Pinhole

Collimator in front of the detector to select gamma rays from certain directions only …

Rotated around the object for collecting multiple projections …

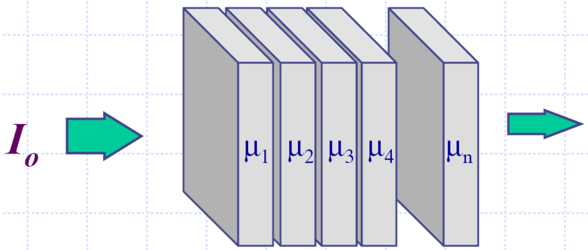


Coded Aperture



Compton

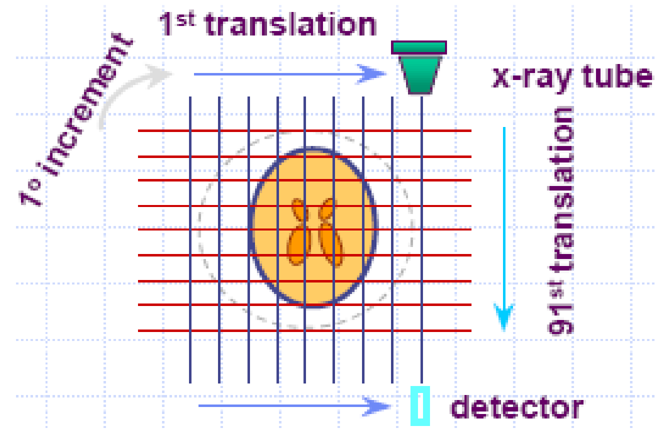
Single Photon Emission Computed Tomography (SPECT)

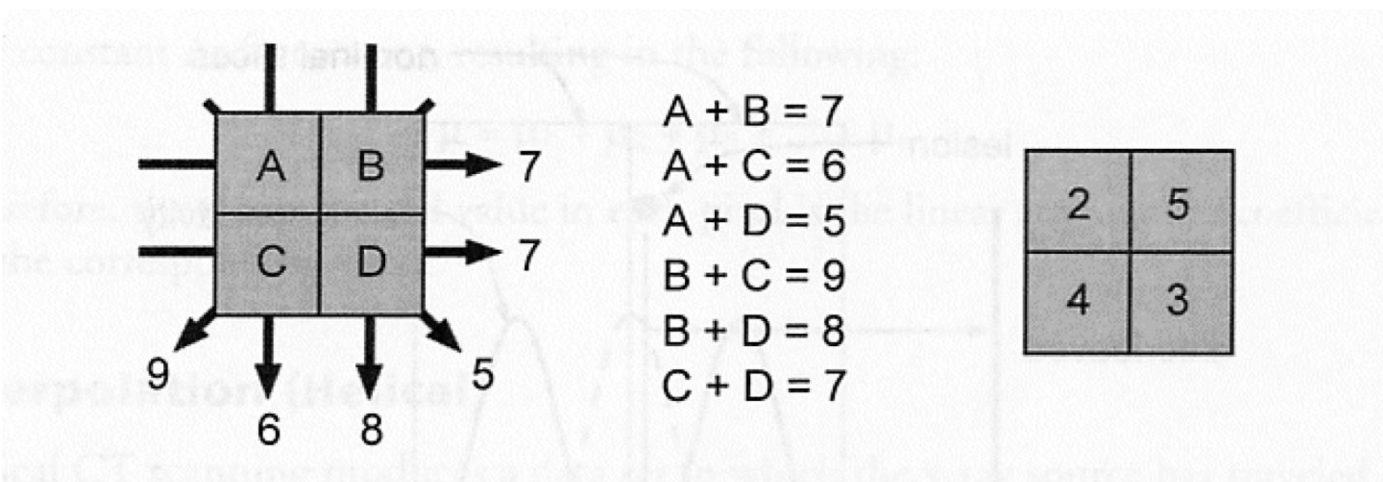


$$I = I_o e^{-\mu_1 \Delta x} e^{-\mu_2 \Delta x} \cdots e^{-\mu}$$

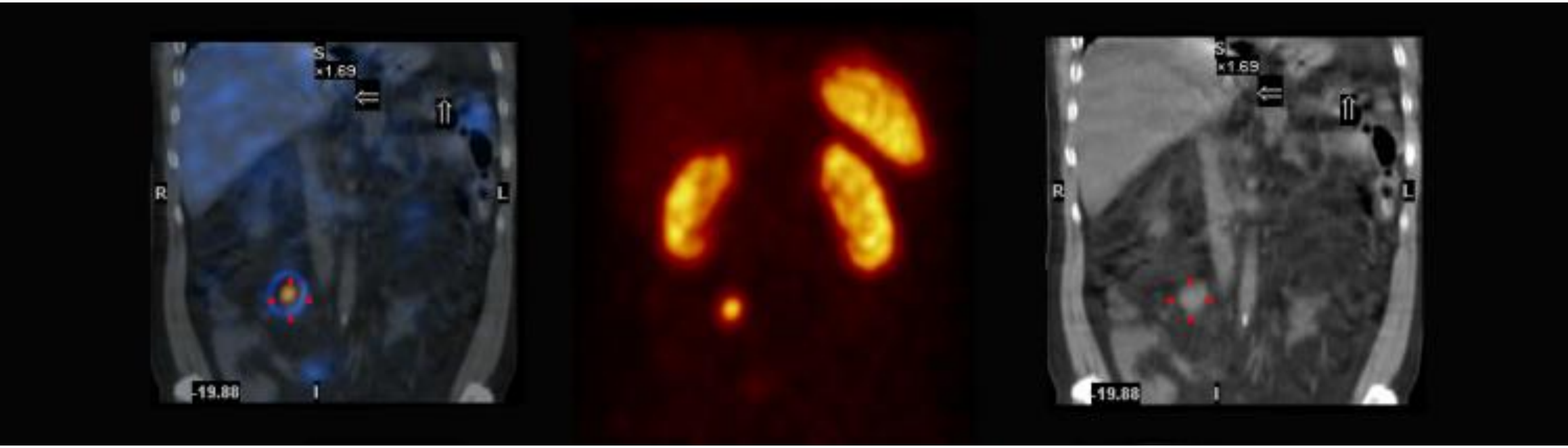
$$= I_o e^{-(\mu_1 + \mu_2 + \cdots + \mu_n)\Delta x}$$

$$\Delta x \rightarrow 0, \qquad P = -\ln\left(\frac{I}{I_o}\right) = \int_{-\infty}^{\infty} \mu(x)\,dx$$





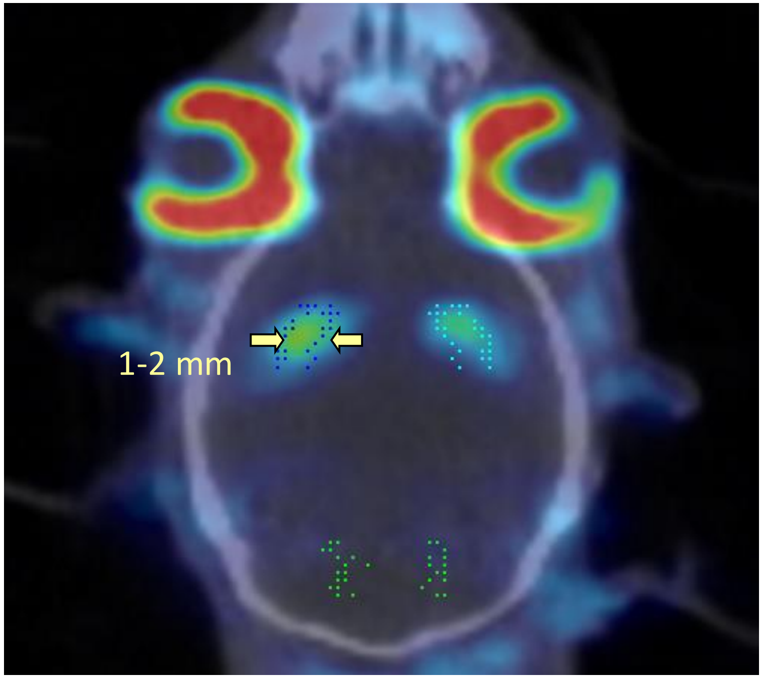
Single Photon Emission Computed Tomography (SPECT)



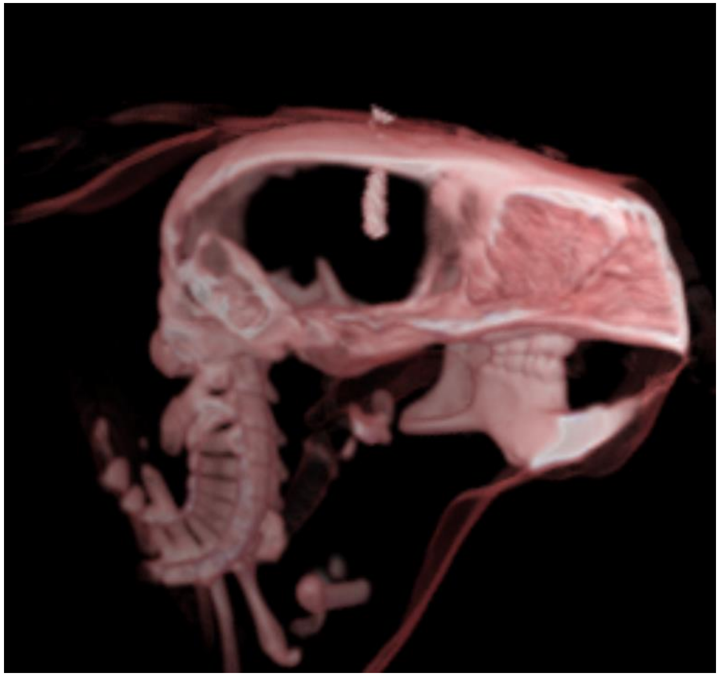
Endocrine tumor visualized with a commercial SPECT system.

http://images.google.com/imgres?imgurl=http://www.gehealthcare.com/euen/fun_img/products/nuclear_medicine/images

Application of SPECT for Small Animal Studies



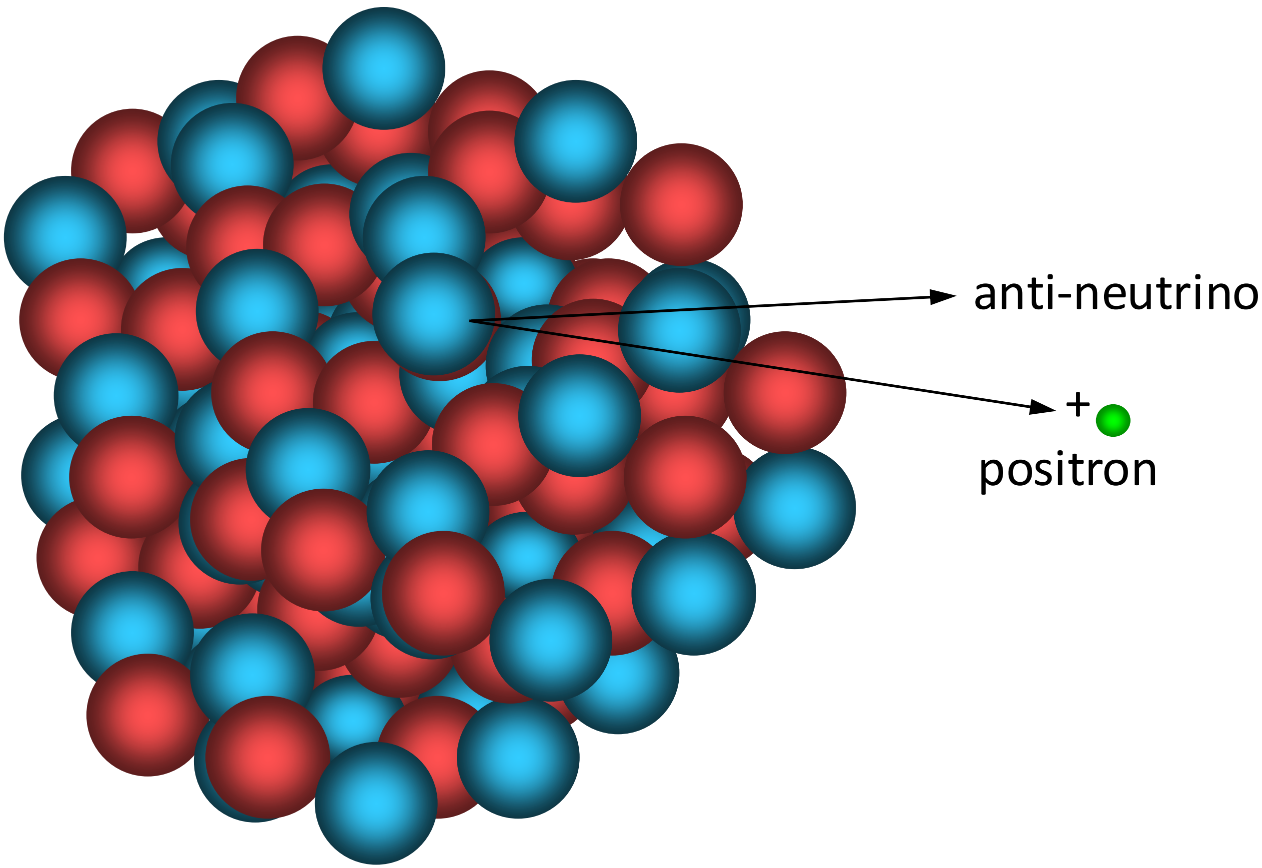
Imaging of dopamine transporter in mouse brain



In vivo tracking of radiolabeled T cells in mouse brain.

