BME I5000: Biomedical Imaging

Lecture 6
Nuclear Imaging

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some slides inspired by lecture notes of Andreas H. Hilscher at Columbia University.

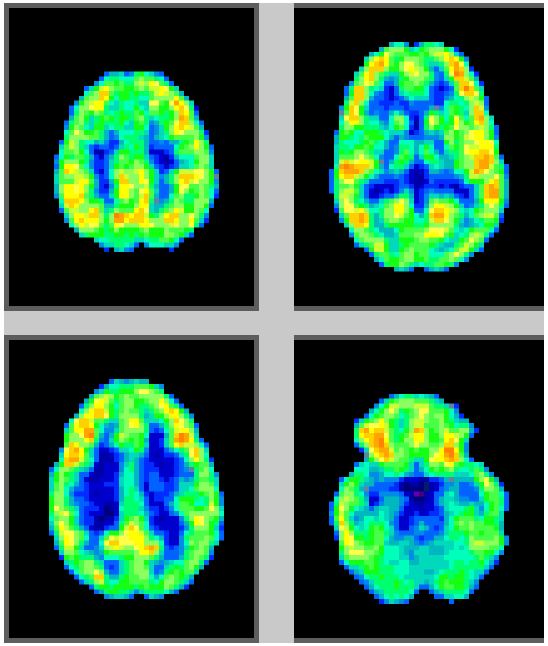
Blackboard: http://cityonline.ccny.cuny.edu/

Schedule

1. Introduction, Spatial Resolution, Intensity Resolution, Noise
2. X-Ray Imaging, Mammography, Angiography, Fluoroscopy
3. Intensity manipulations: Contrast Enhancement, Histogram Equalisation
4. Computed Tomography
5. Image Reconstruction, Radon & Fourier Transform, Filtered Back Projection
6. Nuclear Imaging, PET and SPECT
7. Maximum Likelihood Reconstruction
8. Magnetic Resonance Imaging
9. Fourier reconstruction, k-space, frequency and phase encoding
10. Optical imaging, Fluorescence, Microscopy, Confocal Imaging
11. Enhancement: Point Spread Function, Filtering, Sharpening, Wiener filter
12. Segmentation: Thresholding, Matched filter, Morphological operations
13. Pattern Recognition: Feature extraction, PCA, Wavelets
14. Pattern Recognition: Bayesian Inference, Linear classification

Nuclear Imaging

- Molecules tagged with radioactive isotopes are injected.
- Disperse through the body according to biologic function.
- Meta-stable isotopes emit gamma rays in radioactive decay.
- Gamma rays are detected and converted into images as in x-ray CT.
- Images represent concentration of radiating isotopes in the body.
- Called emission tomography (as opposed to transmission tomography)
- Images represent anatomy and **function!**



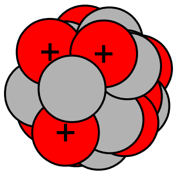
Example: PET of the brain

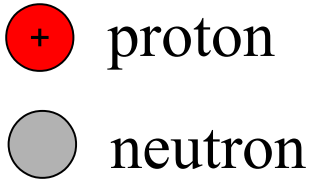
Biomedical Imaging

Imaging Modality	Year	Inventor	Wavelength Energy	Physical principle
X-Ray	1895	Röntgen (Nobel 191)	3-100 keV	Measures variable tissue absorption of X-Rays
Single Photon Emission Comp. Tomography (SPECT)	**1963**	**Kuhl, Edwards**	**150 keV**	**Radioactive decay. Measures variable concentration of radioactive agent.**
Positron Emission Tomography (PET)	**1953**	**Brownell, Sweet**	**150 keV**	**SPECT with improved SNR due to increased number of useful events.**
Computed Axial Tomography (CAT)	1972	Hounsfield, Cormack (Nobel 1979)	keV	Multiple axial X-Ray views to obtain 3D volume of absorption.
Magnetic Resonance Imaging (MRI)	1973	Lauterbur, Mansfield (Nobel 2003)	GHz	Space and tissue dependent resonance frequency of kern spin in variable magnetic field.
Ultrasound	1940-1955	many	MHz	Measures echo of sound at tissue boundaries.

Nuclear Imaging – Isotopes

Nucleus consists of proton and neutrons





Nomenclature: $\ ^{A}_{Z}X$ or ^{A}X

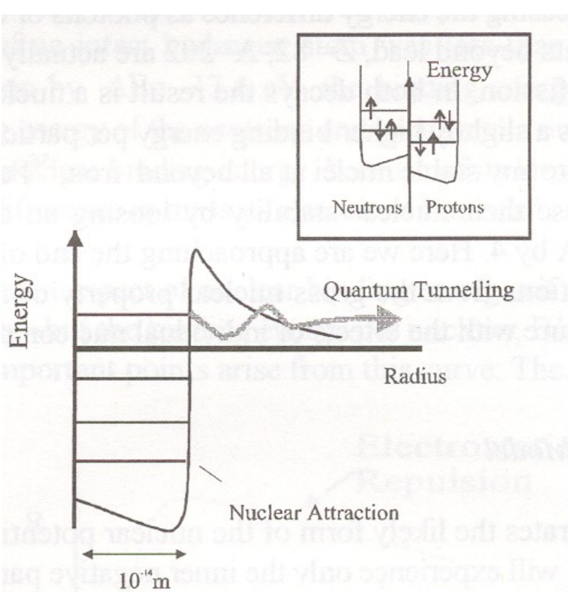
A := mass number (number of protons + neutrons)

