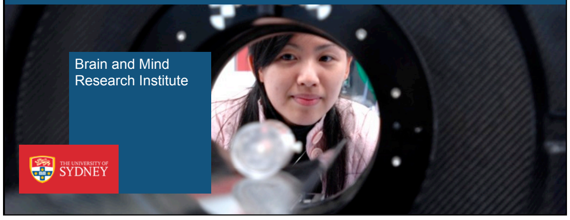
Principles of PET and SPECT

Steven Meikle
Professor of Medical Imaging Physics

WMIC Educational Program – Nuclear Imaging
Dublin, Wednesday September 5, 2012

Brain and Mind Research Institute



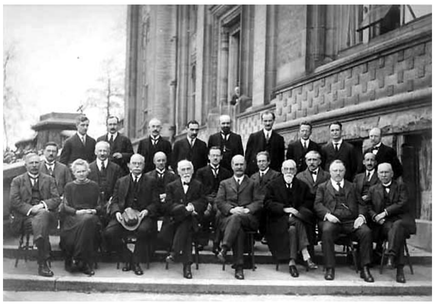
THE UNIVERSITY OF SYDNEY

Learning Outcomes

You should be able to explain:

- the tracer principle and its importance in PET and SPECT molecular imaging.
- how radiation emitted from the body is detected externally using SPECT and PET instrumentation.
- the key principles in forming a reconstructed image of the tracer distribution in the body

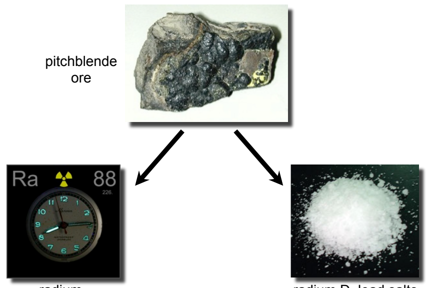
The Tracer Principle

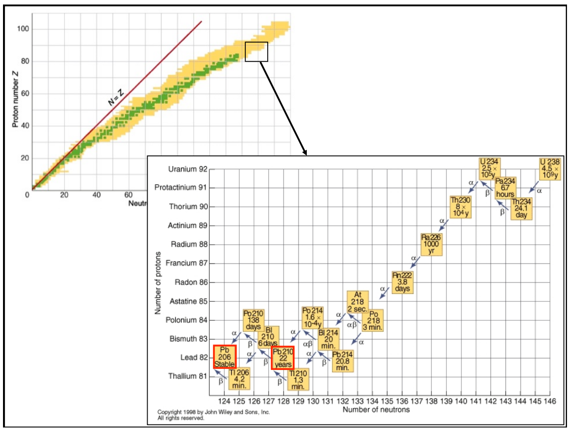


Fourth Solvay Conference, Brussels, 1924

The Tracer Principle

Rutherford to de Hevesy: "My boy if you are worth your salt, you try to separate radium D from all that lead"





The Tracer Principle: Key Features

- Isotopes of the same element have the **same chemical properties**. They act in the same way in chemical and biological reactions.
- Therefore, when placed in biological or environmental systems, radioisotopes can be used as **indicators** of their non-radioactive counterpart.
- To act as a tracer, the radioactive compound must be present in such small quantities that it **does not perturb the system**. Typically, the concentration in the body is on the order of nanomolar (10^{-9} mol/L) or picomolar (10^{-12} mol/L).
- When used in biological systems, a radiotracer is usually called a **radiopharmaceutical**.

SPECT and PET: Key Features

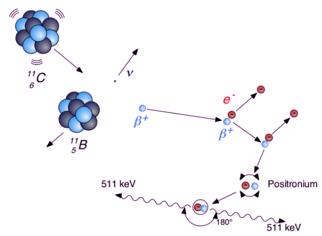
PET
- isotopes are cyclotron produced
- isotopes typically have short half-lives (min-hrs)
- 2 γ per nuclear decay (requires coincidence detection)
- electronic collimation (good detection efficiency)
- stationary ring detector

SPECT
- isotopes may be reactor, generator or cyclotron produced
- isotopes typically have longer half-lives (hrs-days)
- 1 γ per nuclear decay (requires collimator)
- physical collimation (poor detection efficiency)
- rotating detector/s (usually)