Positron Decay

Neutron-deficient isotopes can decay by emitting positrons – β^+ decay



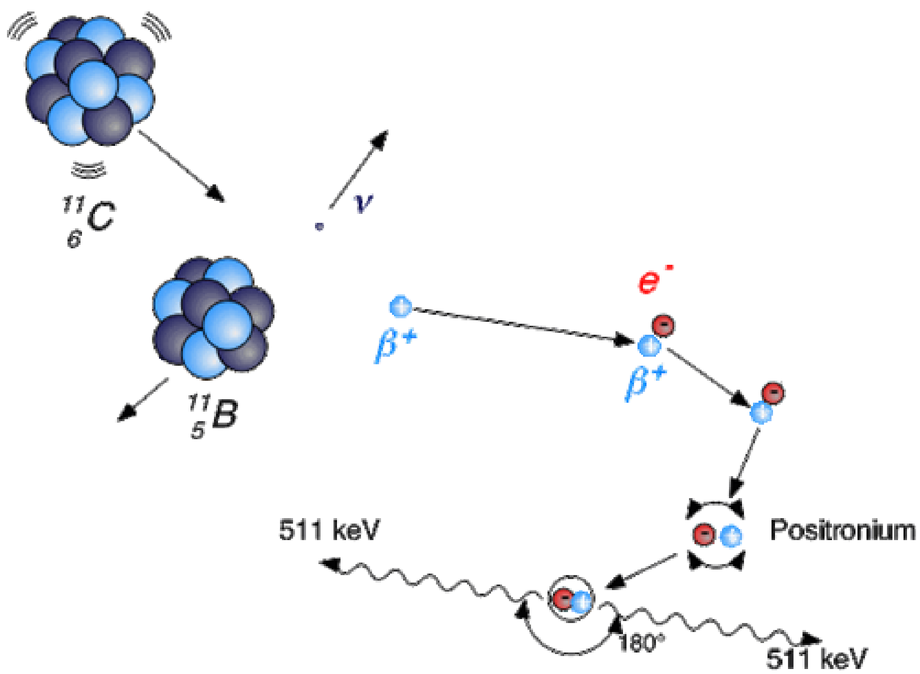
Net effect: one proton replaced by

- neutron
- anti-neutrino
- positron

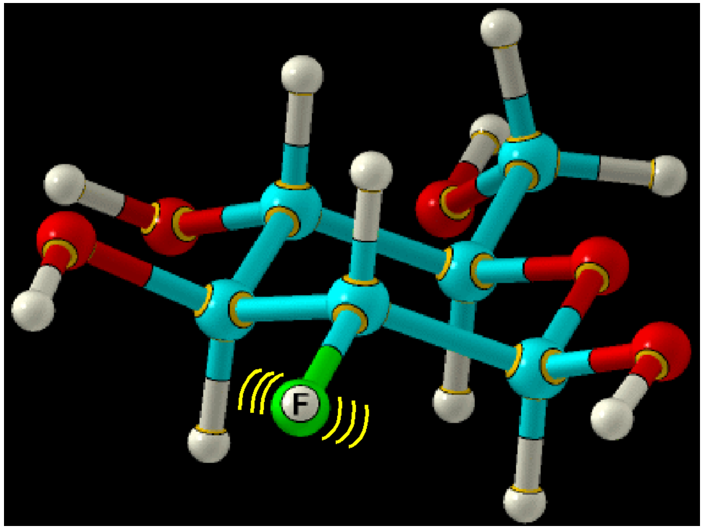
Positron Emission, Positron Annihilation, and Gamma Ray Emission Processes

Beta-plus decay or positron decay:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \upsilon$$

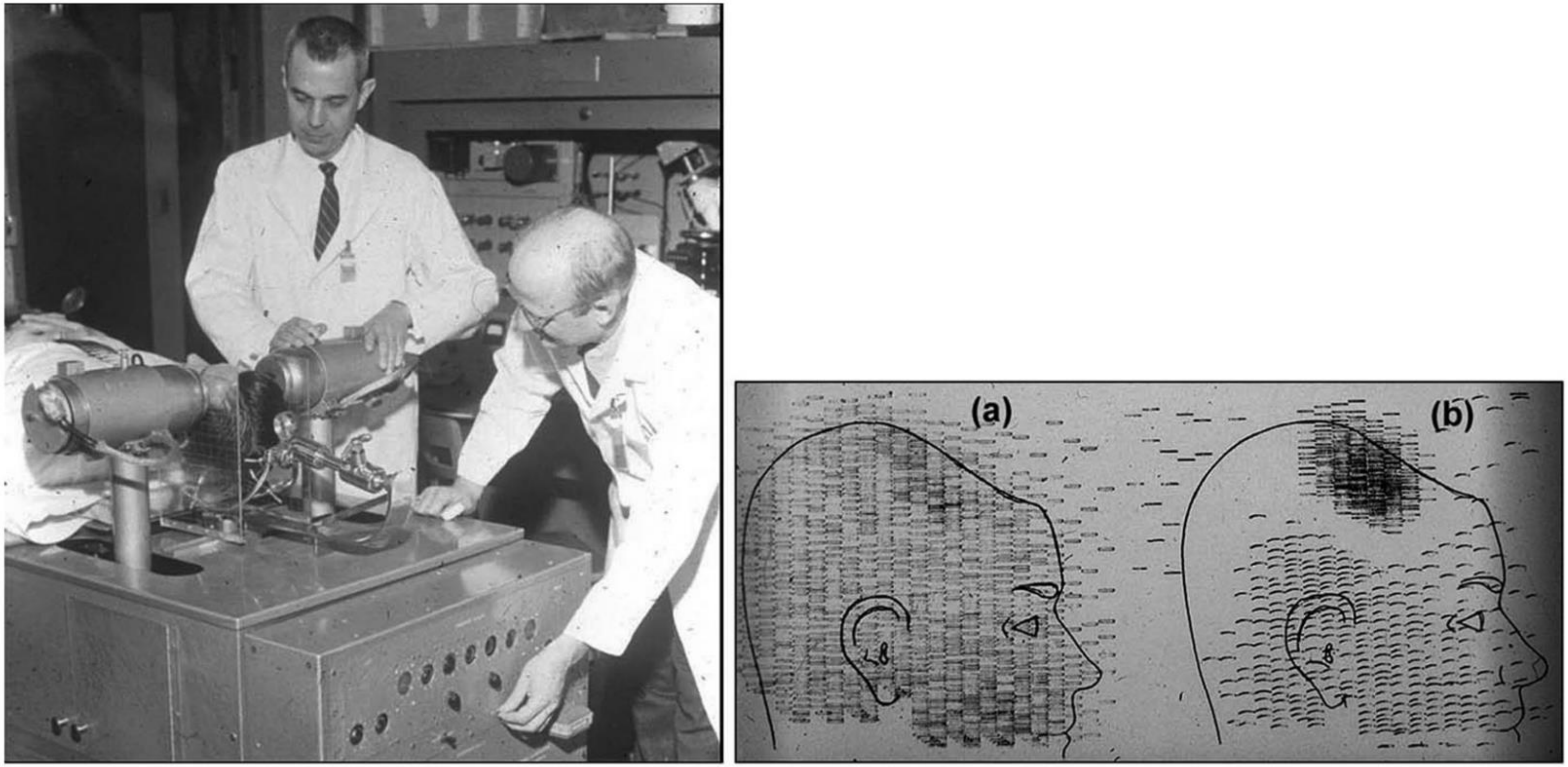


Example of positron annihilation



Radiolabeling

Positron Emission Tomography

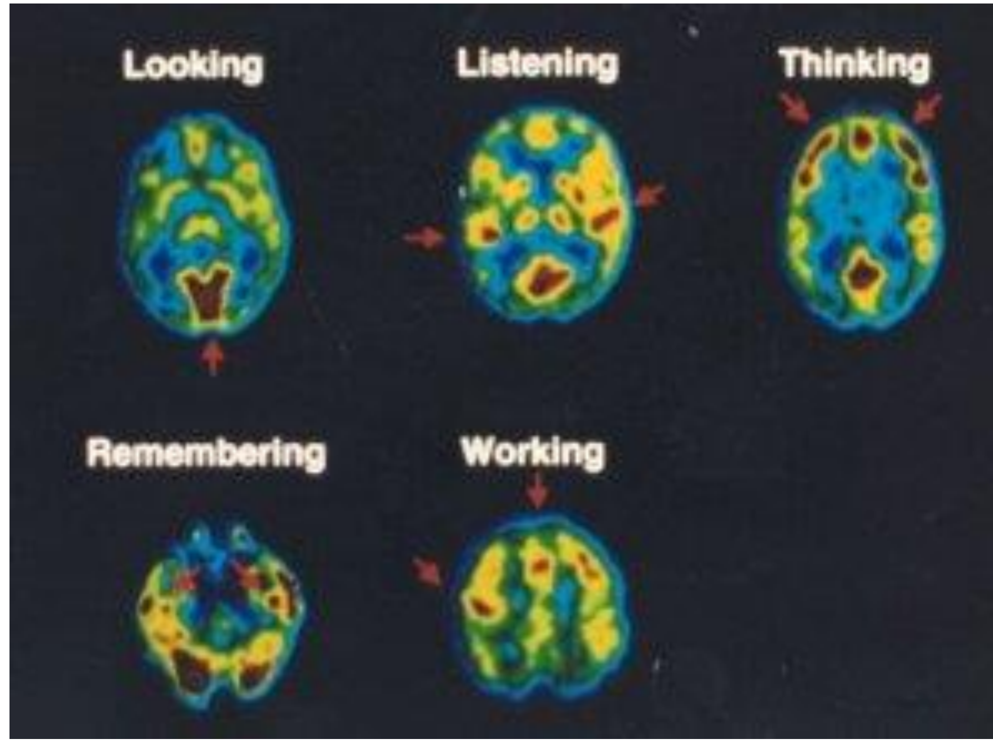


(A) (B)

Fig 1 (A) First clinical positron imaging device developed in 1953 by Dr. Brownell (left) and Dr. Aronow (right), and (B) the coincidence and unbalance scans of patient with recurring brain tumor. The coincidence scan (a) of a patient showing recurrence of a tumor under the previous operation site, and unbalance scan (b) showing asymmetry to the left. G. L. Brownell and W. H. Sweet, “Localization of brain tumors with positron emitters,” Nucleonics 11(11), 40–45 (1953).