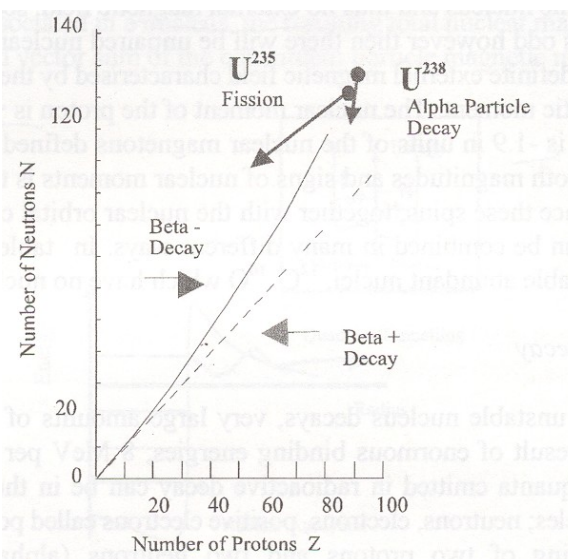
Z := atomic number (number of protons)

Species with same Z but different A are called "isotopes."
E.g.: 64Zn, 66Zn, 67Zn, 68Zn, 70Zn (49%, 28%, 4%, 19%, 0.6%)

Nuclear Imaging – Isotopes

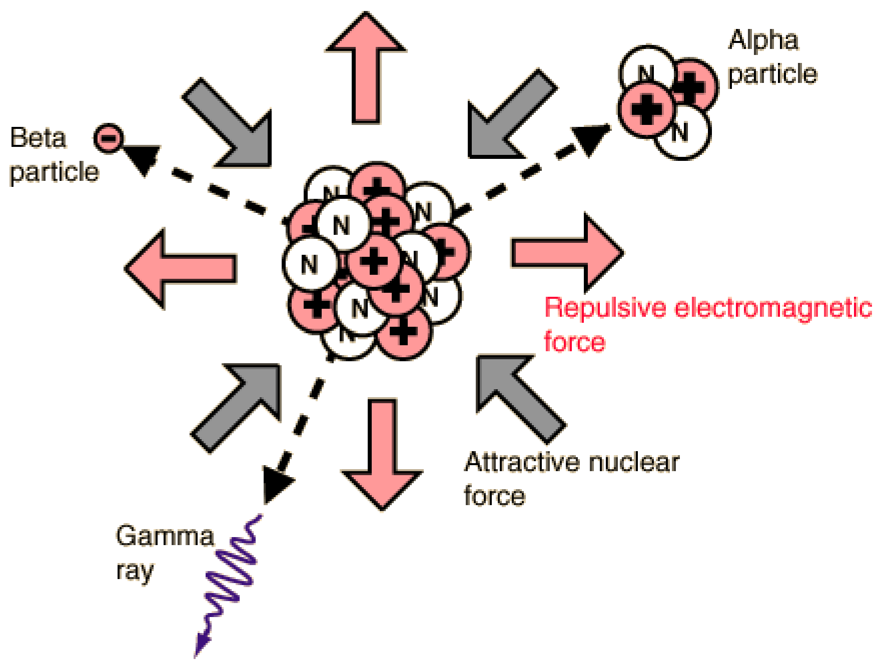
- Electrostatic repulsion is counter balanced by 'strong' nuclear force. As the number of protons Z increases the number of neutrons has to increase to counterbalance increased electrostatic repulsion.
- At large nucleus sizes more neutrons are needed to keep nucleus stable because strong force decays rapidly with distance.
- As Z increases there tends to be a larger range of metastable isotopes.





Nuclear Imaging – Radioactive decay

- Alpha radiation: Mass rich nuclei emit alpha particle (He^{+2})
- Beta radiation:
    - Neutron rich nuclei emits electron (e^-) by converting a neutron into a proton.
    - Proton rich nuclei converts a proton into a neutron and emits positron (e^+).
- Gamma radiation: After beta decay nucleus is in exited state and relaxed with gamma (electromagnetic) radiation.



Nuclear Imaging – Gamma Radiation

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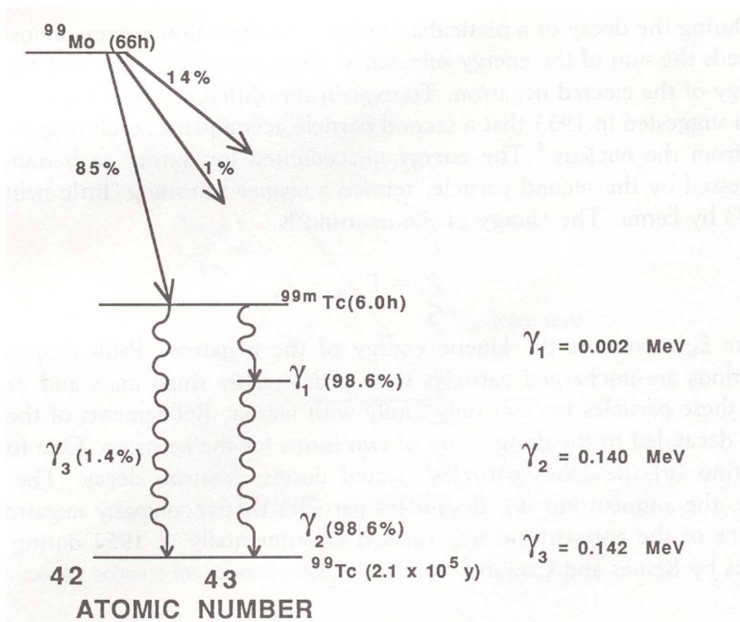
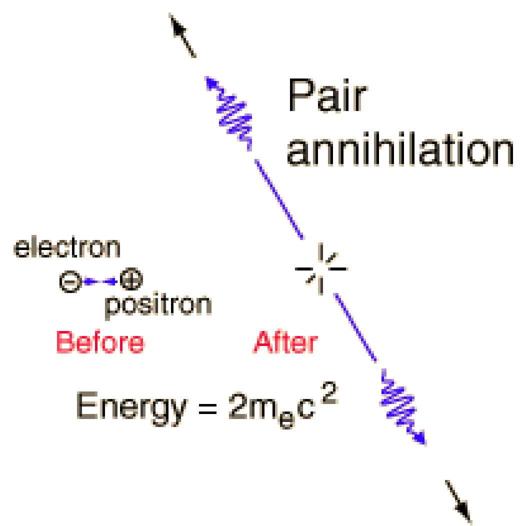


