5: Emission (Computed) Tomography

1. What is a tracer ?
2. Why is collimation necessary and what are its consequences ?
3. How are the effects of attenuation taken into account ?
4. What is the principle of x-ray detection ?
   scintillation
5. How are scintillation photons converted to an electrical signal ?
6. How can scattered photons be eliminated ?

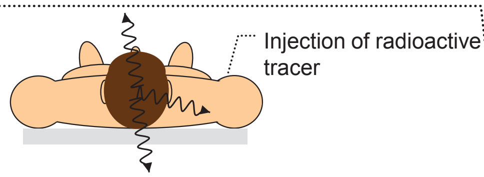
After this course you

1. Understand the reason for collimation in imaging γ-emitting tracers and its implication on resolution/sensitivity
2. Understand the implications of x-ray absorption on emission tomography
3. Understand the basic principle of radiation measurement using scintillation
4. Are familiar with the principle/limitations of photomultiplier tube amplification
5. Understand the use of energy discrimination for scatter correction

What is Emission Computed Tomography ?

Until now: CT and x-ray imaging measure attenuation of incident x-ray

Emission tomography: X-rays emitted by exogenous substance (tracer) in body are measured



Two issues:

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

What is a tracer ?

Exogenously administered substance (infused into blood vessel) that

(a) alters image contrast (CT, MRI)

(b) has a unique signal (γ **emitting**)

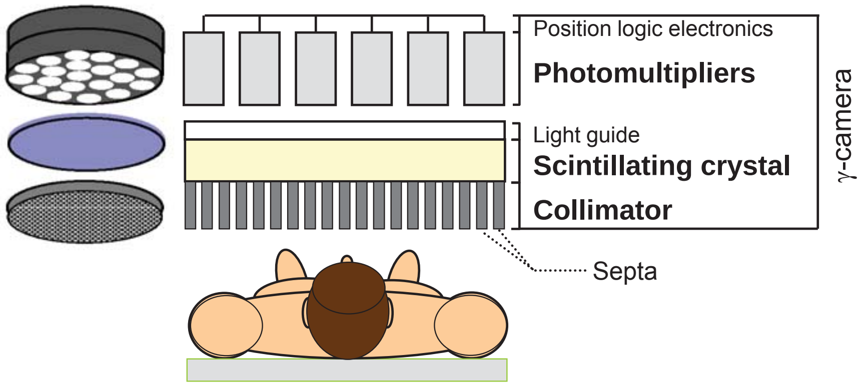
-> Emission computed tomography

Typical tracers for emission tomography

half-life and photon energies

	[h]	[keV]
^{99m}Tc	6	140
^{201}Tl	73	70
^{123}I	13	159
^{133}Xe	0.08	81

What are the basic elements needed for γ-emitter imaging ?

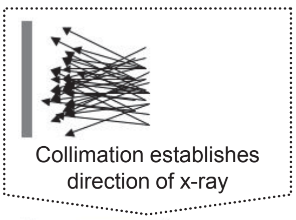


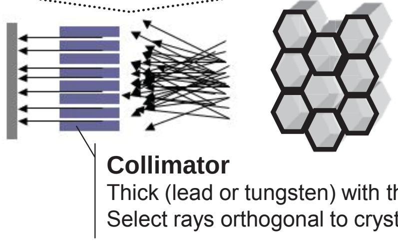
5-2. How can directionality of x-rays be established ?

Collimation

Problem: Photon detection alone does not give directionality

Solution:

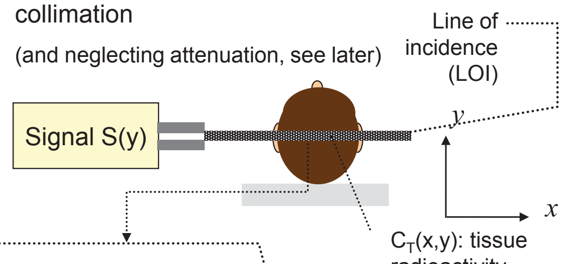




Collimator
Thick (lead or tungsten) with thin holes
Select rays orthogonal to crystal