Clinical Applications of PET – Functional Brain Imaging

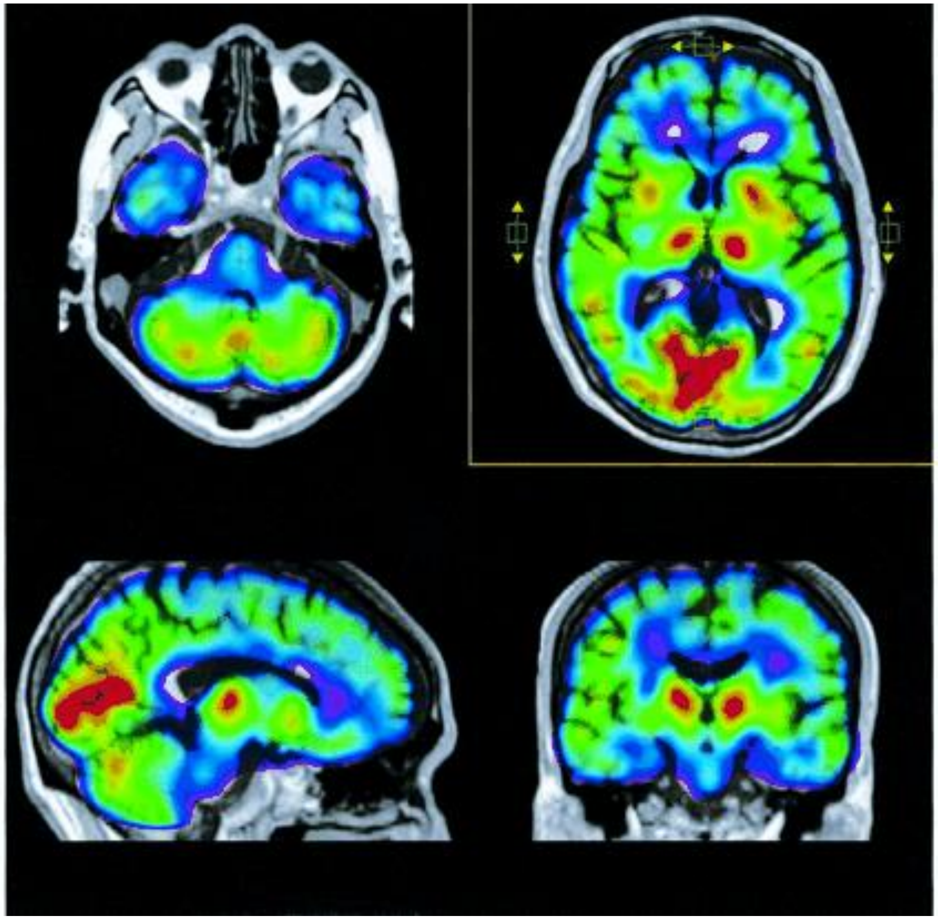
PET Scan



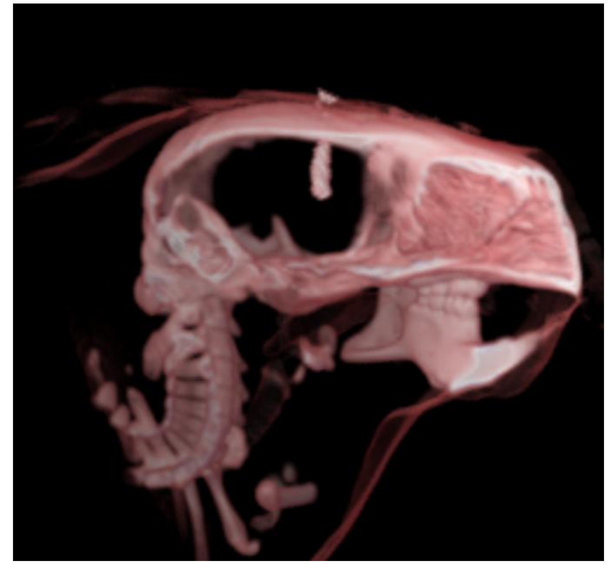
Functional Brain Imaging with Fluorodeoxyglucose (FDG)

http://www.osti.gov/accomplishments/pet.html

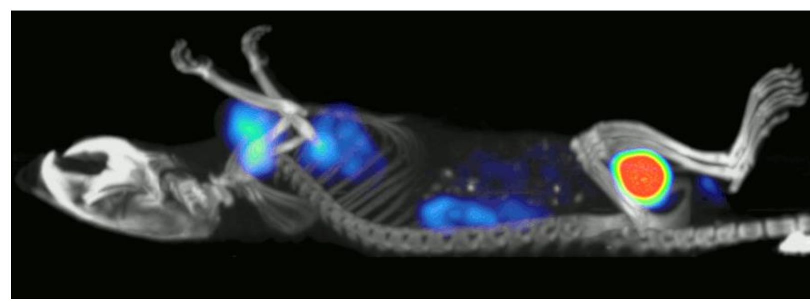
SPECT/CT Images



T. Pfluger et al, *Radiology,* vol. 217, pp. 453-454, 2000.

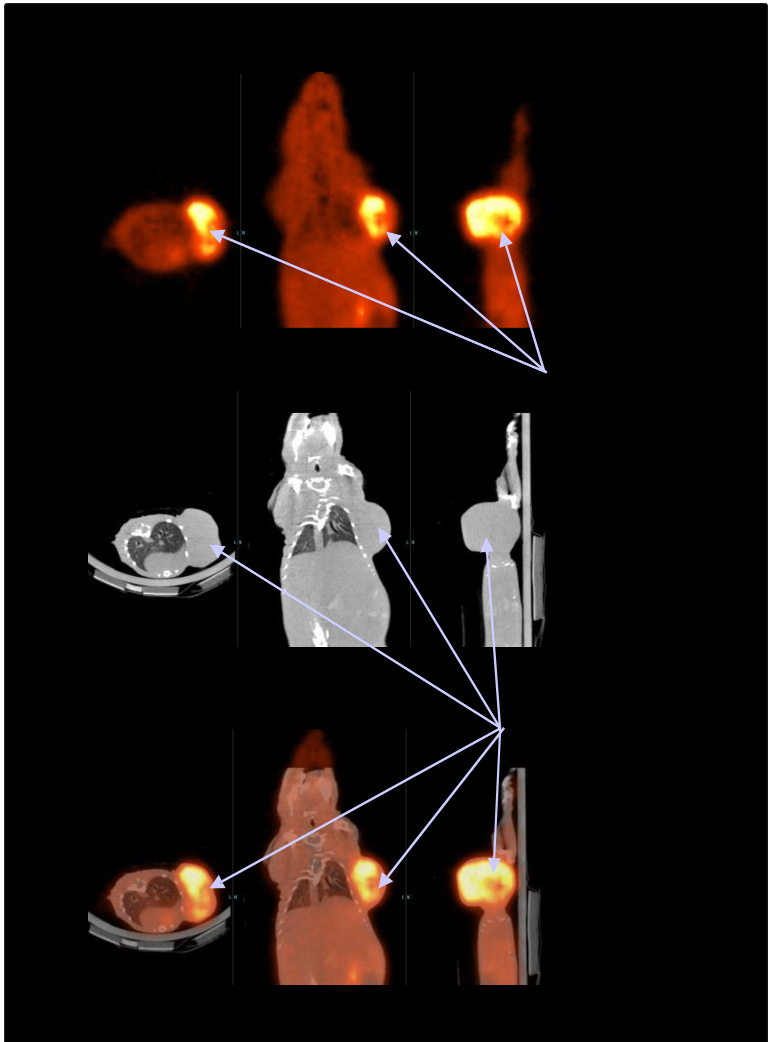


Fused SPEM/CT image of a mouse's brain. Two groups (5μL and 0.3μL) of radiolabeled T cells are visible in the brain. Meng et al, NIM, 2009.



^{99m}Tc-Labeled RGD Dimers and Tetramer in Tumor-Bearing Mice, Image courtesy Shuang Liu

Why Combine PET/SPECT with MRI



- Large variety of PET/SPECT tracers
- Sensitivity of PET/SPECT is in the pico-molar range
- MR delivers exquisite soft tissue contrast, and functional imaging capabilities (spectroscopy, fMRI)
- No additional radiation dose (from CT) Simultaneous imaging of PET and MRI
  - Reduced total acquisition time
  - Image multiple dynamic processes
  - Use MRI to correct for motion in PET data

Martin S. Judenhofer, Seminars in Nuclear Medicine

Why Combine PET/SPECT with MRI

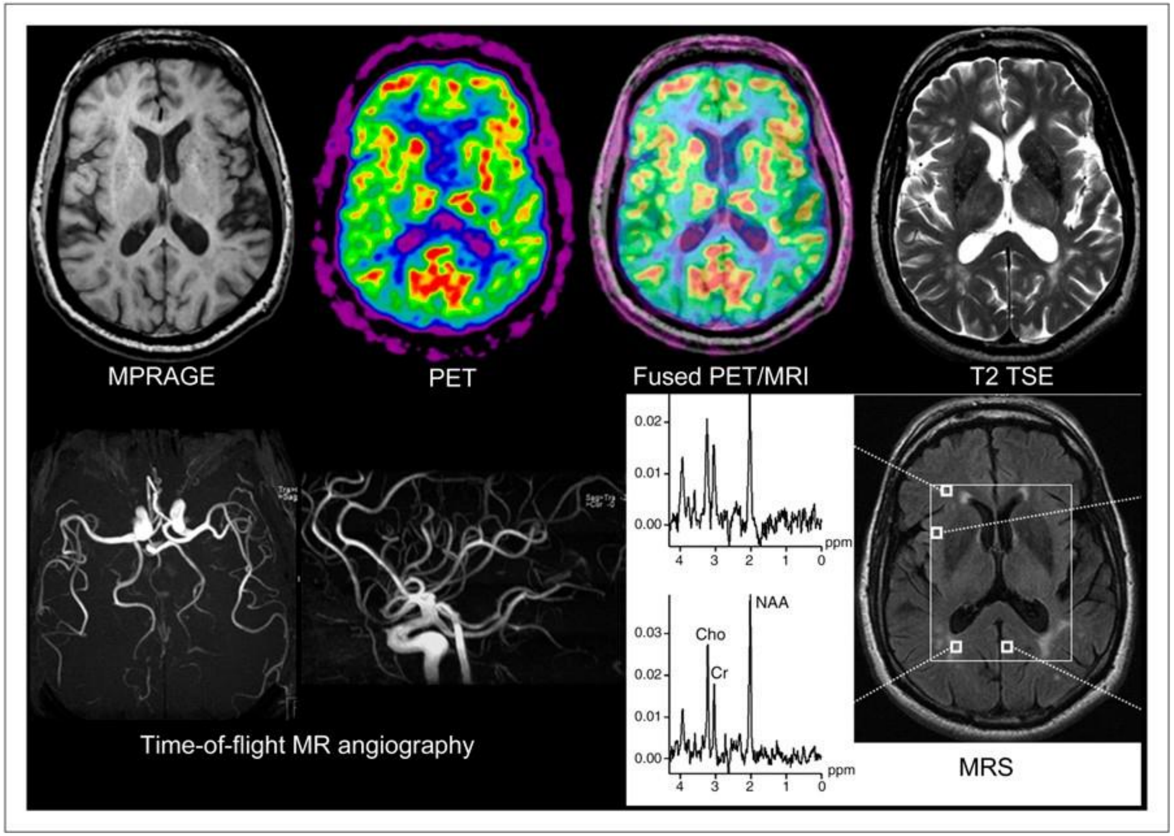
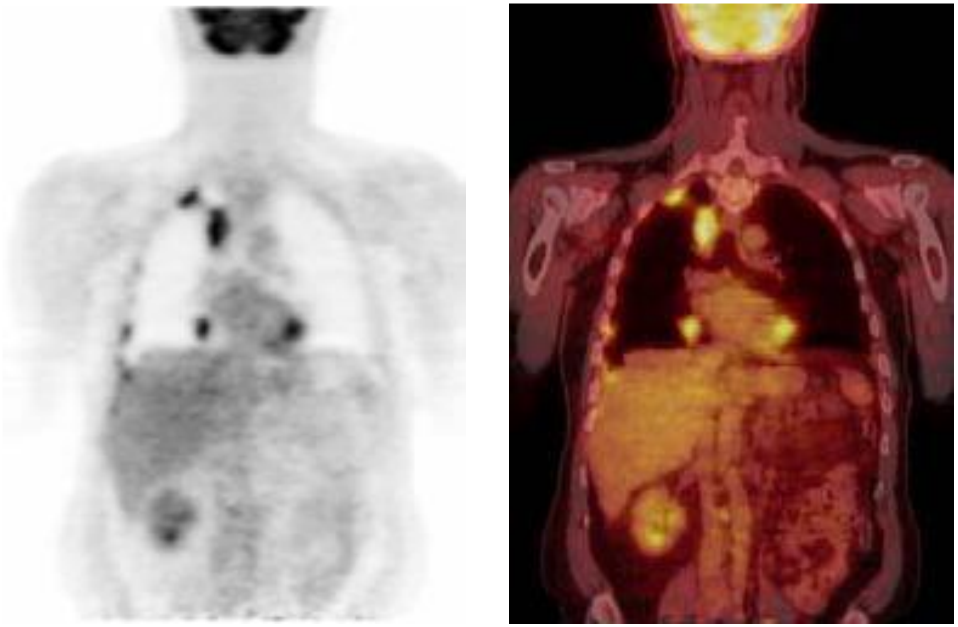