- Important in SPECT

Nuclear Imaging – Positron Emission

- After emission the positron (antimatter) annihilates as soon as if encounters an electron crating a pair of gamma quants (510keV) at a 180^{o} angle.



- Important in positron emission tomography (PET)

Nuclear Imaging – Radioactive decay

Likelihood of decay is proportional to the number of radioactive isotopes.

$$\frac{dN}{dt} = -\lambda N(t) \quad \Rightarrow \quad N(t) = N_0 e^{-\lambda t}$$

Half time: $$\frac{1}{2} = \frac{N}{N_0} = e^{-\lambda T_{1/2}} \quad \Rightarrow \quad T_{1/2} = \frac{\ln 2}{\lambda}$$

Common Radioisotopes in Nuclear Medicine

Isotope	*Half-life*	*Decay*
^{123}I (Iodine 123)	13.2 hours	EC
^{125}I (Iodine 125)	60.14 days	EC
^{131}I (Iodine 131)	8.04 days	EC
^{99m}Tc (Technetium 99m)	6.02 hours	IT
^{133}X (Xenon 133)	5.245 days	β^-
^{51}Cr (Chromium 51)	27.704 days	EC
^{111}In (Indium 111)	2.83 days	EC

source: Bronzino, *Biomedical Engineering and Instrumentation*, PWS

Nuclear Imaging – useful Isotopes

Nuclear imaging useful for diagnosis. Altered metabolism in decease state leads to selective uptake of radio-labelled tracer molecules.

A few examples:

Common Procedures in Nuclear Medicine

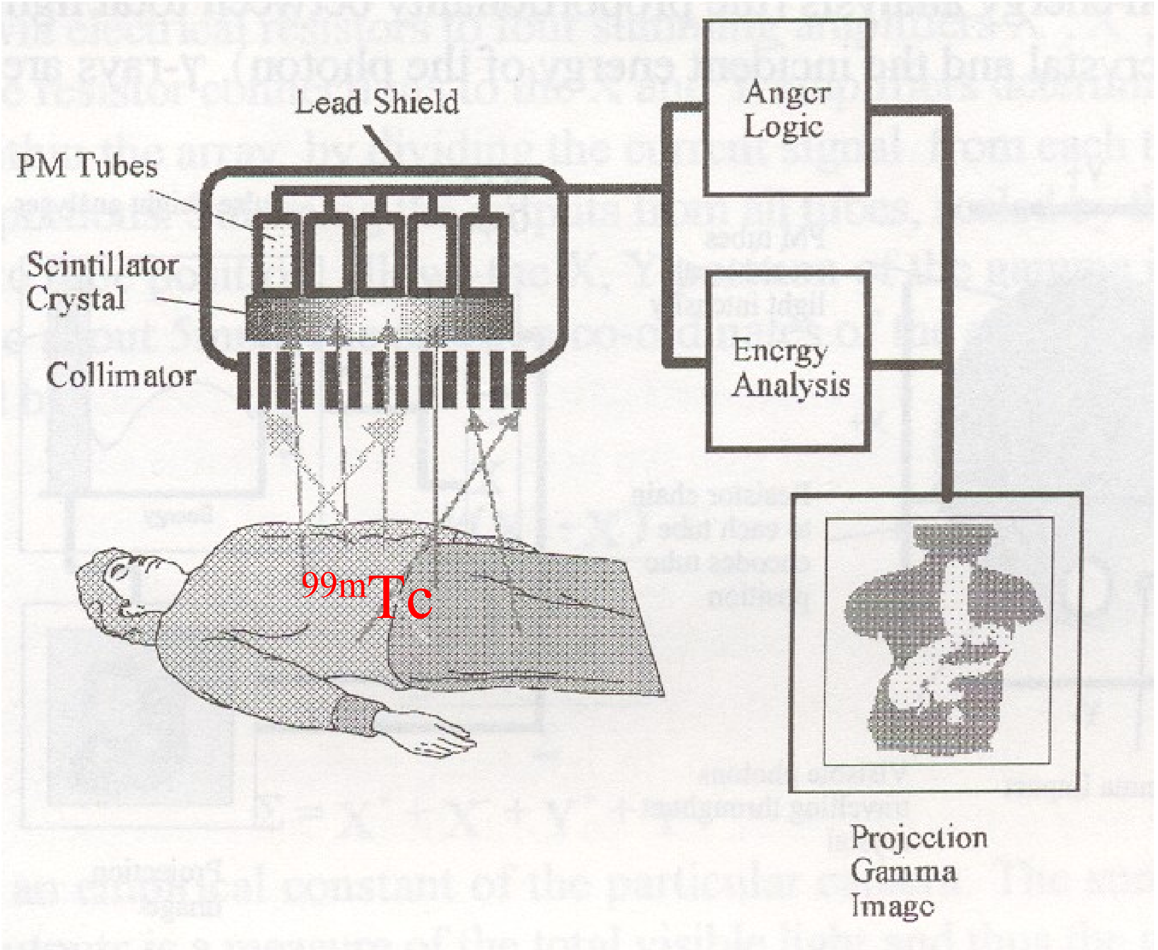
Test	*Isotope*
plasma/blood volume estimation	^{125}I, ^{131}I
red blood cell life and mass estimation	^{51}Cr
thyroid function	^{123}I, ^{131}I
cardiac blood pool imaging	^{99m}Tc
brain, liver, kidney, spleen, gallbladder imaging	^{99m}Tc
lung perfusion scan	^{99m}Tc
lung ventilation scan	^{133}Xe
thyroid therapy	^{131}I
bone imaging	^{99m}Tc