Consider one detector, assuming perfect collimation

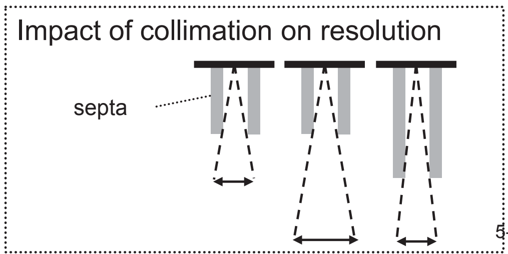
(and neglecting attenuation, see later)



$$S(y) = \int_{\infty}^{-\infty} C_T(x,y)\,dx$$

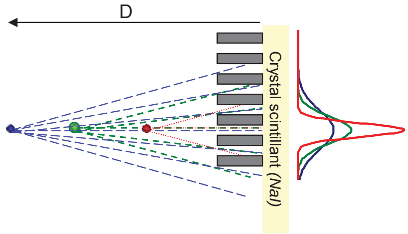
Radon transform

⇒ Reconstruction as in CT



How does collimation affect resolution ?

It's never perfect …

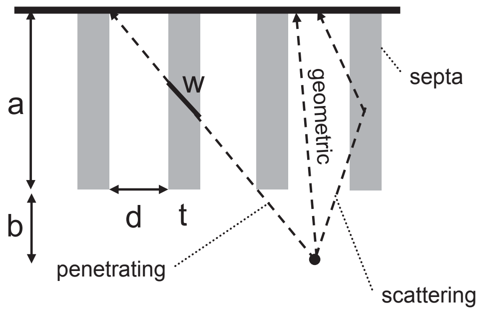


Perfect collimation, i.e. resolution ?

$d/a \to 0$

$\mu_{collimator} t \to \infty$

Impossible to achieve (Why?)



Septa penetration < 5% occurs when $t = t_{5\%}$:

$$t_{5\%} \approx \frac{6d/\mu}{a - 3/\mu}$$

Collimator resolution:

Two objects have to be separated by distance >R

$$R = \frac{d(a_e + b)}{a_e}$$

$a_e = a - 2/\mu$

(a_e: imperfect septal absorption)

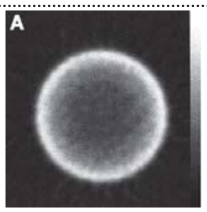
Price of collimation (resolution) ?

Sensitivity !

5-3. How to deal with attenuation of the emitted x-rays ?

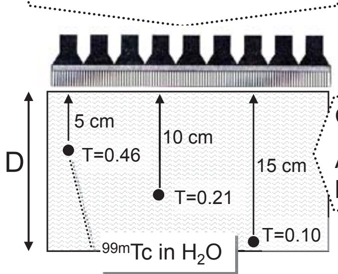
result of x-ray absorption in tissue

Signal measured from a homogeneous sphere ($C_T(x,y)$=constant)



Intensity distortion:
Cause ?

$n(D) = N_0 e^{-\mu D}$



$\mu_{water}(140keV) = 0.16\,cm^{-1}$

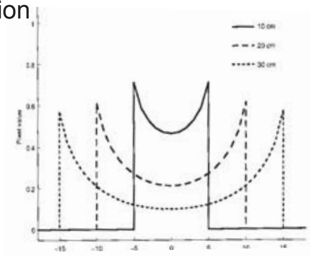
$\text{HVL} = 0.693/\mu \cong 4.5\text{cm}$

Consider point source:

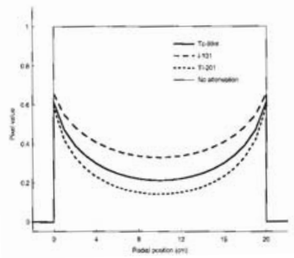
Attenuation depends on location of source in tissue

Attenuation T $\quad T = \frac{n(D)}{N_0} = e^{-\mu D}$

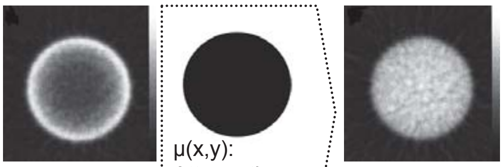
1. depends on object dimension and source location (D=f(object))



2. Photon energy $\mu = f(E_\gamma)$



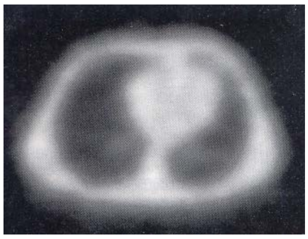
What are the basic steps in attenuation correction ?