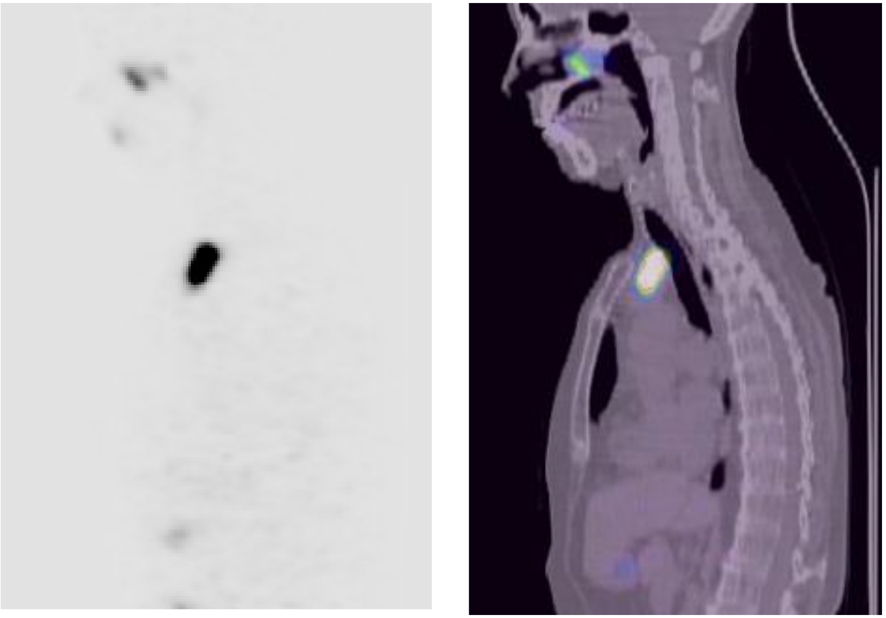
FIGURE 1. First simultaneous PET/MRI study in 66-y-old healthy volunteer. MRI sequences included T2-weighted turbo spin echo, echo planar, time-of-flight MR angiog- raphy, and MR spectroscopy. PET image displayed was reconstructed from 20-min emission data recorded at steady state after injection of 370 MBq of 18F-FDG. Data were acquired on BrainPET prototype (Siemens). MPRAGE 5 magnetization-prepared rapid gradient echo; MRS 5 MR scintigraphy; TSE 5 turbo spin echo. (Ciprian Catana et al, Journal of Nuclear Medicine, 2012)

Clinical Applications of PET – Diagnosis of Cancer

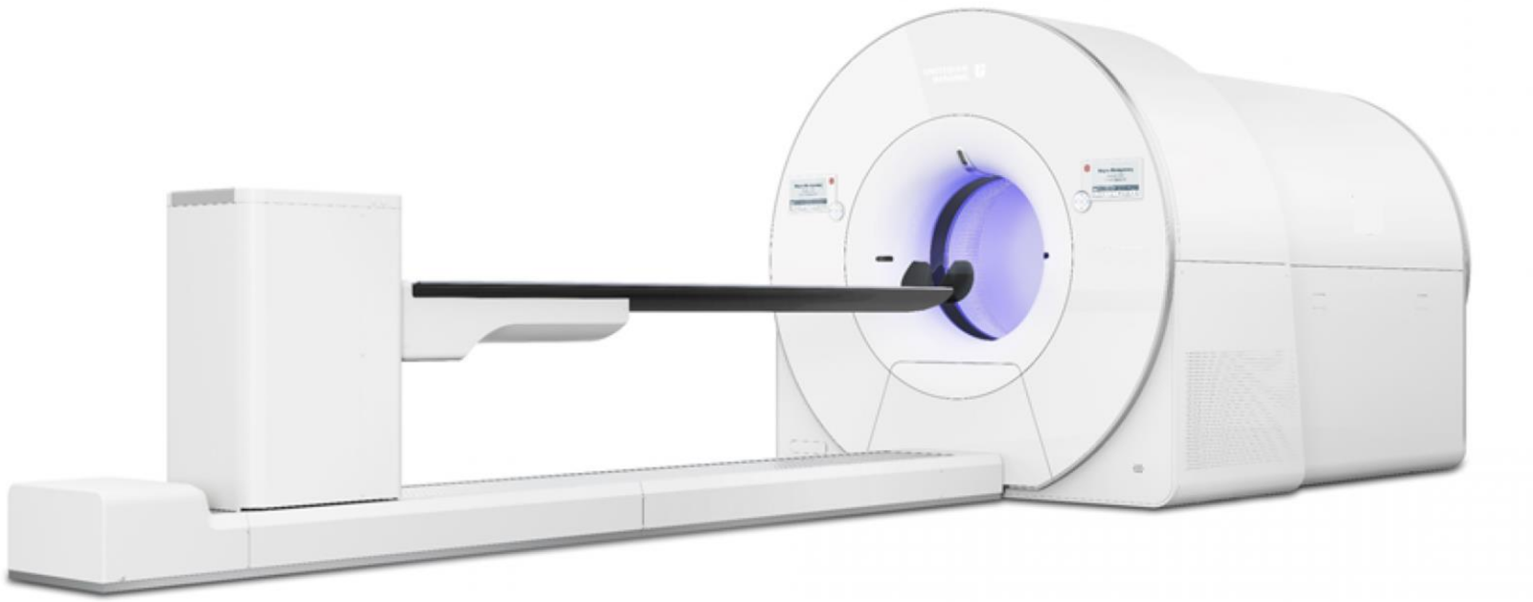


FDG study: lung or ribs?

I-124 study: bone or soft tissue?



Clinical Applications of PET – Diagnosis of Cancer

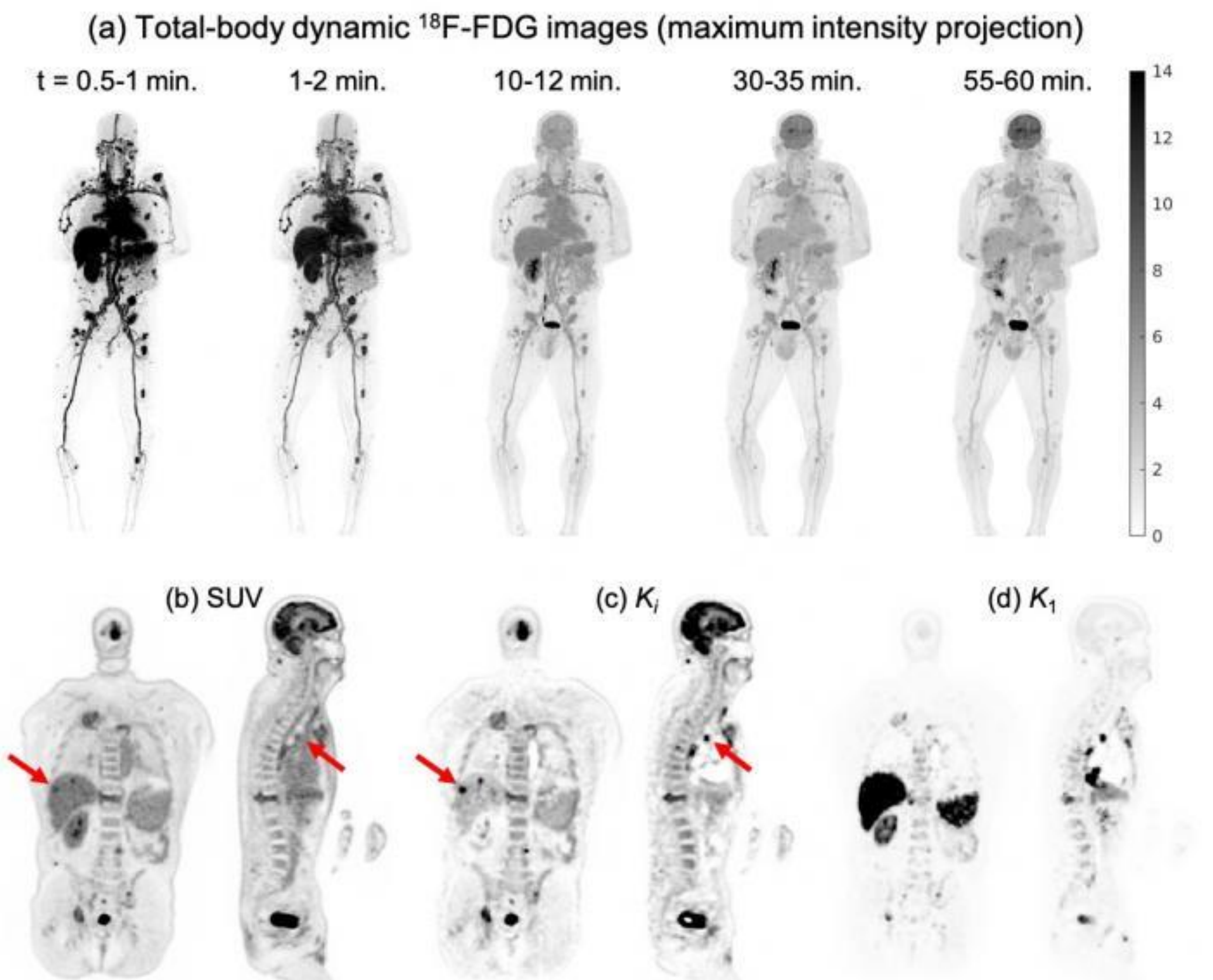


The Explorer whole-body PET scanner developed by UC Davis and United Imaging

https://explorer.ucdavis.edu/

Total-body dynamic 18F-FDG PET imaging with the uEXPLORER scanner

News Release from the SOCIETY OF NUCLEAR MEDICINE AND MOLECULAR IMAGING



Autoradiography

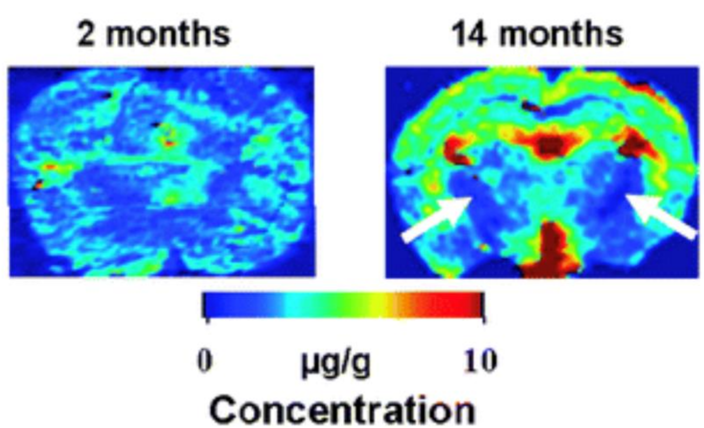
View PDF Version | Previous Article | Next Article