Common nuclear reactions and radioisotopes

	Reaction	Product $\tau_{1/2}$
PET	^{18}O (p,n) ^{18}F	109 min
	^{16}O (p,α) ^{13}N	10 min
	^{14}N (p,α) ^{11}C	20 min
	^{15}N (p,n) ^{15}O	2 min
	^{14}N (d,n) ^{15}O	2 min
SPECT	^{98}Mo (n,γ) $^{99}Mo \longrightarrow {}^{99m}Tc$	6.02 hr
	^{112}Cd (p,2n) ^{111}In	2.8 day
	^{203}Tl (p,3n) $^{201}Pb \longrightarrow {}^{201}Tl$	73 hr

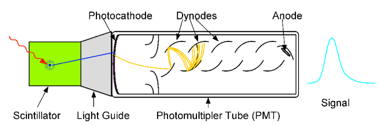
Positron Annihilation



$$E = mc^2$$

Scintillation Detector

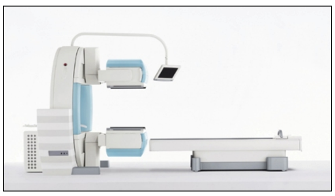
The basic scintillation detector consists of:
- Scintillator
- Light guide
- Photo-detector

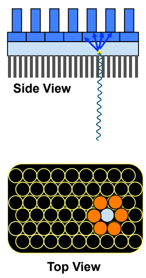


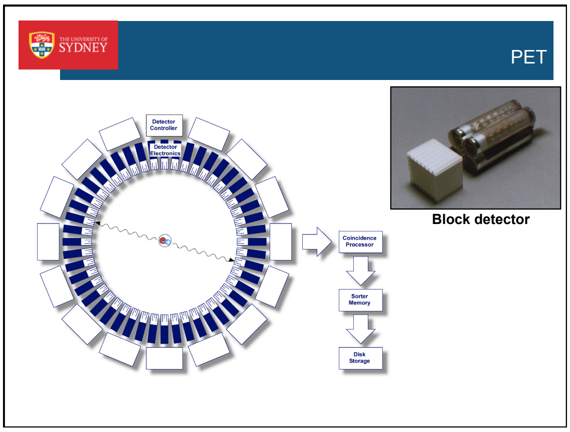
SPECT and PET Scintillators

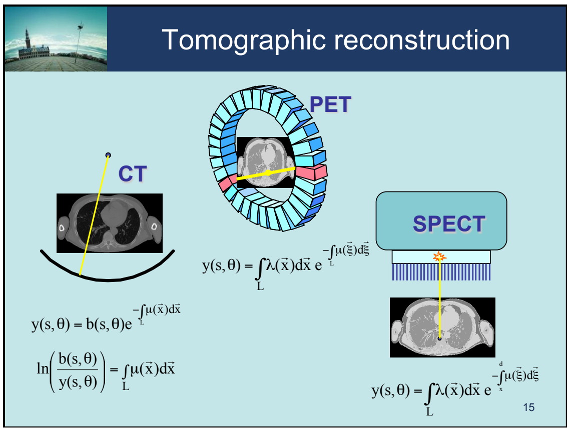
Scintillator	ρ (g/cc)	Z_{eff}	Yield (%)	τ (ns)	λ (nm)	Hygro?
NaI(Tl)	**3.67**	**51**	**100**	**230**	**410**	**yes**
CsF	4.64	53	5	4	390	very
BaF_2	4.88	53	12	0.8, 600	220, 310	no
$YAlO_3$(Ce) **(YAP)**	5.37	39	40	25	370	no
Gd_2SiO_5(Ce) **(GSO)**	6.71	59	30	60, 600	**430**	**no**
$Bi_4Ge_3O_{12}$ **(BGO)**	7.13	75	15	300	480	no
Lu_2SiO_5(Ce) (LSO)	**7.40**	**65**	**75**	**40**	**420**	**no**
$LuAlO_3$(Ce) **(LuAP)**	8.30	53	50	18	365	no