source: Bronzino, *Biomedical Engineering and Instrumentation*, PWS

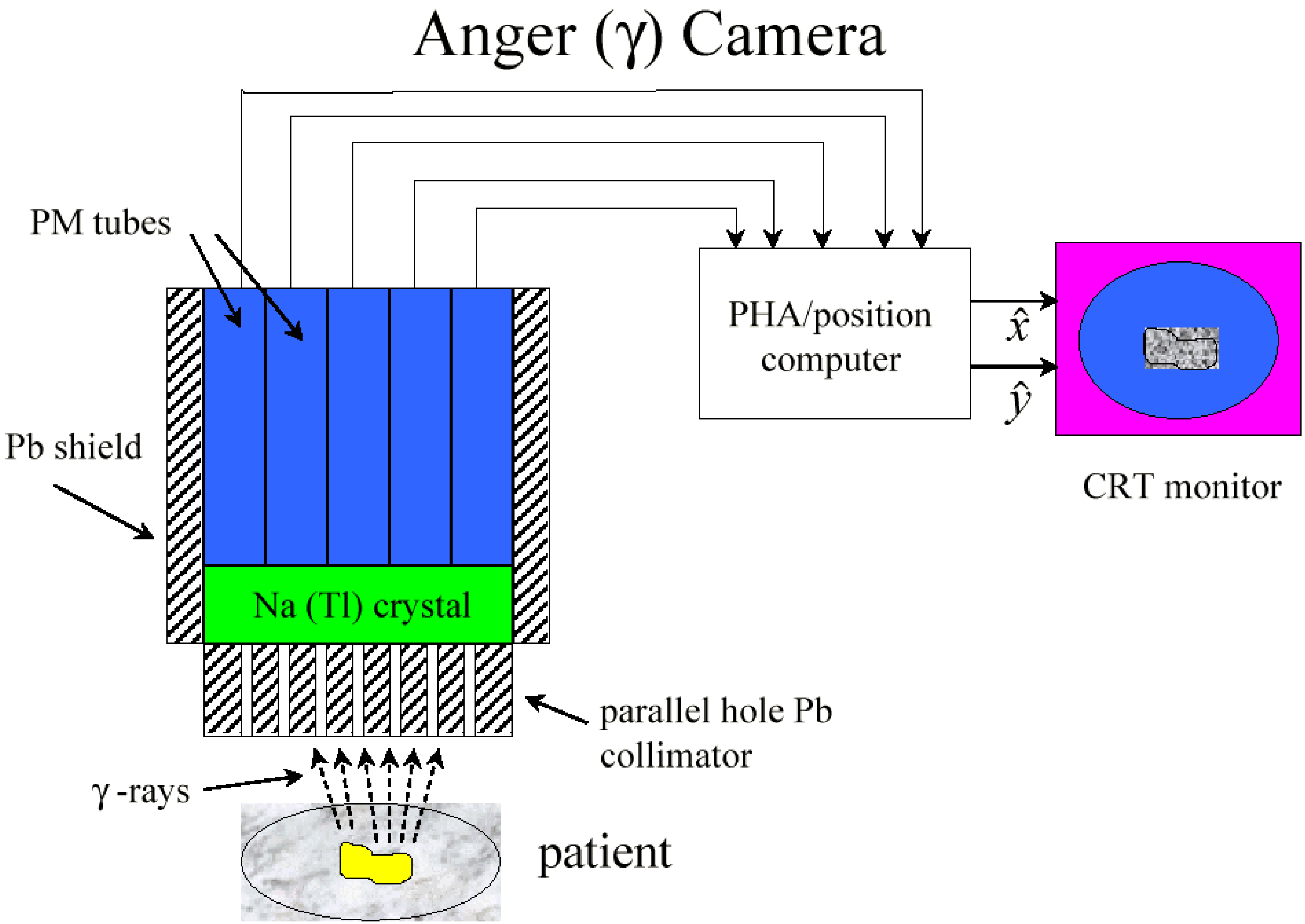
Nuclear Imaging - SPECT

Single photon emission computed tomography (SPECT)

- Parallel-hole collimator needed to establish origine of radiation (filters large fraction of the radiation)
- Photo multiplier covers large area. To obtain location of detected event anger network combines output of multiple photo-multipliers.
- Individual events are detected (unlike x-ray imaging) with typical event counts of 200K-1M.
- Energy of gamma quant is measures and used to filter scattered radiation which lacks information on the source.



