6: Positron Emission Tomography

1. What is the principle of PET imaging ?
   - Positron annihilation
   - Electronic collimation – coincidence detection
2. How are the effects of scatter and attenuation corrected for ?
3. What factors can affect resolution ?
4. Examples: PET tracers in oncology and neuroscience

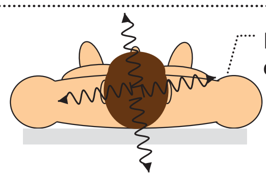
After this course you are capable of
1. Describing the essential elements of a PET scan
2. Distinguish the principle of PET detection from that of SPECT
3. Understand the bases of scatter elimination.
4. Understand the factors affecting spatial resolution in PET.

6-1. What is Positron Emission Tomography ? PET

Positron Emission tomography: measured are x-rays emitted by annihilation of positrons

emitted by exogenous substance (tracer) in body

The principle is as emission tomography, but there is one major difference … (see later)

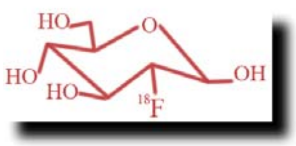


Injection of positron emitter (tracer)

Two issues:
1. How to determine directionality of x-rays ?
2. Absorption is undesirable

Most widely used tracer for PET

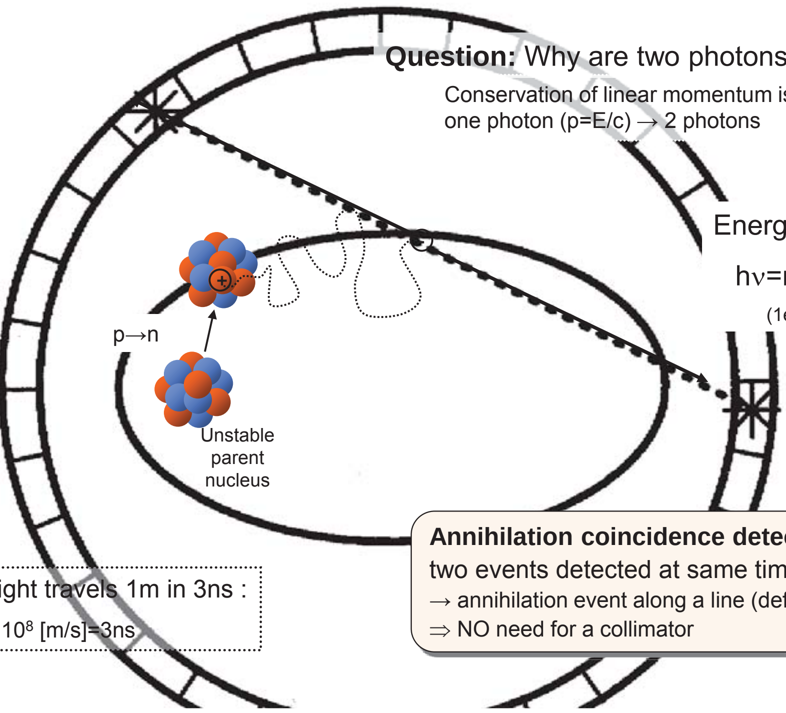
^{18}Fluoro-deoxy-glucose



F-18 FDG

What does one want to measure with PET ?

Annihilation photons



Question: Why are two photons are produced?

Conservation of linear momentum is not possible with one photon (p=E/c) → 2 photons

Energie of photons ?

$h\nu = m_e c^2 = 511 keV$

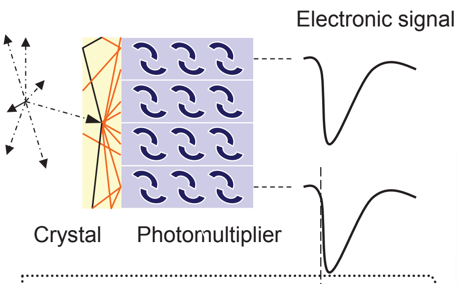
($1 eV = 1.6 \cdot 10^{-19} J$)