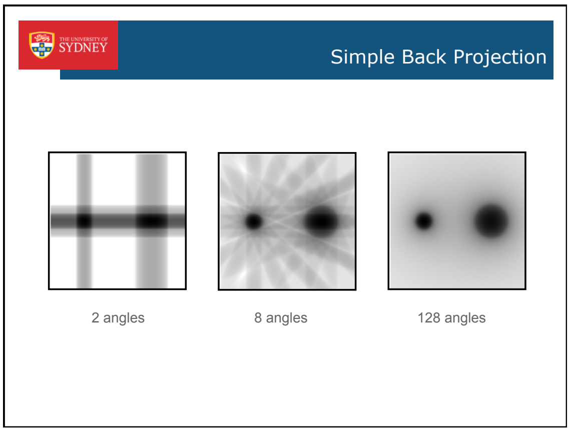
SPECT

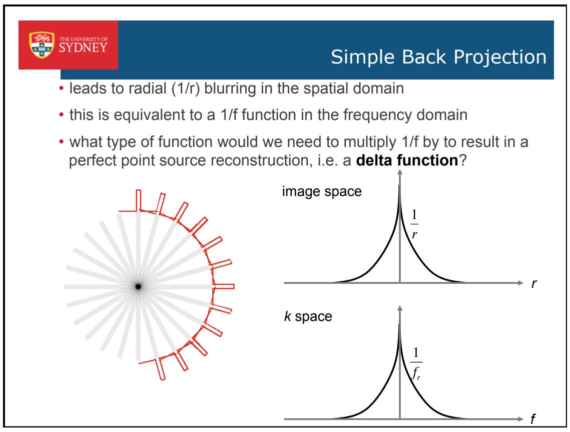


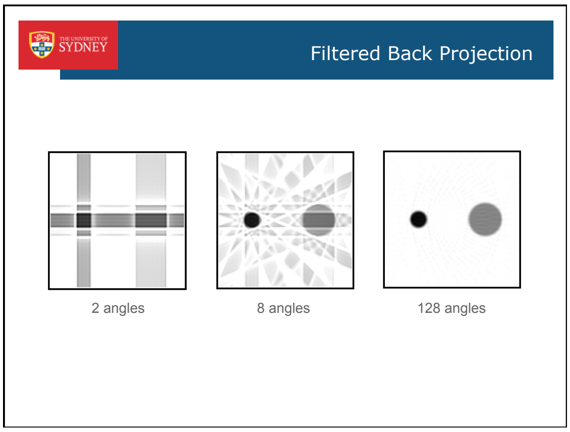


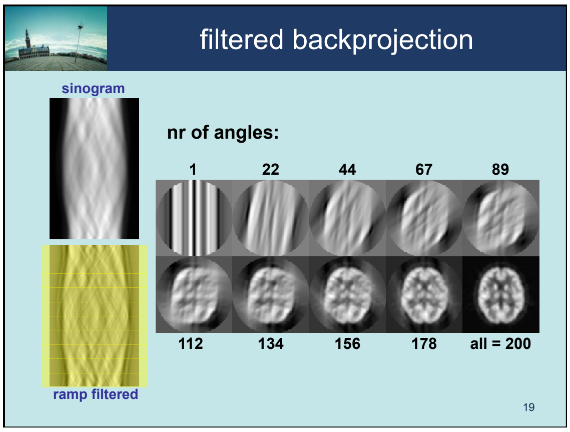

THE UNIVERSITY OF SYDNEY
PET
Block detector


Tomographic reconstruction
CT
PET
SPECT
$y(s,\theta) = b(s,\theta) e^{-\int_L \mu(\vec{x}) d\vec{x}}$
$\ln\left(\frac{b(s,\theta)}{y(s,\theta)}\right) = \int_L \mu(\vec{x}) d\vec{x}$
$y(s,\theta) = \int_L \lambda(\vec{x}) d\vec{x}\, e^{-\int_L \mu(\vec{\xi}) d\vec{\xi}}$
$y(s,\theta) = \int_L \lambda(\vec{x}) d\vec{x}\, e^{-\int_{\vec{x}}^{d} \mu(\vec{\xi}) d\vec{\xi}}$
15