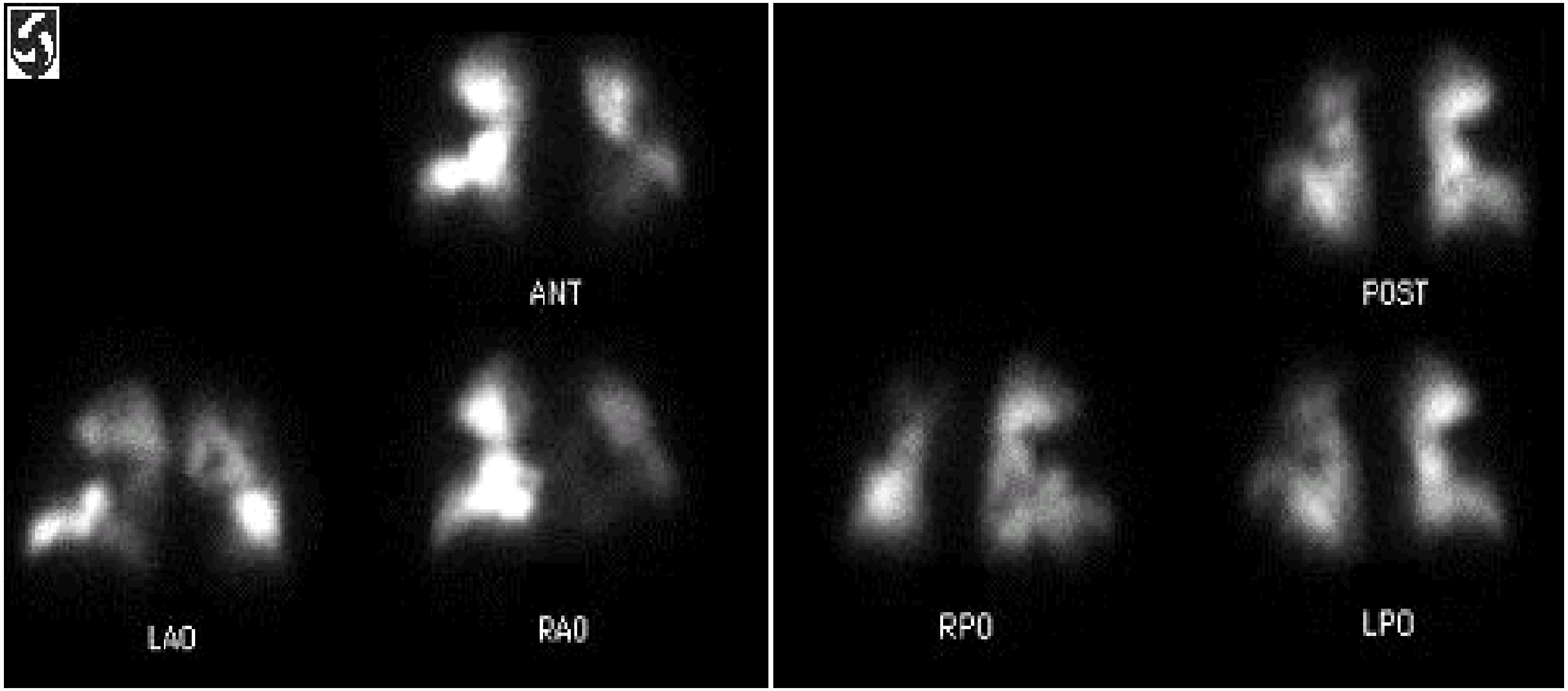
Nuclear Imaging - SPECT



Nuclear Imaging - SPECT

Example: Lung Perfusion Scan

- Inject micro-bubbles (15 μm diameter) labelled with ^{99m}Tc into vein.
- Micro-bubbles lodge in lungs before dissolving into blood steam.
- SPECT images blood flow in lung.
- Used to detect pulmonary embolus.



Nuclear Imaging

Advantage of SPECT:

- Simple mechanism
- Inexpensive
- Many possible isotopes.

Disadvantage of SPECT

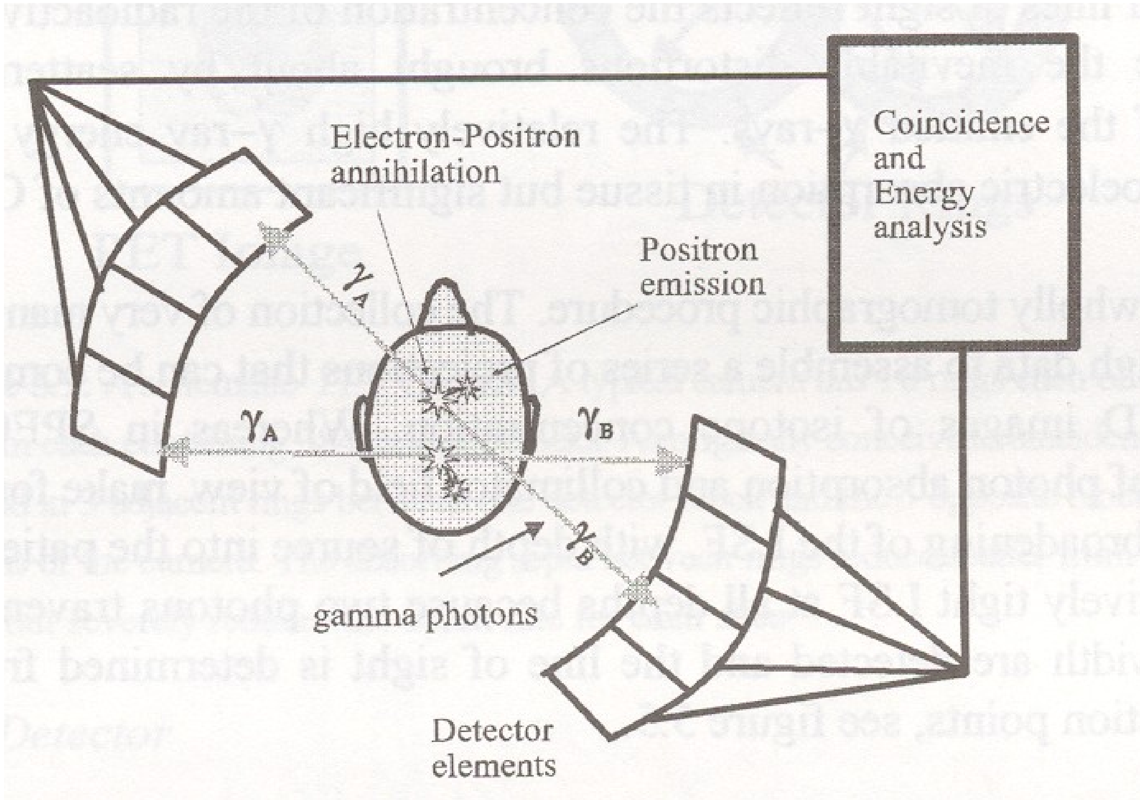
- Collimation reduces photon count resulting in poor SNR and/or high does.