Annihilation coincidence detection :
two events detected at same time
→ annihilation event along a line (defined by detector)
⇒ NO need for a collimator

NB. Light travels 1m in 3ns :
$1[m]/3\ 10^8\ [m/s] = 3ns$

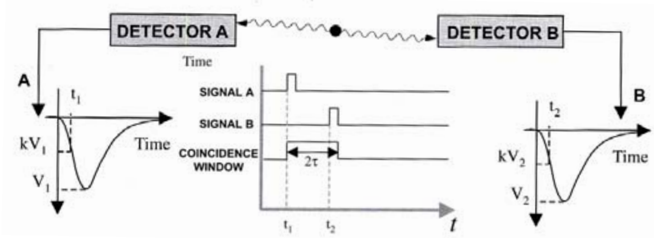
What is coincidence detection ?

electronic collimation (i.e. w/o physical collimators)

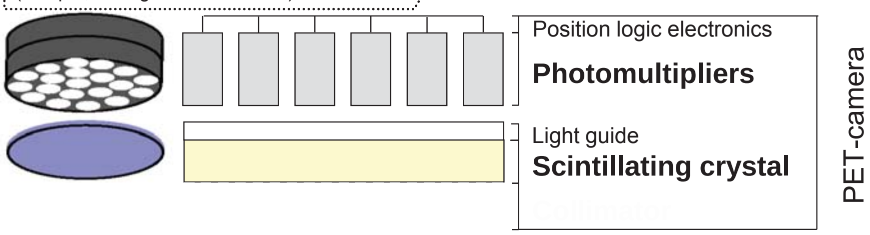


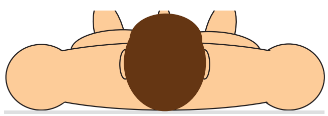
Leading edge defines time of detection
(sharper, i.e. higher 1st derivative)

What defines simultaneity (coincidence) ?



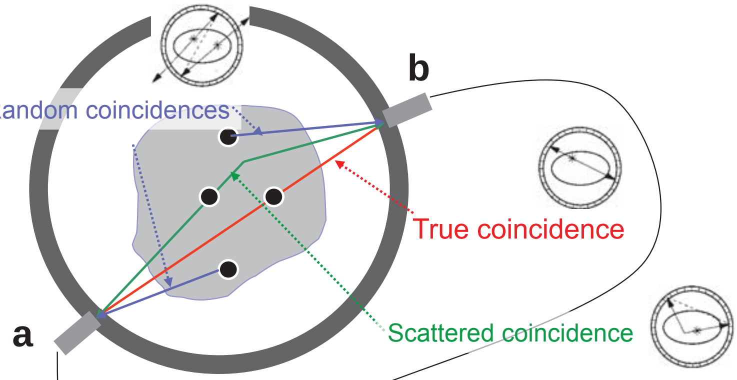
$Bi_4Ge_3O_{12}$ (BGO): $\tau \sim 10ns$.





Elimination of collimator material is a major source of sensitivity increase (why?)

6-2. What is really measured with PET ?



Trues

$$Y_{ab} = N_{ab}(A_{ab}T_{ab} + S_{ab} + R_{ab})$$

What is measured

Normalization

(Instrument imperfection)

Attenuation

Scatter

Randoms

Why are Random and Scattered Events bad?

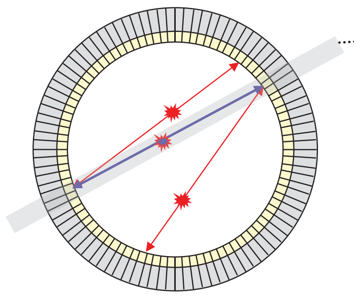
mimic a true coincidence

Random

emissions from unrelated nuclear transformations interact simultaneously with the detectors

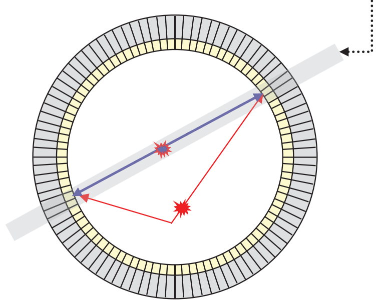
Scatter

At least one annihilation photon is (Compton) scattered



Erroneous Line of incidence (LOI)