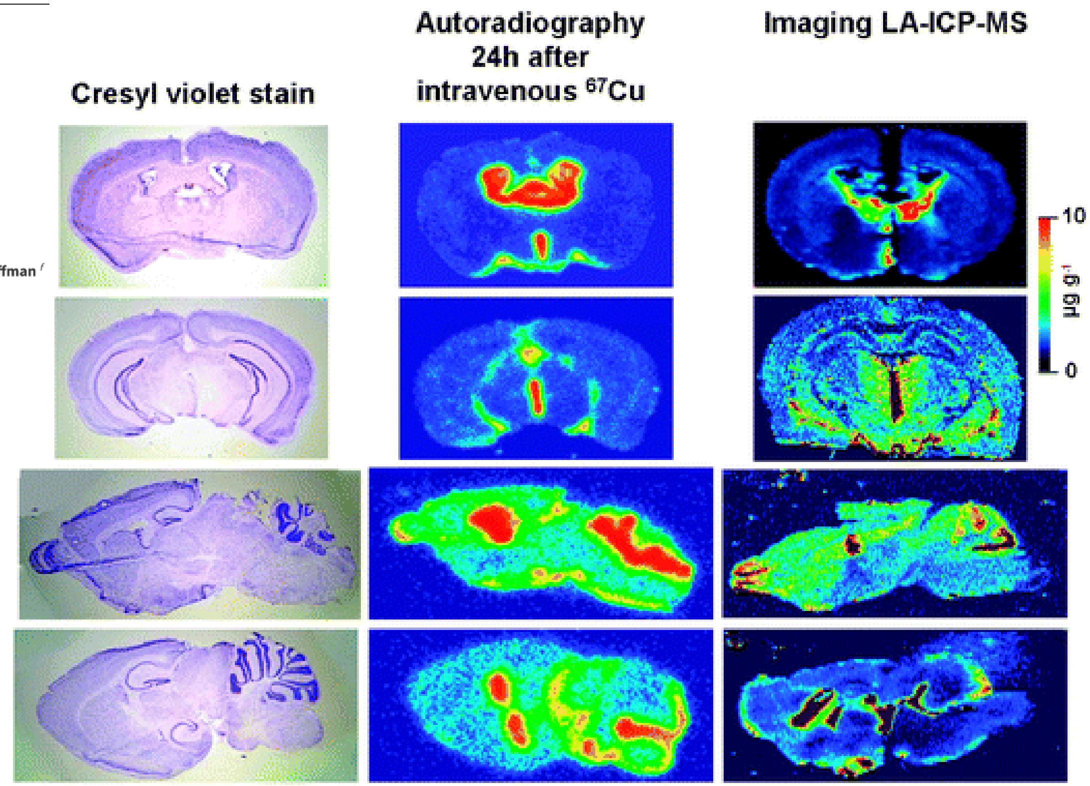
DOI: 10.1039/C003875J (Paper) *Metallomics*, 2010, **2**, 348-353

Show Chemical Terms | Show Biomedical Terms

Bioimaging of copper alterations in the aging mouse brain by autoradiography, laser ablation inductively coupled plasma mass spectrometry and immunohistochemistry

Li-Ming Wang [a], J. Sabine Becker *[b], Qi Wu [a], Marcus F. Oliveira [c], Fernando A. Bozza [d], Andrea L. Schwager [e], John M. Hoffman [f] and Kathryn A. Morton [a]





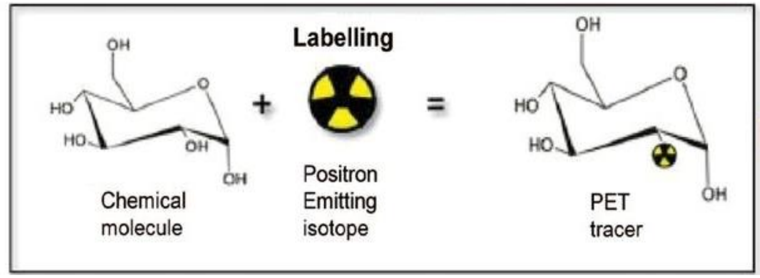
Autoradiography

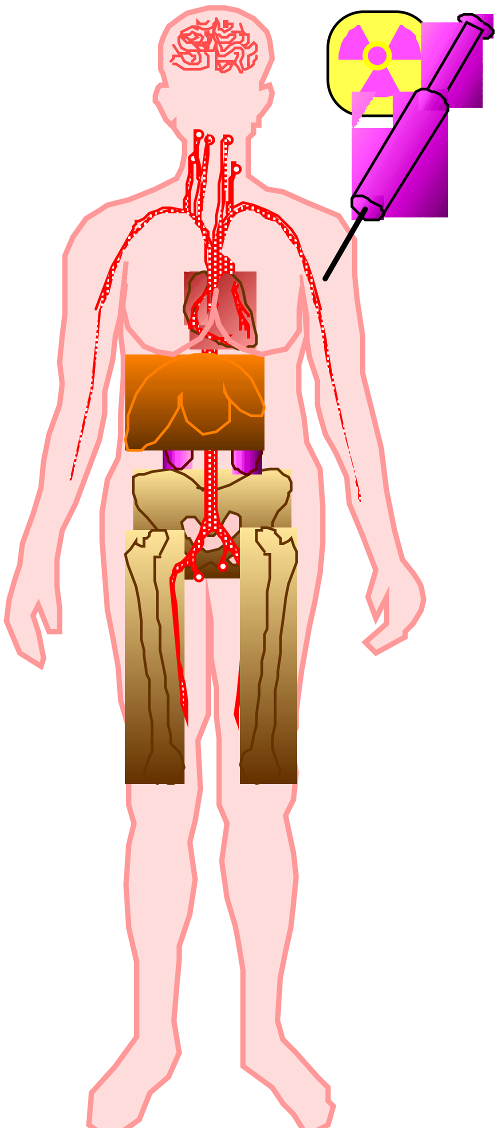
Autoradiography
with ^{14}C, ^{3}H, ^{35}S, ^{125}I labeled tracers

Basic Ideas Behind Radiological Imaging:

IV: Limitations of Emission Tomography and Potential Ways to Improve?

Emission Tomography

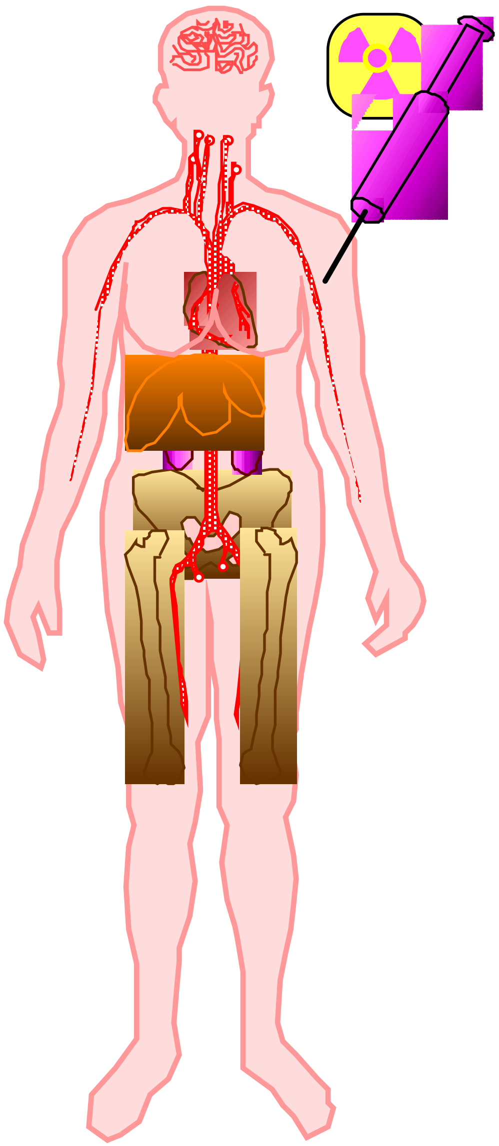


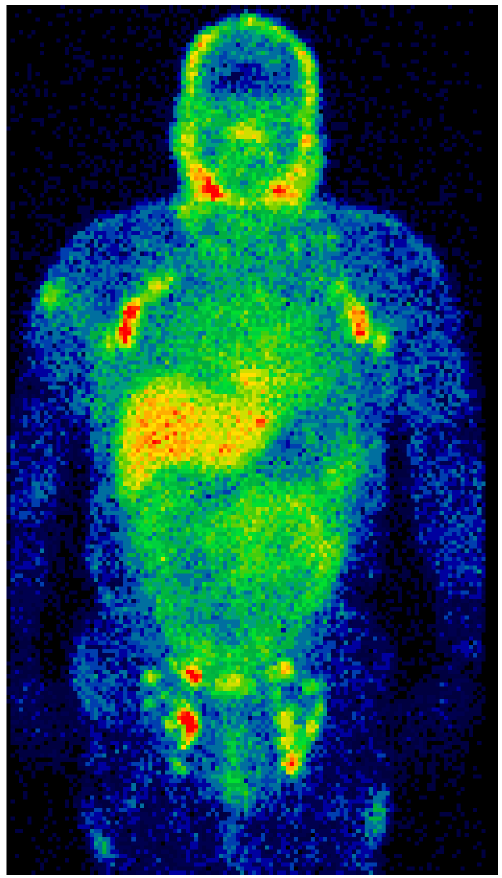


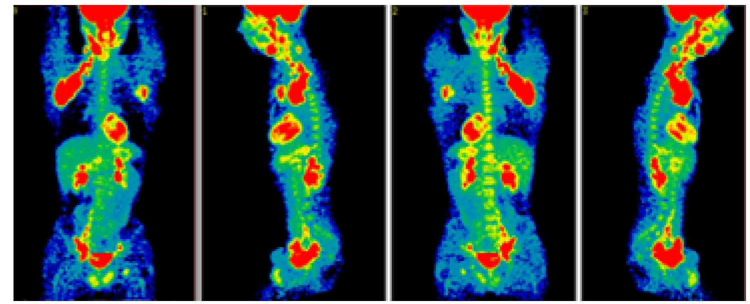
- Drug is labeled with radioisotopes that emit gamma rays.
- Drug localizes in patient according to metabolic properties of that drug.
- Trace (pico-molar) quantities of drug are sufficient.
- Radiation dose fairly small (<1 rem).

Drug Distributes in Body

Emission Tomography





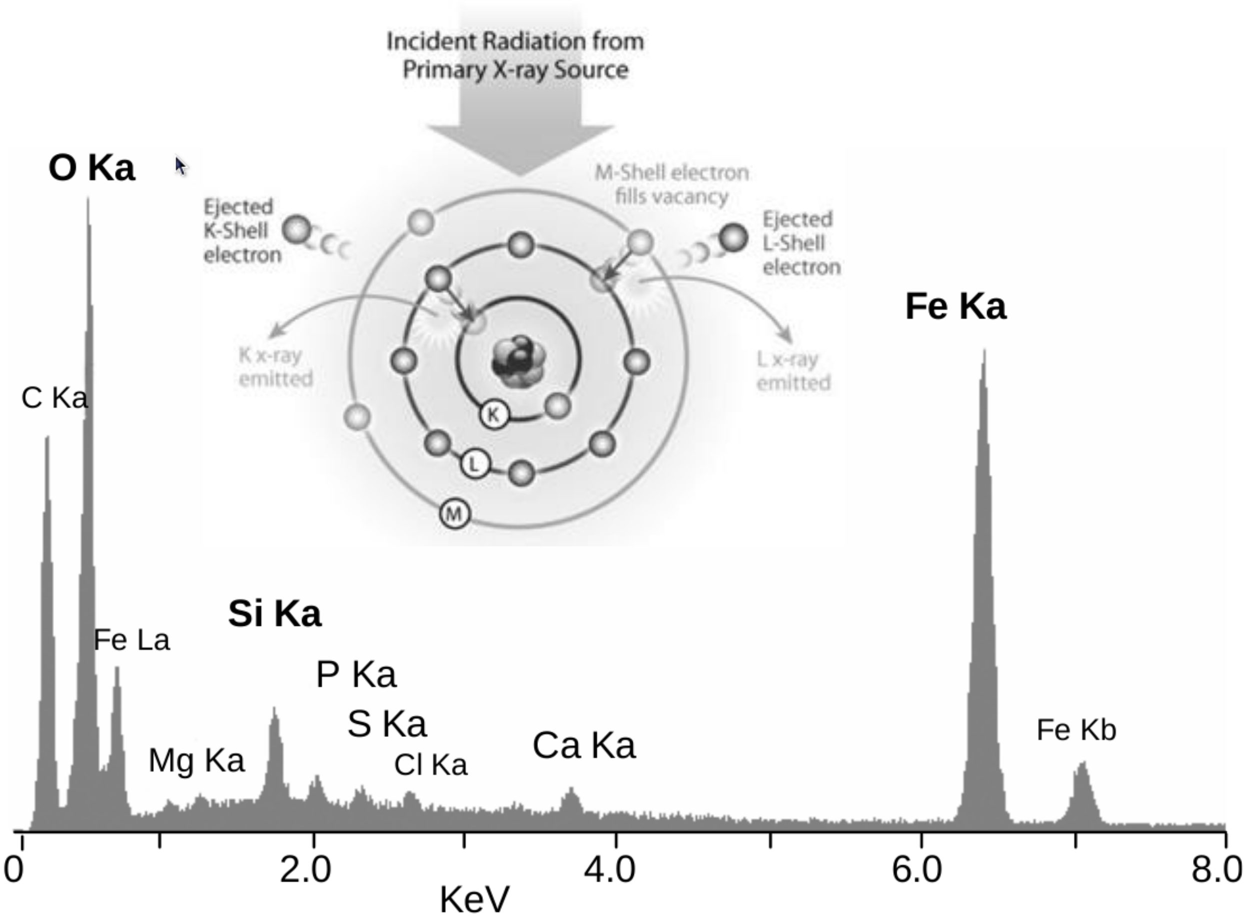


(Left and above) Typical emission tomography images

Is there anything that we do not like??