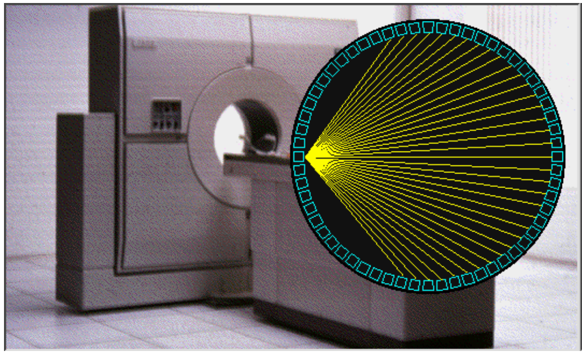
Solution:

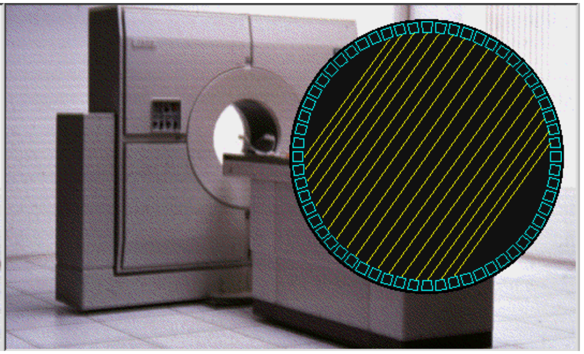
- Use positron emission which gives directional information.

Nuclear Imaging - PET

- Coincidence detection (<12ns) ensures directional information.
- Energy filter at 511keV filter Compton scattered events.
- Reduced patient dose as no collimation is required!
- SNR usually 5 times improved over SPECT (+13dB).
- Detectors must cover 180^{o} increased cost over SPECT
- Due to poor SNR resolution only about 1cm.
- Time of flight detection gives some location information (1ns~30cm)







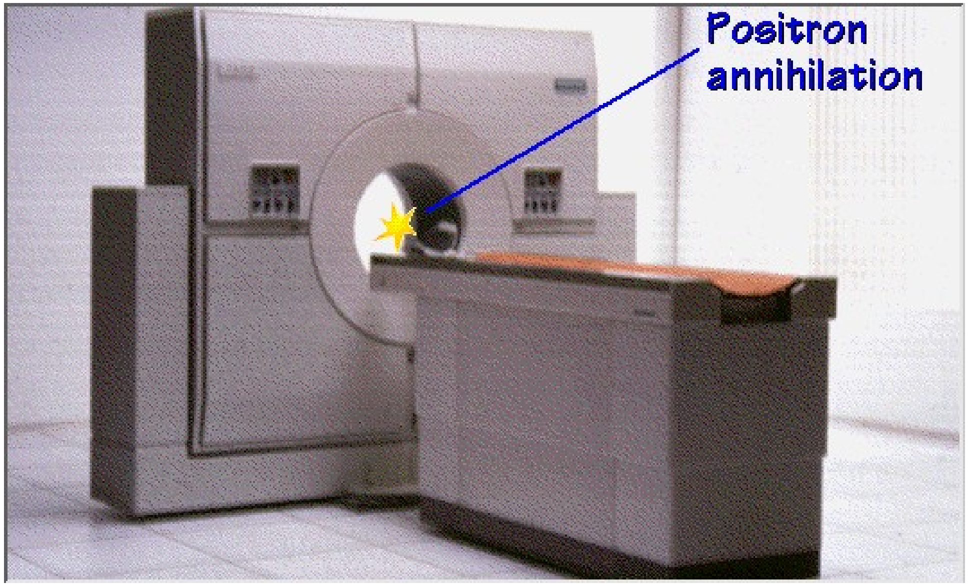
Nuclear Imaging – Clinical PET

Typical isotopes in PET

Radionuclide	Half-live (min)
^{11}C	20.4
^{15}O	2.07
^{13}N	9.96
^{18}F	1009.7

- Common tracer ^{18}F-labelled glucose, Fluorodeoxyglucose (FDG)
- But many other tracers available to follow the path of a number of important metabolic interactions.