⇒ assignment to wrong Radon transform



Rate of random coincidences :

$$R_{rand} = 2\tau S_1 S_2$$

S_1 and S_2 : count rates on the individual detectors (singles rates)

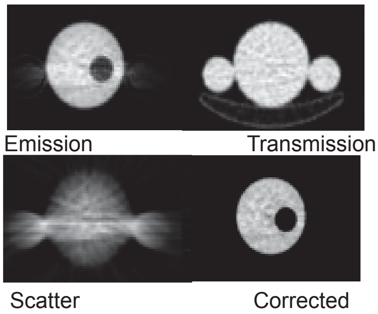
τ : separation of singles (=coincidence time)

Reduce randoms by reducing τ (coincidence interval)

Does not work for scattered events (why?)

How can scattered events be distinguished from true coincidence ?

Energy discrimination & background subtraction

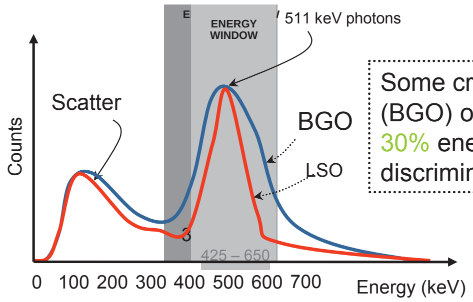


Most scattering is by Compton

$$E_f = \frac{m_e c^2}{2 - \cos\theta}$$

theta/Ei	511	(keV)
20	482	
45	395	
90	256	
110	218	
180	170	

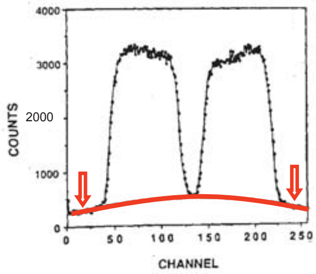
Measure E_f → identify severely scattered photons

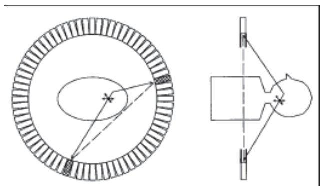


Some crystals (BGO) only allow 30% energy discrimination

Other approaches are needed:

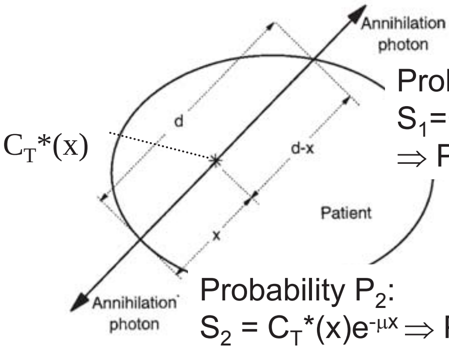
Subtract background (= scatter + randoms) measured in signal void regions → polynomial interpolation





6-3. How is attenuation correction performed ?

simpler for PET than SPECT



$C_T^*(x)$

Probability P_1:
$S_1 = C_T(x)^* e^{-\mu(d-x)}$
$\Rightarrow P_1 = S_1 / C_T^*(x)$

Probability P_2:
$S_2 = C_T^*(x) e^{-\mu x} \Rightarrow P_2 = S_2 / C_T^*(x)$

Attenuation :
Probability of detecting the photon pair

$$P_1 P_2 = e^{-\mu x} e^{-\mu(d-x)} \qquad S = C_T^*(x) e^{-\mu d}$$

$$S = P_1 \cdot P_2 \cdot C_T^*$$

Compare to geometric average of SPECT (Lesson 5)

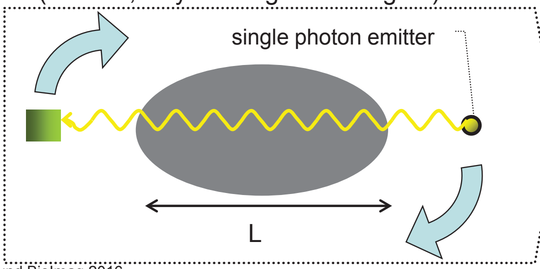
What are the steps in Attenuation Correction for PET ?