Measured

μ(x,y): Attenuation correction

Corrected image



A(x,y) of thorax

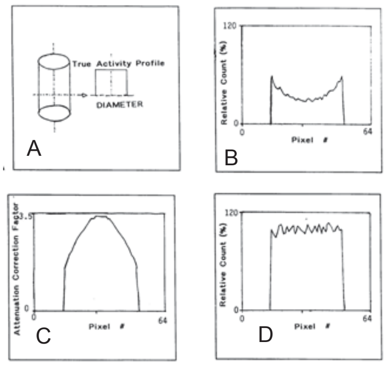
Attenuation correction procedure

A. Estimated object geometry and estimated μ(x,y) or measured μ(x,y)

B. Transmission loss : T(projection)=f(μ(object), projection)

C. Attenuation correction A(x,y)=1/T(x,y)

D. Corrected $C_{corr}(x,y)$=A(x,y) C(x,y)



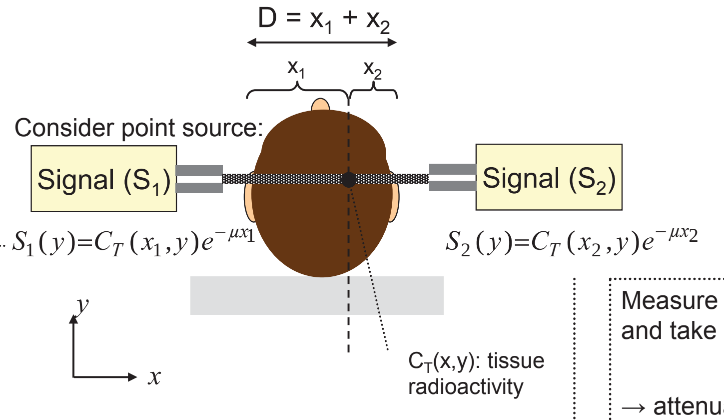
Problem is prior knowledge needed for A (i.e. μ(x,y))

Attenuation correction rarely applied!

How to simplify attenuation correction ?

by measuring at 180^0 using geometric mean

Problem: Spatial dependence of correction



$S_1(y) = C_T(x_1,y)e^{-\mu x_1}$

$S_2(y) = C_T(x_2,y)e^{-\mu x_2}$

$$\sqrt{S_1 \cdot S_2} = C_T(x,y)e^{-\mu D/2}$$

NB. This correction can be used in emission tomography for focal uptake (i.e. uptake limited to a specific region)

Solution: Geometric mean of the two 180^0 opposite signals:

$$\sqrt{S_1 \cdot S_2} = \sqrt{C_T(x_1,y)e^{-\mu x_1} C_T(x_2,y)e^{-\mu x_2}}$$

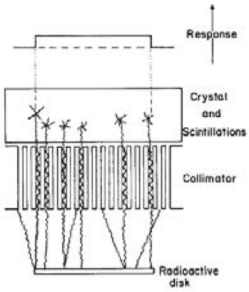
$$= C_T(x,y)\sqrt{e^{-\mu(x_1+x_2)}} = C_T(x,y)\sqrt{e^{-\mu D}}$$ (D = x_1 + x_2)

Measure at 180^0 simultaneously and take the geometric mean

→ attenuation correction depends only on dimension of object along the measured Radon transform

5-4. What is the principle of x-ray detection ?