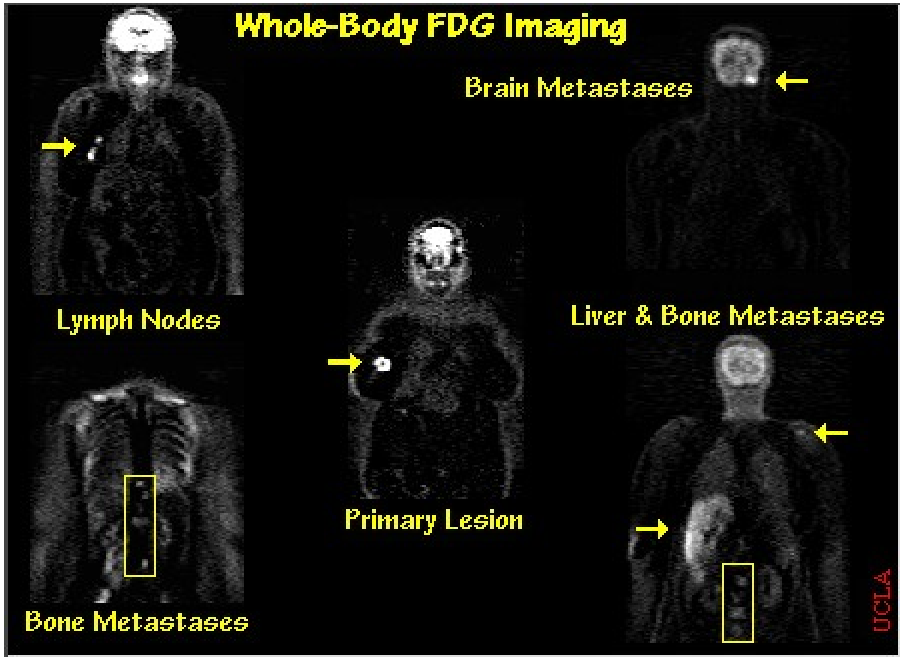
Applications:
- Neurology
- Oncology
- Cardiac function

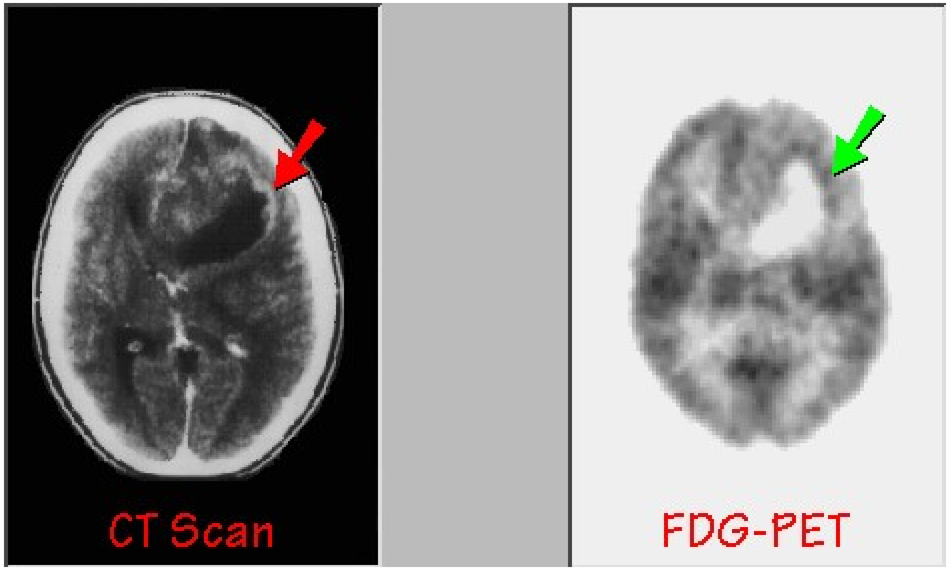


PET Demo
http://www.crump.ucla.edu/lpp

Nuclear Imaging – PET Applications

- Oncology: Tumour detection and diagnosis





Nuclear Imaging – PET Applications

Neurology:
- normal brain function,
- Alzheimer's, Parkinson's,
- development,
- Trauma, ...

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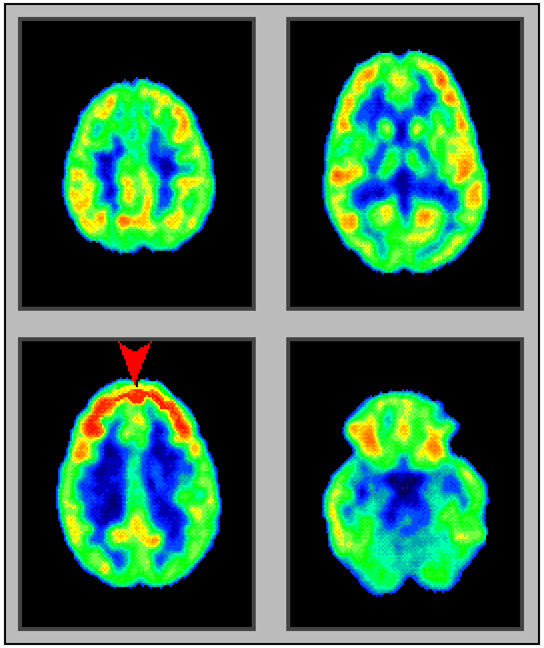

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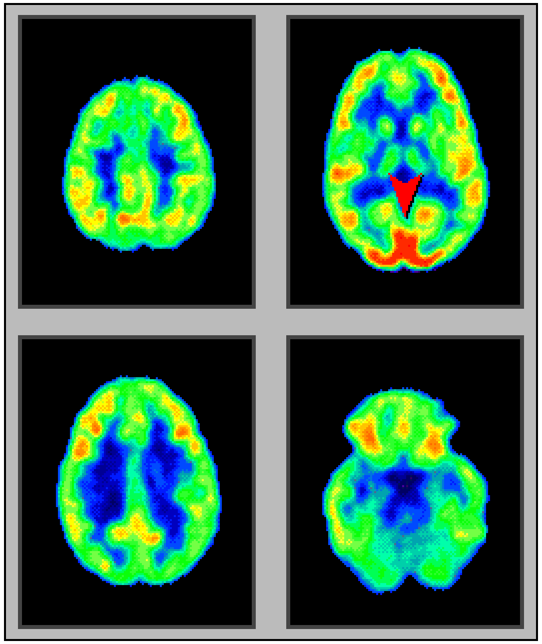