http://imaging.cancer.gov/patientsandproviders/cancerimaging/nuclearimaging

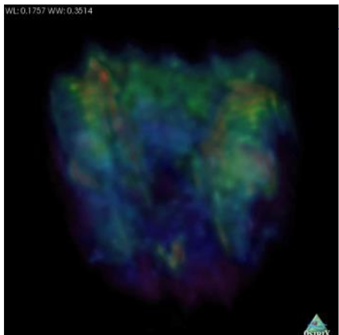
X-ray Fluorescence Emission



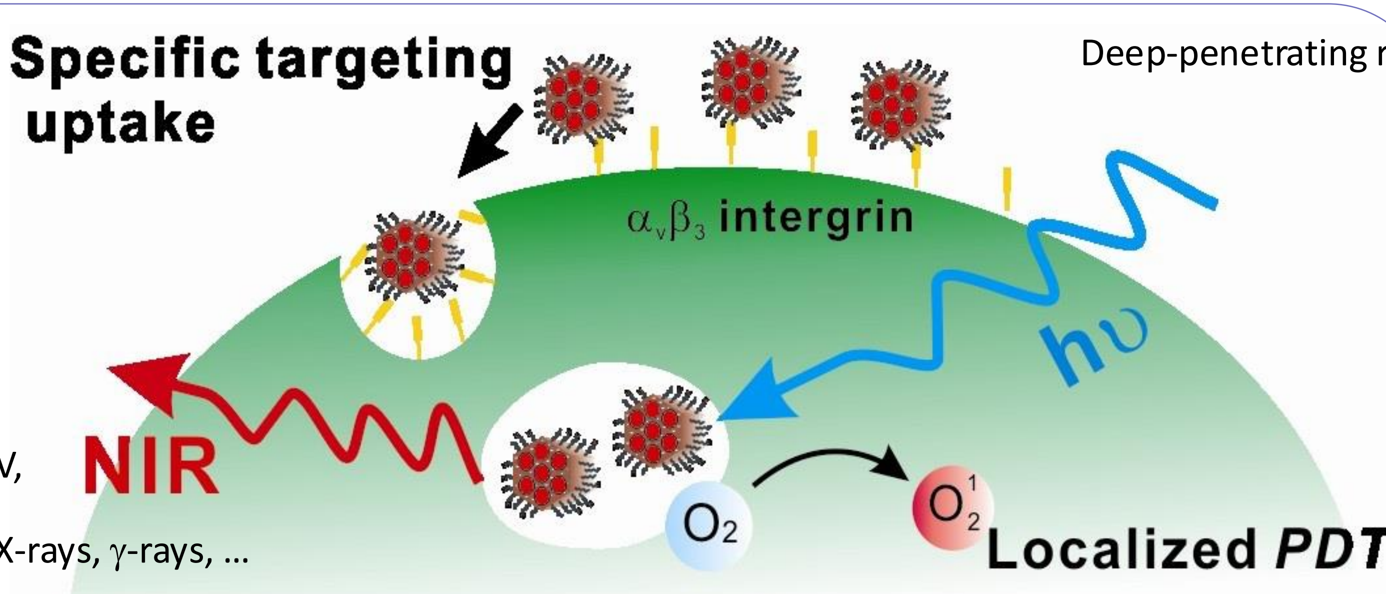
Re-Engineering the Way that Ionizing Radiation Interacting with Tissue

Combined chemical and physical targeting ?

Nano-materials that preferably receive radiation and react in various ways ?



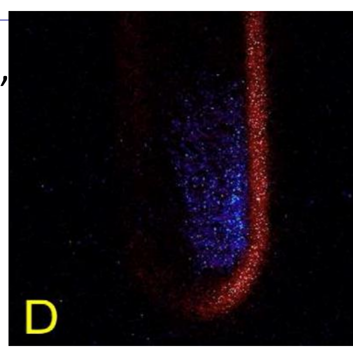
Deep-penetrating radiation



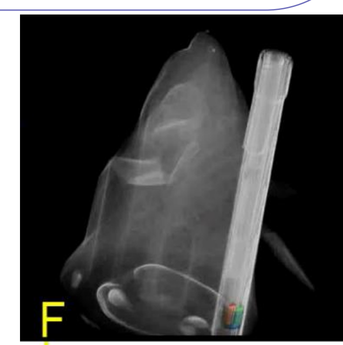
UV,

X-rays, γ-rays, ...

Imaging, Sensing, Detection



Precisely modulate therapeutic delivery ?



Center figure from L-W Luo, Dept. Radiology, U Chicago

X-ray Fluorescence Emission Tomography (XFET)

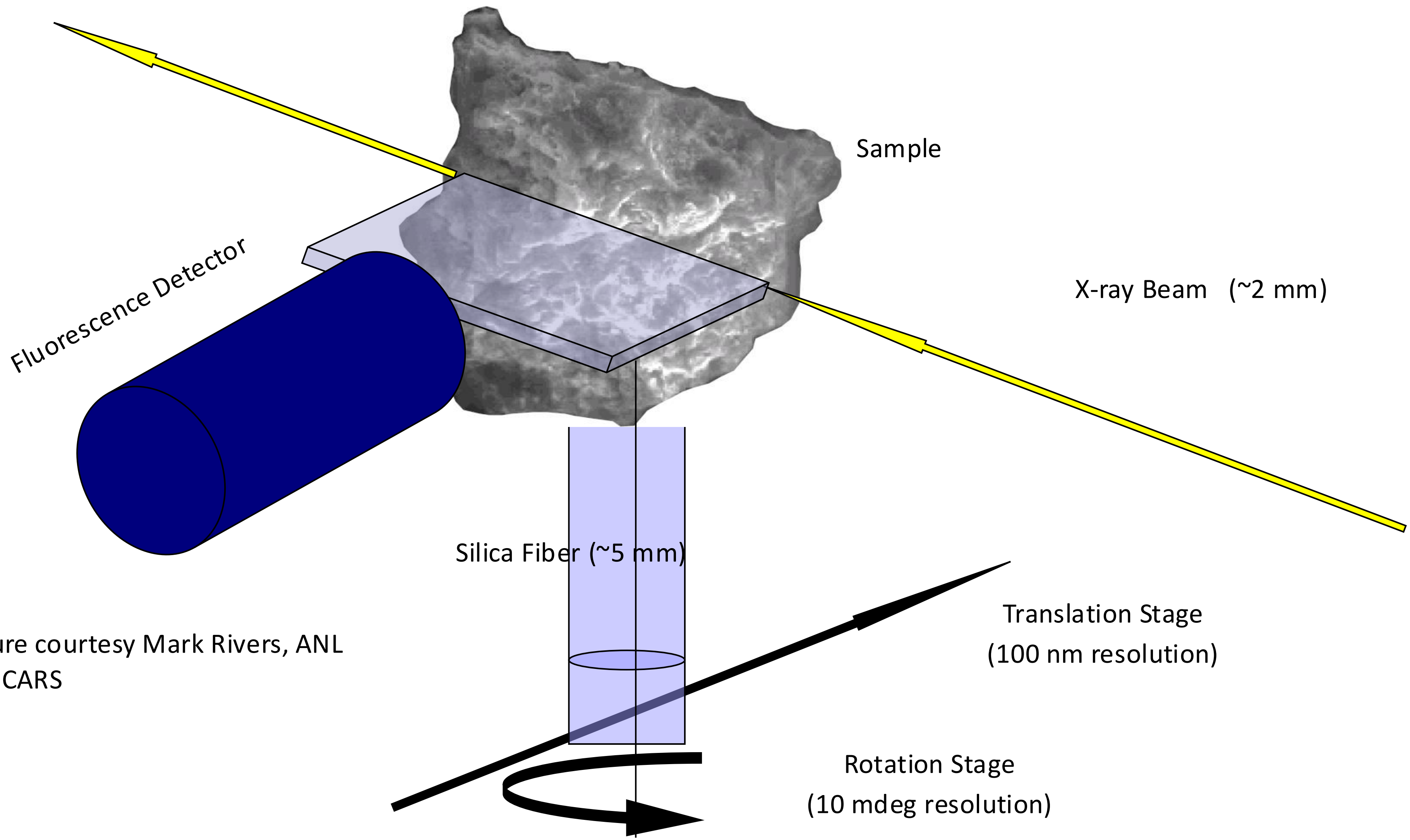
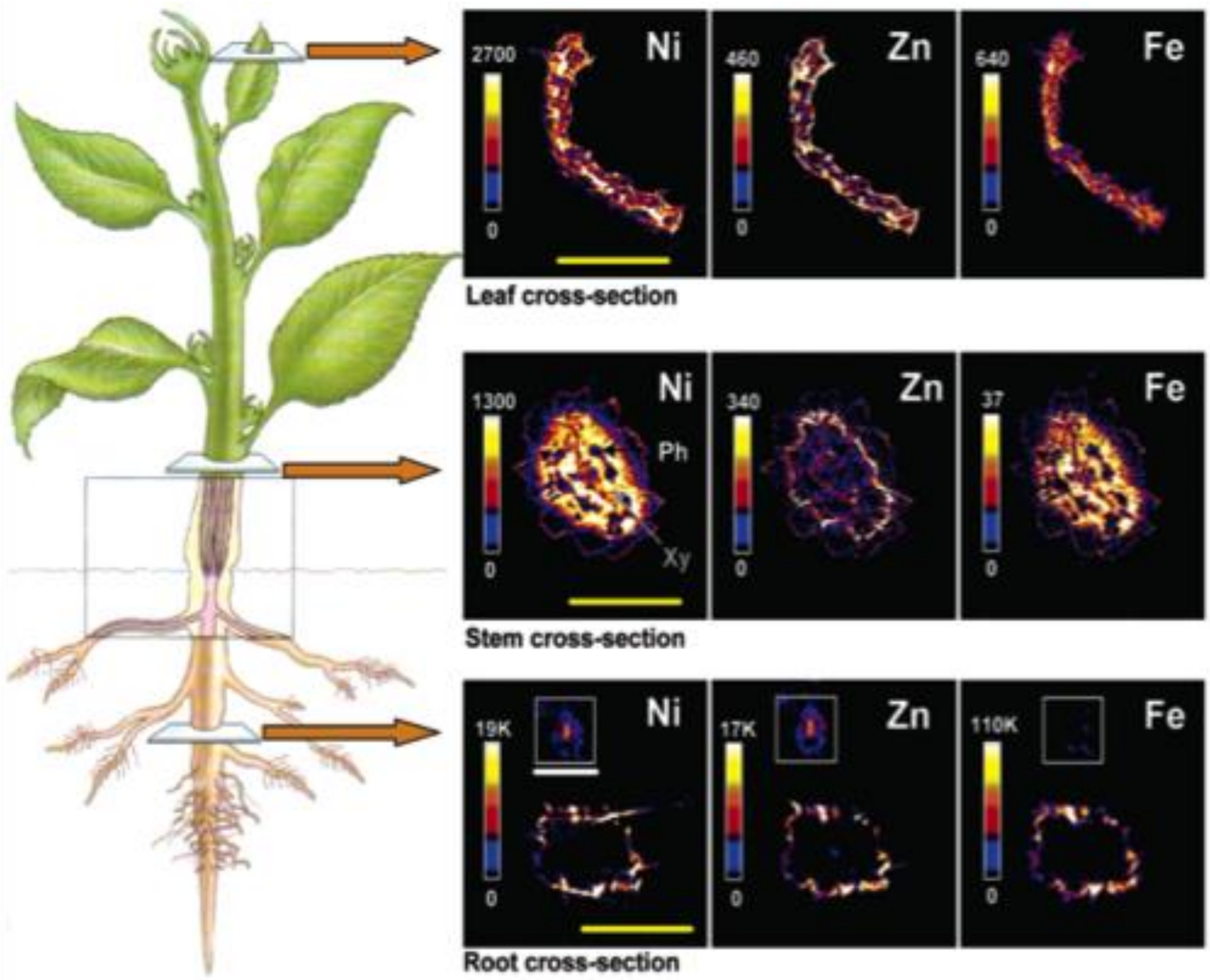