Mass attenuation coefficient μ/ρ in soft tissue = $0.095 cm^2/g$ (511keV)

$HVL = 0.693/\mu$ → HVL≅7cm

Average path length for the photon pair
- longer than for a single photon
- different lines of response attenuate to varying degrees

Attenuation correction in practice:
- Spatially uniform attenuation coefficient assumed
- Transmission technique using e.g. Cs source (662keV, why is this good enough ?)



Comparison with blank scan

i.e. subject removed

$$e^{-\mu d(\varphi)}$$

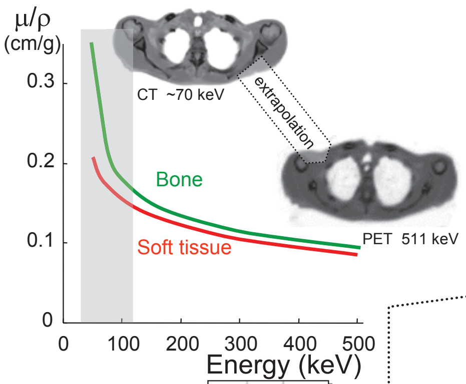
$$e^{-\int \mu(x) dx}$$

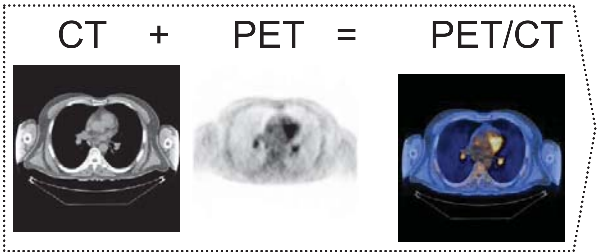
Correction factor for each Radon transform

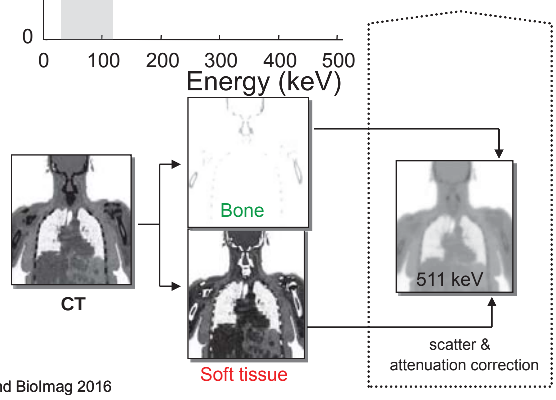
(μ homogeneous)

Why is PET/CT the industry standard ?

PET-Attenuation correction using CT-Data

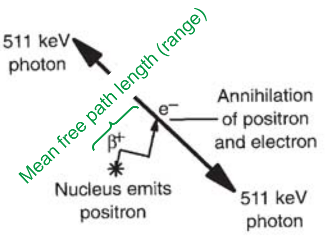






6-4. Why is Resolution never perfect ?

Annihilation Range and photon non-collinearity



Range: limits spatial resolution

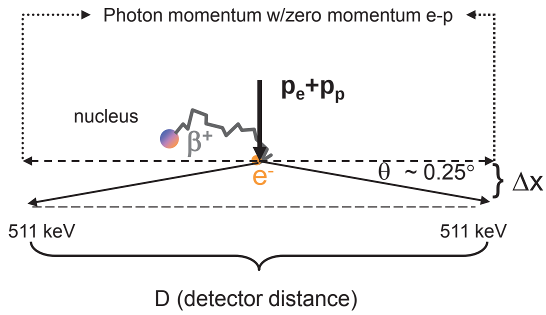
(In air, β^+ range ~ several m)

Isotope	Half-life (min)	Max. Energy (MeV)	Range in H_2O (FWHM, mm)
^{18}F	110	0.6	1
^{11}C	21	1.0	1.2
^{15}O	2	1.7	1.5
^{13}N	10	1.2	1.4
^{68}Ga	68	1.9	1.7
^{82}Rb	1	3.2	1.7

Collinearity: Assumed for Reconstruction

Background: At time of annihilation, e-p pair has non-zero kinetic energy

→ conservation of momentum



$\Delta x = 0.5\ D \tan(0.25°)$

D (cm)	Δx (mm)
60	1.3
80	1.7
100	2.2

How does the detector affect PET spatial resolution ?