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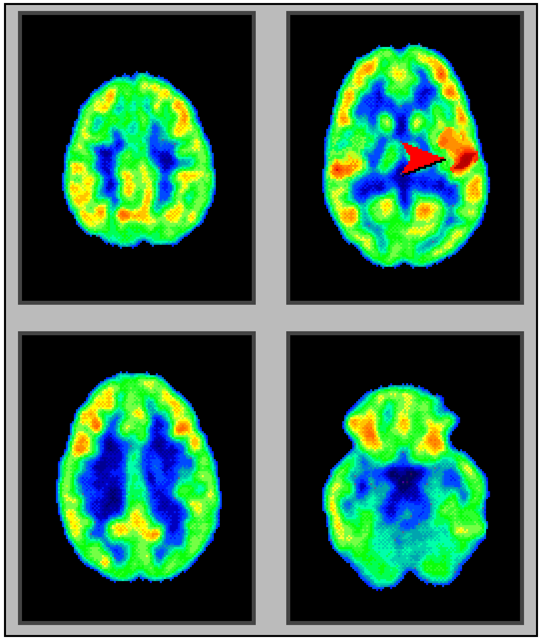
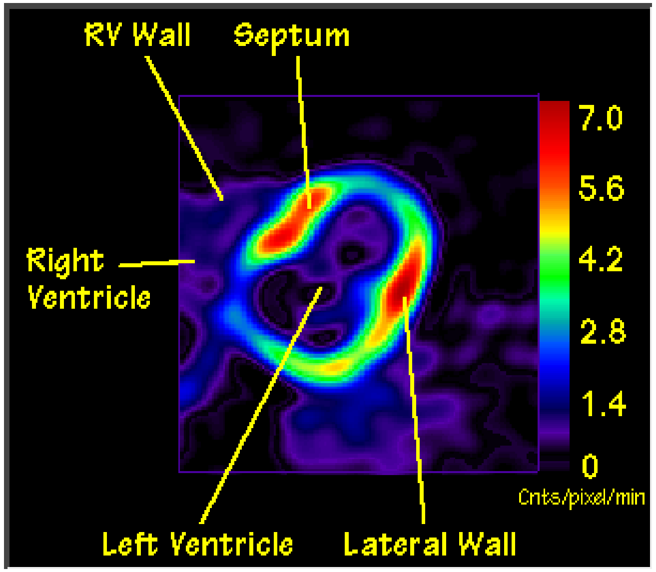
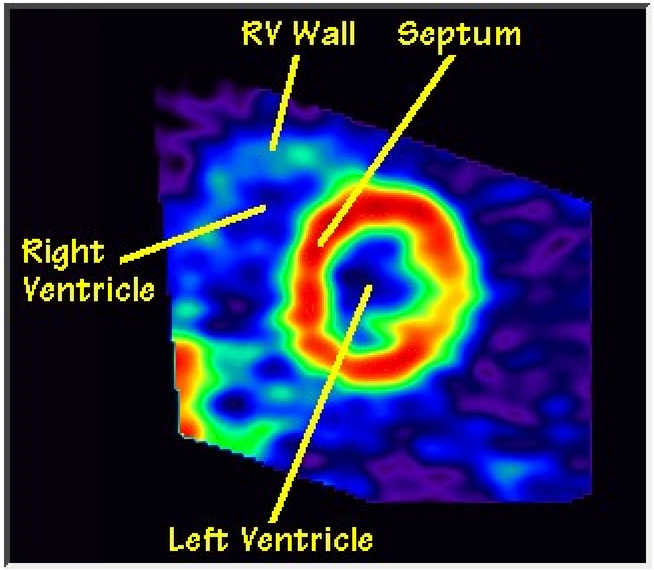
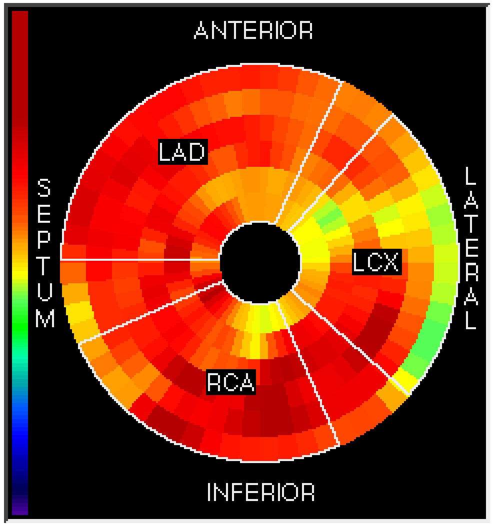


Nuclear Imaging – PET Applications

Cardiac function







Nuclear Imaging – PET Problems

- Resolution limited to 2-5 mm because of positron mean-free path before annihilation.
- False Coincidence Events
  - Unrelated photons arrive at same time (<20ns, ~ 15% of signal)
  - One or both photons of an annihilation event are scattered (10-30% of signal)
- Relatively high radiation dose to patient
- Unknown photon absorption profile

Nuclear Imaging – PET Reconstruction

Coincident counts originate along a line. Counts at each pair of detectors give an integral of the source density $f(x,y)$ along that line:

$$g(\phi, s) = \int_L dl\, f(x, y)$$

One can use standard CT reconstruction (filtered back-projection).

511KeV are primarily Compton scattered and not attenuated. However, attenuation does occur and complicates algorithms considerably

$$g(\phi, s) = \int_L dl\, f(x, y) \exp\left(-\int_L dl'\, \mu(x, y)\right)$$

Filtered back-projection is not appropriate for this 'forward model'.

Nuclear Imaging – PET Reconstruction

- Sometimes CAT image is obtained in the same system to compute attenuation coefficient $\mu(x,y)$ and factors into PET reconstruction.
- An alternative algorithm that can take more complicated forward models into account is the Expectation Maximisation (EM) algorithm.