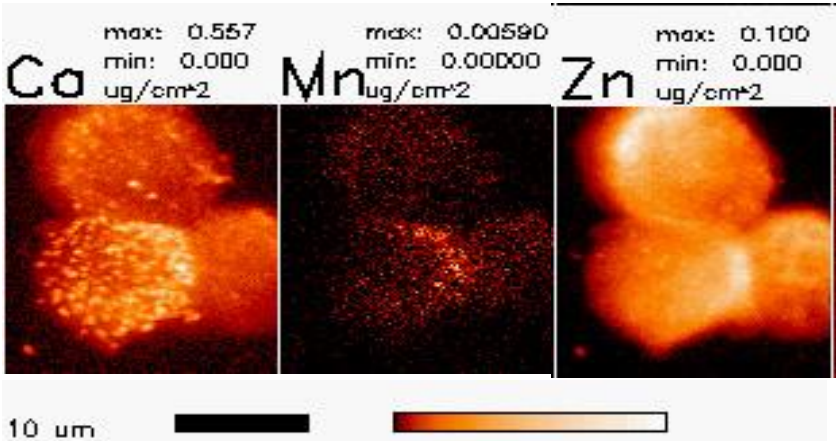
Figure courtesy Mark Rivers, ANL GSECARS

Examples of XFET Images

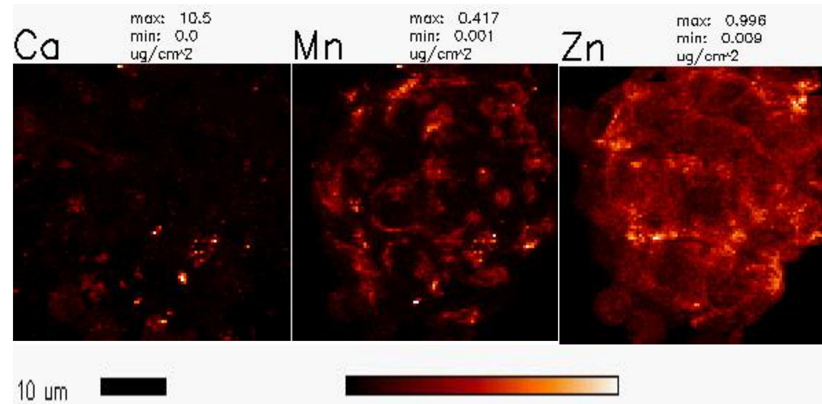


Mapping the Distribution of Metal Elements in β-cells

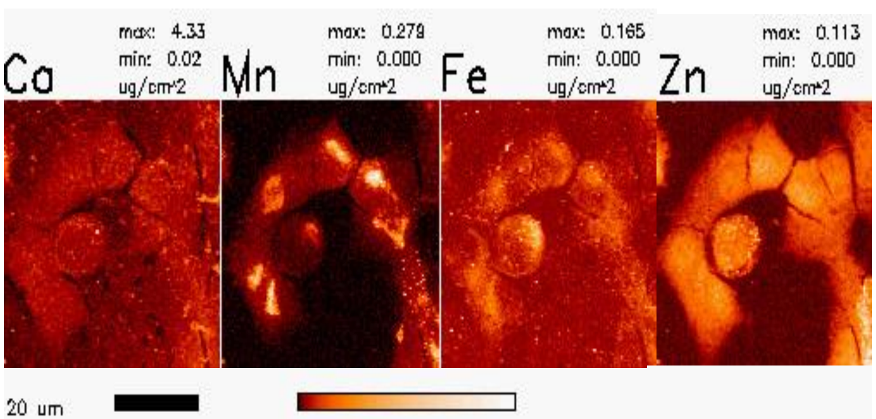
UNTREATED

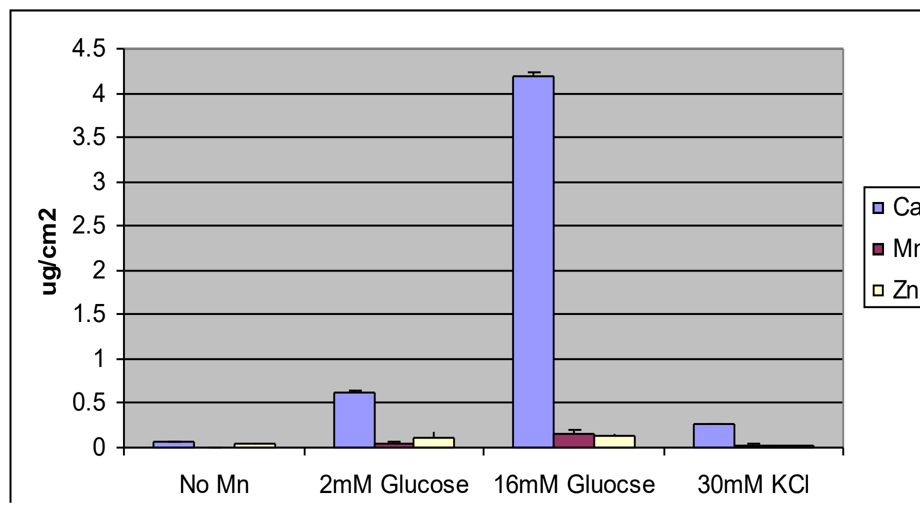


50 uM Mn and 16 Mm Glucose



50 uM Mn, 16 Mm Glucose and 30 mM KCl



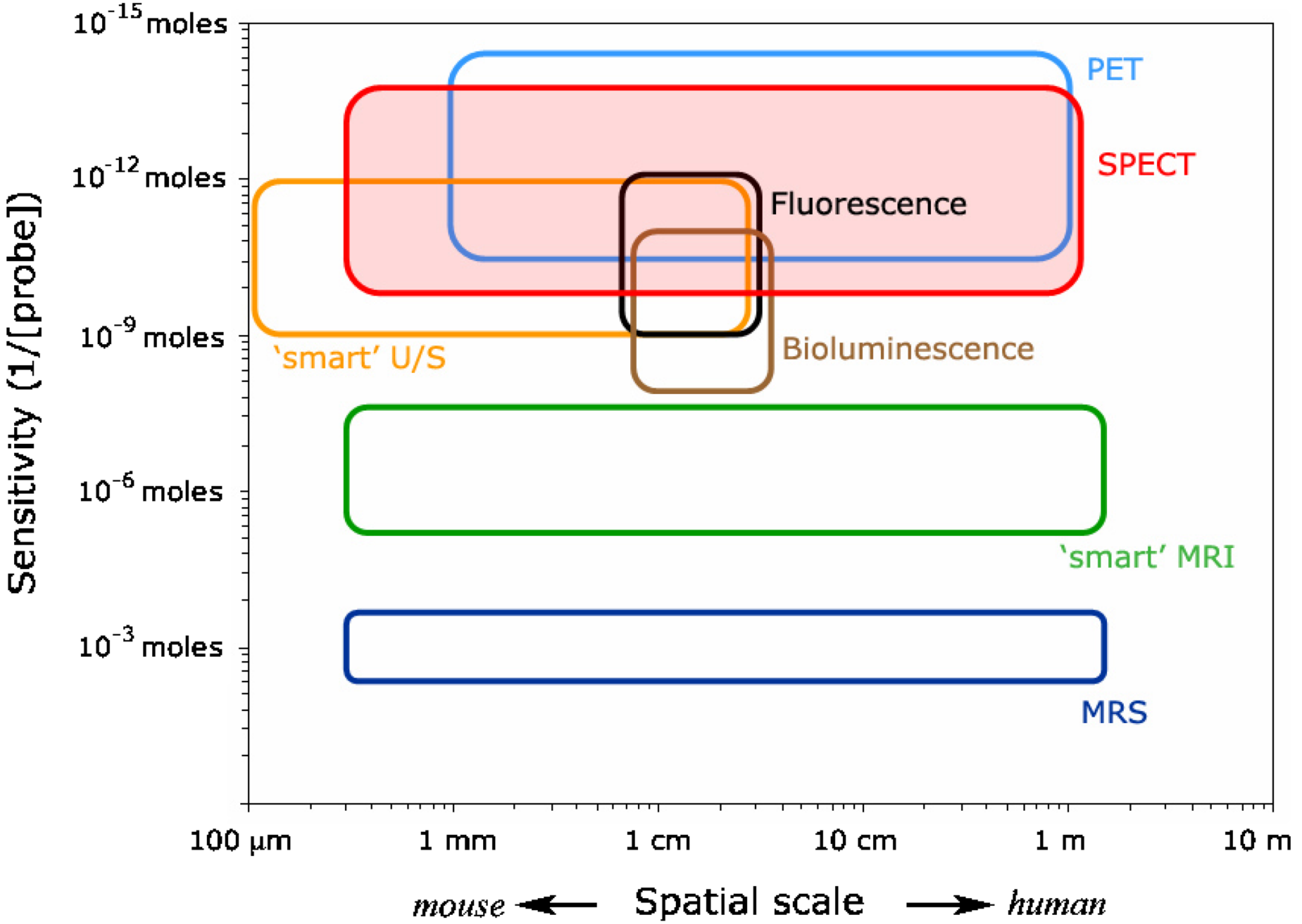


Unpublished results by Patrick La Riviere

Basic Ideas Behind Radiological Imaging:

V: Nothing is Perfect

"Emission tomography and its place in the matrix of molecular imaging technologies"



From S. R. Meikle et al, PMB Vol. 50, Topical Review, 2005.