THE UNIVERSITY OF SYDNEY
Simple Back Projection
2 angles
8 angles
128 angles


THE UNIVERSITY OF SYDNEY
Simple Back Projection
• leads to radial (1/r) blurring in the spatial domain
• this is equivalent to a 1/f function in the frequency domain
• what type of function would we need to multiply 1/f by to result in a perfect point source reconstruction, i.e. a **delta function**?
image space
$\frac{1}{r}$
r
k space
$\frac{1}{f_r}$
f


THE UNIVERSITY OF SYDNEY
Filtered Back Projection
2 angles
8 angles
128 angles

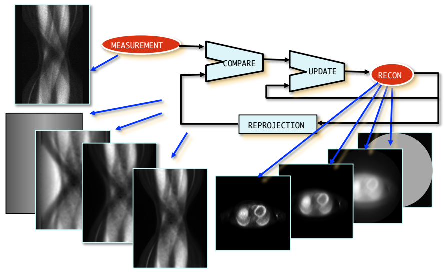

filtered backprojection
sinogram
ramp filtered
nr of angles:
1
22
44
67
89
112
134
156
178
all = 200
19

Filtered Back Projection

SBP | FBP without noise | FBP with noise

Work's great when there's no noise, but real projections contain noise...

Iterative Reconstruction



Maximum Likelihood - Expectation Maximisation

$$\lambda_j^{new} = \lambda_j \frac{1}{\sum_i a_{ij}} \sum_i a_{ij} \frac{y_i}{\hat{y}_i}$$

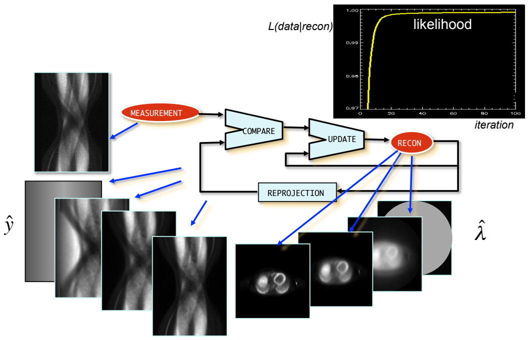
where: y_i = sinogram counts measured in bin i

λ_j = image value in voxel j

a_{ij} = probability of voxel j contributing to sinogram bin i

- produces non-negative solution
- only involves projections and back projections ("easy" forward operations)
- guaranteed to increase the log likelihood (of estimated image given measured projections) with increasing iterations

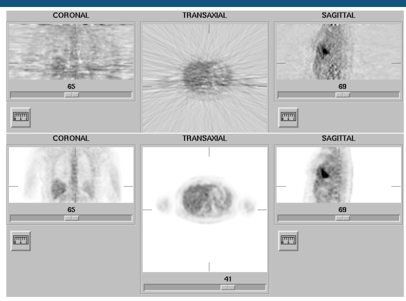
ML-EM



FBP vs ML-EM

FBP

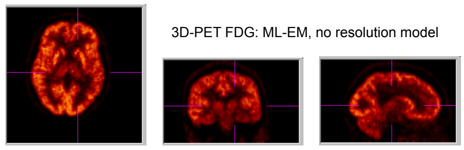
MLEM



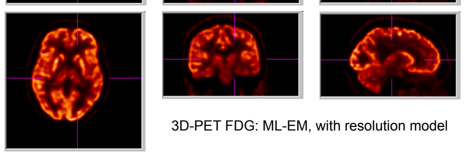
ML-EM produces visually more pleasing images than FBP...

FBP vs ML-EM

...it also allows modeling of the physics



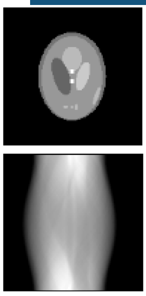
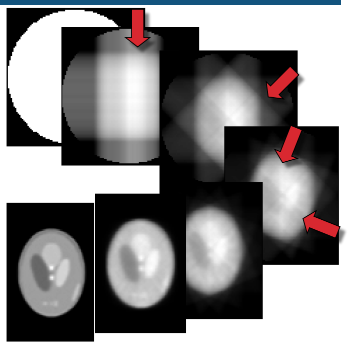
3D-PET FDG: ML-EM, no resolution model