Example: BGO Block Detector

Coincidence window: 12 ns

Energy resolution: ~ 25%

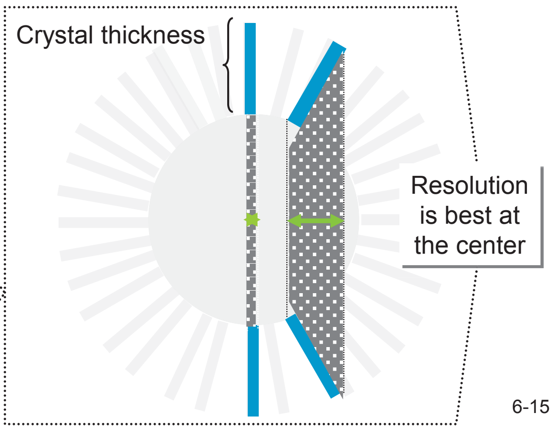
True coincidence count rate R_T

$$R_T=2C^*_T G\varepsilon^2$$

1. C_T^* - tissue activity of a voxel
2. ε : the intrinsic detector efficiency ($1-e^{-\mu x}$)
3. G : the geometric efficiency (solid angle defined by the detector surface/4π).

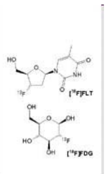
NB. ε = 0.9→ 81% of photon pairs emitted towards detectors produce coincidence

This is a reason for the 3cm thick crystals used for PET detection.



6-5. What are typical PET tracers ?

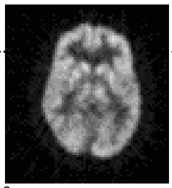
Oncology and neuroscience



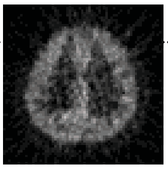
Oncology

^{18}Fluoroethyl-Tyrosine (FET)	Amino acid transport
Deoxy-^{18}fluoro-thymidine (FLT)	Proliferation
^{18}Fluoromisonidazole (FMISO)	Hypoxia
^{11}C-Methionine	Amino acid transport and metabolism
$H_2{}^{15}O$	Blood flow
^{18}Fluoro-Deoxyglucose (FDG)	Glucose metabolism
^{18}FDOPA	Presynaptic dopaminergic function
^{15}O-Butanol	Blood Flow
^{11}C-Flumazenil	Benzodiazepine-receptor mapping

Neuroscience



FDG or
F_{18} fluorodeoxyglucose



O_{15} Water

X-ray imaging modalities. Overview

CT, SPECT, PET

Measurement of signal integrated along line of incidence (LOI)
(Radon transform)

1. CT: attenuated incident x-ray beam
(direction of beam given by source)
2. SPECT: emitted single photon
(need collimation to determine ray direction)
3. PET: annihilation photon pair
(directionality by electronic collimation)

Apply correction to measured Radon transform
(attenuation, scatter, etc.)
Backprojection or central slice theorem:

Finally an image!

	CT	SPECT	PET
Projection Encoding	Defined by incident x-ray (collimation to reduce scatter)	Collimator essential	Coincidence detection (electronic collimation)
Spatial Resolution (rodent)	100µm-mm (µm)	Typical 10mm (Variable and complex) (1.5-3 mm)	4.5-5mm at center (1mm)
Attenuation	= measurement variable (Varies with energy)	Complex correction (Varies with photon energy)	Accurate correction (transmission method)
Radionuclides	None (contrast agents)	Any with hν= 60-200keV	Positron emitters only