An Overview of Mouse Imaging Systems

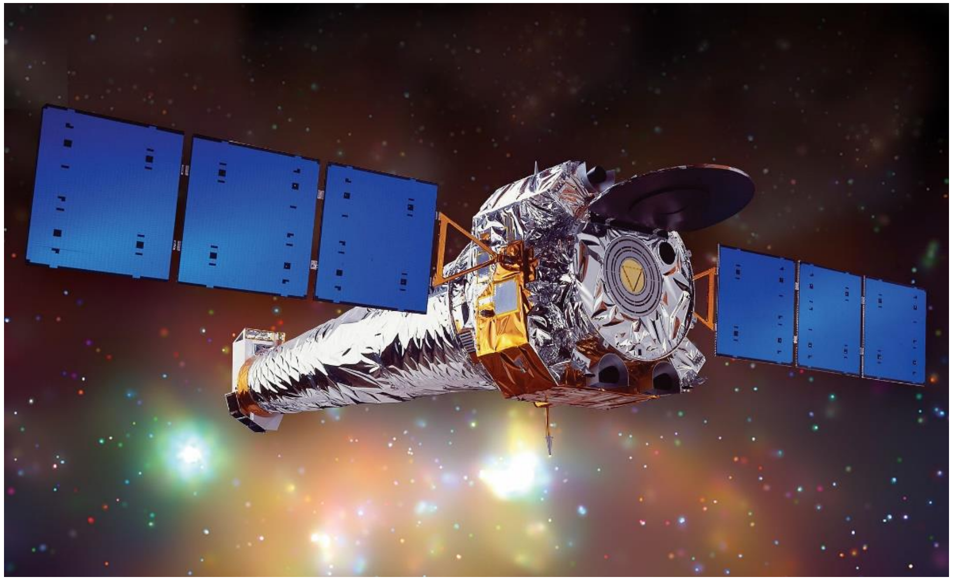
From "Scaling down imaging: molecular mapping of cancer in mice", Ralph Weissleder, Nature Reviews Cancer 2, 11-18 (January 2002)

Technique	Resolution	Depth	Time	Imaging agents	Cost	Primary use
Magnetic resonance imaging (MRI)	10–100 µm	No limit	Min/hours	Gadolinium, dysprosium, iron oxide particles	$$$	phenotyping, physiological imaging and cell tracking
X-ray computed tomography (CT)	50 µm	No limit	Min	Iodine	$$	Lung, bone, tumour imaging
Ultrasound imaging	50 µm	mm	Min	Microbubbles	$$	Vascular and interventional imaging
Positron emission Tomography (PET)	0.8–2 mm	No limit	Min	18F, 11C, 15O	$$$	Imaging metabolism of molecules, such as glucose, thymidine …
Single photon emission tomography (SPECT)	0.1-1 mm	No limit	Min	99mTc, 111In	$$	Imaging of probes such as antibodies, peptides …
Fluorescence reflectance imaging (FRI)	1–2 mm	< 1 cm	Sec/min	Fluorescent proteinsNIR fluorochromes	$	Rapid screening of molecular events in surface-based tumours
Fluorescence-mediated tomography (FMT)	1–2 mm	< 10 cm	Sec/min	NIR fluorochromes	$$	Quantitative imaging of targeted or 'smart' fluorochrome reporters in deep tumours
Bioluminescence imaging (BLI)	Several mm	cm	Min	Luciferin	$$	Gene expression, cell tracking

Basic Ideas Behind Radiological Imaging:

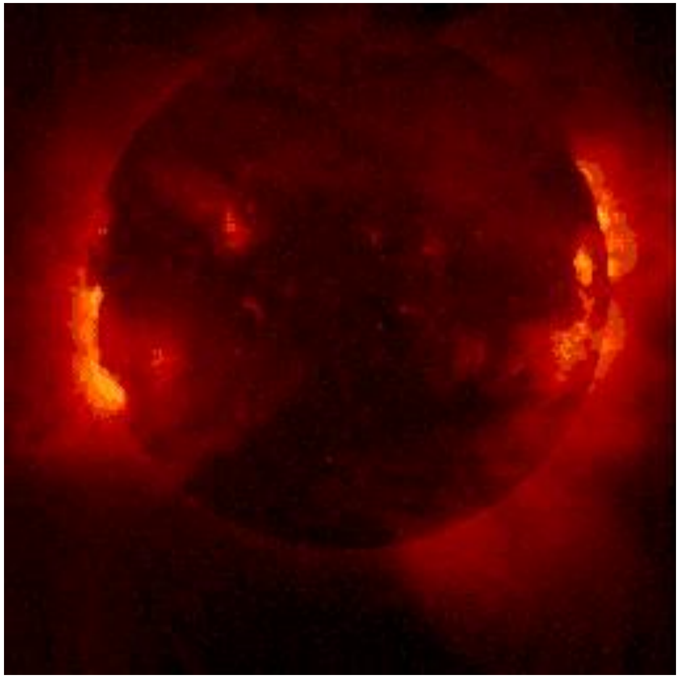
VI: Other Forms of Nuclear Imaging

“Nuclear” Imaging in Astrophysics

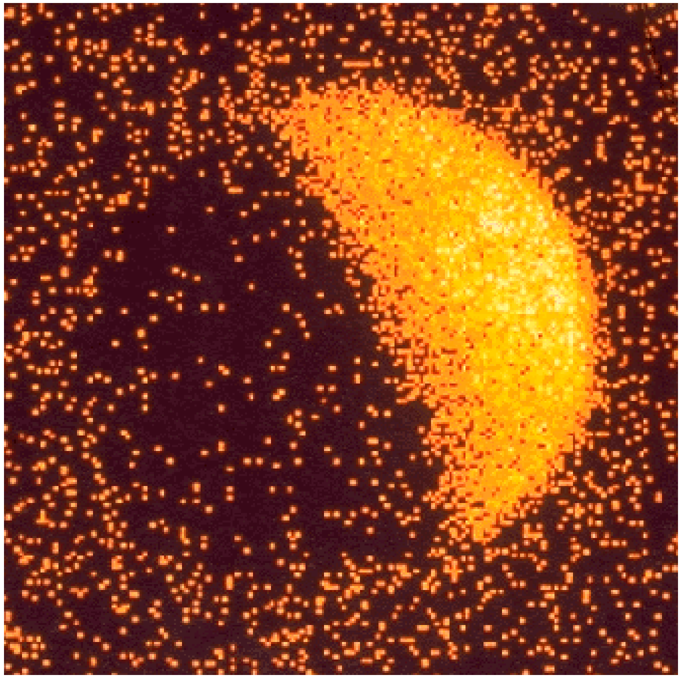


X-ray Emission from the Sun

Using ionizing radiation as a probe to study the invisible properties of an object …



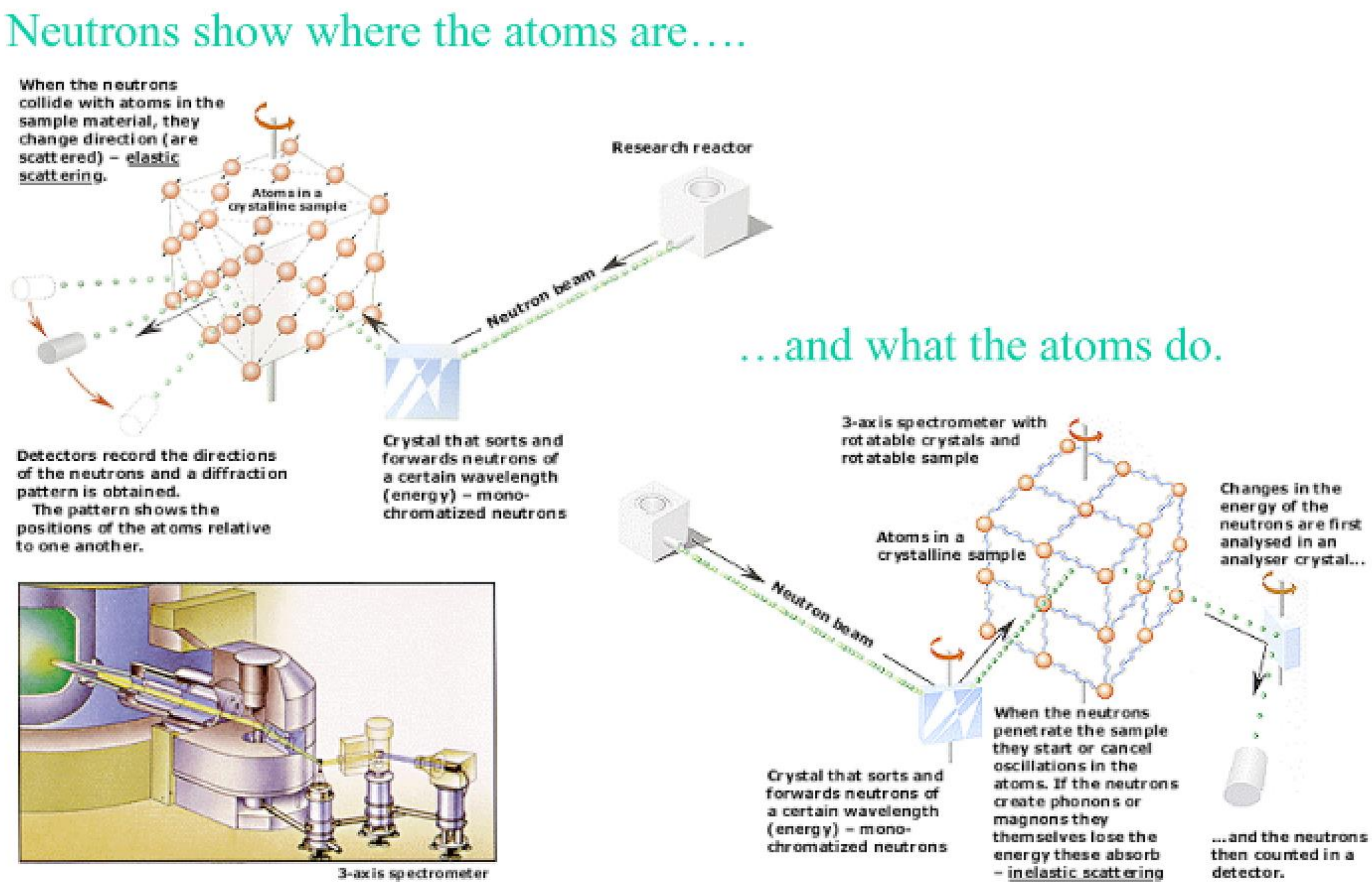
The Sun as seen in X-rays
(image taken by the Yohkoh satellite)



X-ray detection of the Moon, taken by ROSAT.
http://wave.xray.mpe.mpg.de/rosat/mission/rosat/introduction

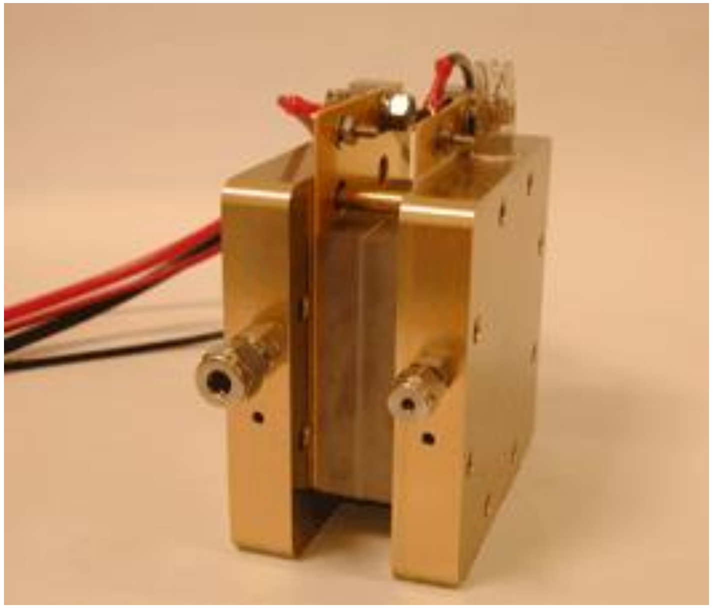
Imaging With Neutrons

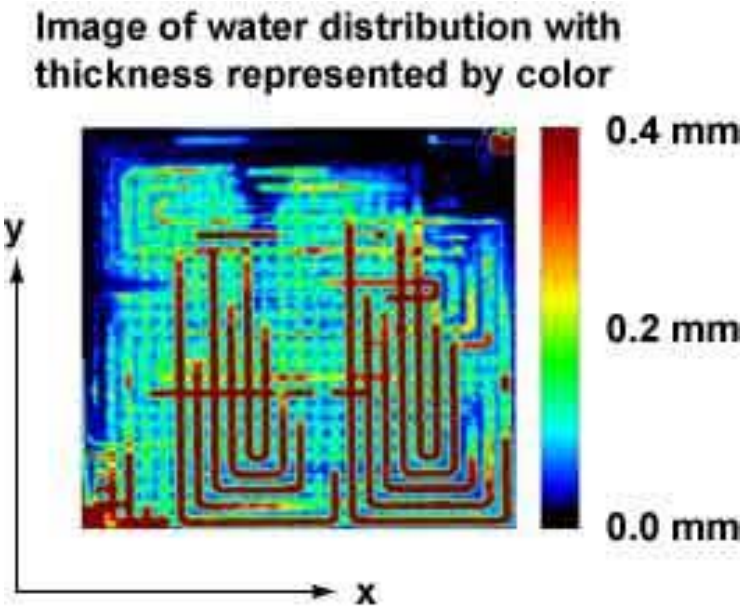
The 1994 Nobel Prize in Physics – Shull & Brockhouse



From http://www.dep.anl.gov/nx/lectrnotes.pdf

Imaging Fuel Cell With Neutrons





http://physics.nist.gov/MajResFac/NIF/index.html