3D-PET FDG: ML-EM, with resolution model

THE UNIVERSITY OF SYDNEY

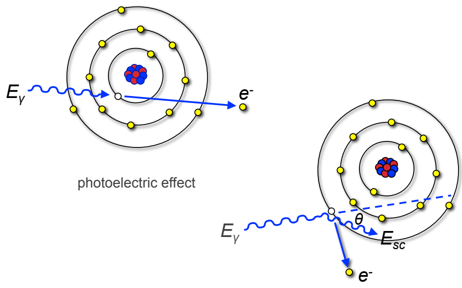
Ordered Subsets EM (OSEM)

1 iteration of 40 subsets
(2 proj per subset)

THE UNIVERSITY OF SYDNEY

Photon interactions in tissue

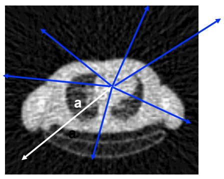


Compton scattering

THE UNIVERSITY OF SYDNEY

Attenuation Factors

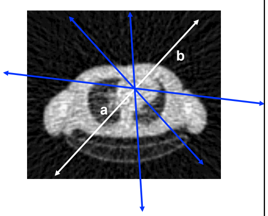
SPECT



$C = C_0 e^{-\mu a}$

ACF ≈ 5-10 in chest for ^{99m}Tc

PET

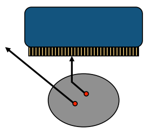


$C = C_0 e^{-\mu(a+b)}$

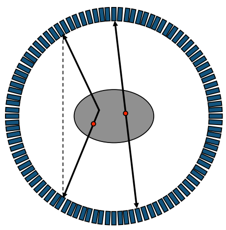
ACF ≈ 20-50 in chest

THE UNIVERSITY OF SYDNEY

Spatial Distribution of Scattered Photons



SPECT
Scattered and unscattered LoRs cannot be formed outside the body

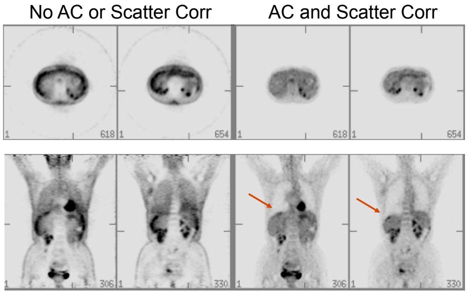


PET
Scattered LoRs can be formed outside the body but unscattered LoRs cannot

THE UNIVERSITY OF SYDNEY

Attenuation/Scatter correction

No AC or Scatter Corr | AC and Scatter Corr

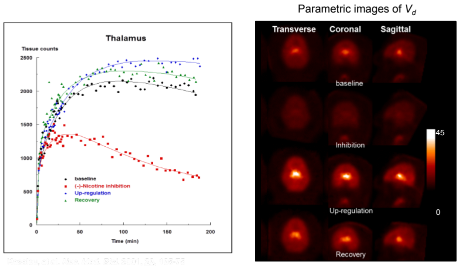


University of Pennsylvania PET Center | Philips *Allegro*

THE UNIVERSITY OF SYDNEY

Quantifying nACh receptor changes in baboon

Parametric images of V_d



Kassiou M, et al. In vivo imaging of nicotinic receptor upregulation following chronic (-)-nicotine treatment in baboon using SPECT. *Nucl Med Biol*, 28:165-175, 2001.

THE UNIVERSITY OF SYDNEY

Summary

- PET and SPECT are based on the Tracer Principle, whereby radiopharmaceuticals are administered at minute concentrations (pM – nM) such that they don't perturb the system
- The radioactive emissions are recorded by very sensitive radiation detectors surrounding the subject
- The recorded emissions form line integrals representing the accumulated activity along lines passing through the subject
- These line integrals are reconstructed into tomographic images (slices) using either FBP or an iterative algorithm such as ML-EM
- ML-EM is slower than FBP but can be accelerated using OSEM and can incorporate a detailed physical model of the imaging process
- PET and SPECT images are inherently quantitative when appropriate corrections for photon attenuation and scattering are performed