Collimation, followed by scintillation and amplification



Scintillator crystal e.g. Tl-doped SodiumIodide (NaI)

Photomultiplier Tube

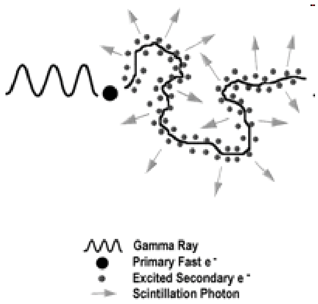
Light electrons El. Signal

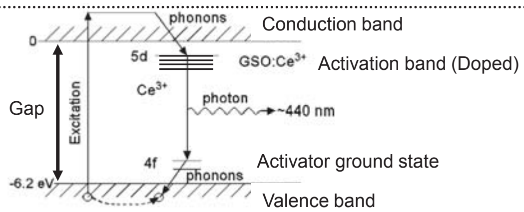
γ-energy ∝ # scintillation photons ∝ Signal

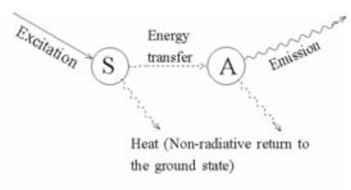
What is Scintillation ?

Sequence of events in scintillation crystal

1. Atom ionized by Compton interaction → Electron-hole pair
2. Hole ionizes activator, electron falls into activator
3. Activator is deactivated by emission of Photons (10^{-7} sec)







Efficiency of scintillators

$$\eta \equiv \frac{\text{energy of scintillation light}}{\text{energy deposited}} \propto \frac{Tq_a}{W_{e-h}}$$

T = energy transfer efficiency from excited ion to luminescence centre

q_A= quantum efficiency of luminescence centre

W_{e-h} = energy required to create one electron-hole pair

What elements characterize scintillation materials ?

Overview of some crystals

Scintillator	Density (g/cm^3)	Attenuation Coefficient (cm^{-1} @ 511 keV)	Light yield ph/keV	λ (nm)	τ (ns)	Z_{eff}	Refr. Index	Yield
$CdWO_4$	7.90	0.886	19	495	~10^4			
$Bi_4Ge_3O_{12}$	7.13	0.964	8,	480	300	73	2.15	13%
$(Y,Gd)_2O_3$:Eu,Pr	5.9	0.503 - 0.637	19	610	~10^6			
Gd_2O_2S:Pr,Ce,F	7.34	0.786	40	510	~10^3			
NaI:Tl	3.67	0.343	40	415	230	51	1.85	100%
Gd_2SiO_5:Ce	6.71	0.704	7,	430	300	59		
Lu_2SiO_5:Ce	7.4	0.869	30	420	40	66		79%
$LuAlO_3$:Ce	8.34	0.956	11	365	~17			
$LuPO_4$:Ce	6.53	0.735	17	360	25			

Requirements for scintillator

- High yield
- Good linearity
- Small time constant τ
- Transparent for scintillation light λ
- good mechanical properties
- Refraction index close to 1.5

Most of the energy of the x-ray is lost as heat (to lattice), see

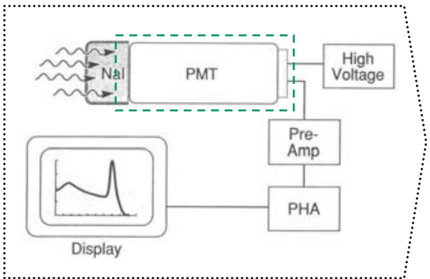
e.g. NaI(140keV)=40·140 =5600 photons at λ≅400nm

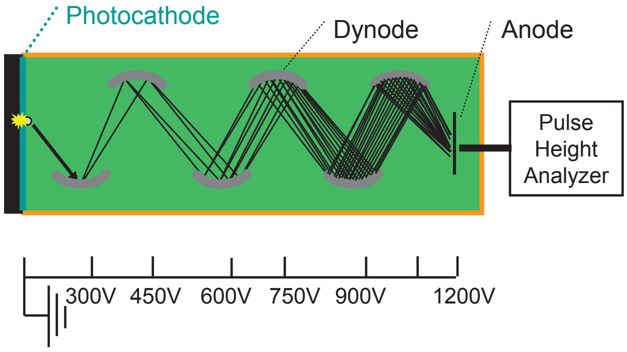
E_{400nm}[keV]=hc/λ = 1.2/λ [nm] =1.2/400 keV=3eV

<20keV or <120eV/keV

5-5. How is the scintillation light converted to an electrical signal ?

Photomultiplier tube (PMT) -Noiseless amplification



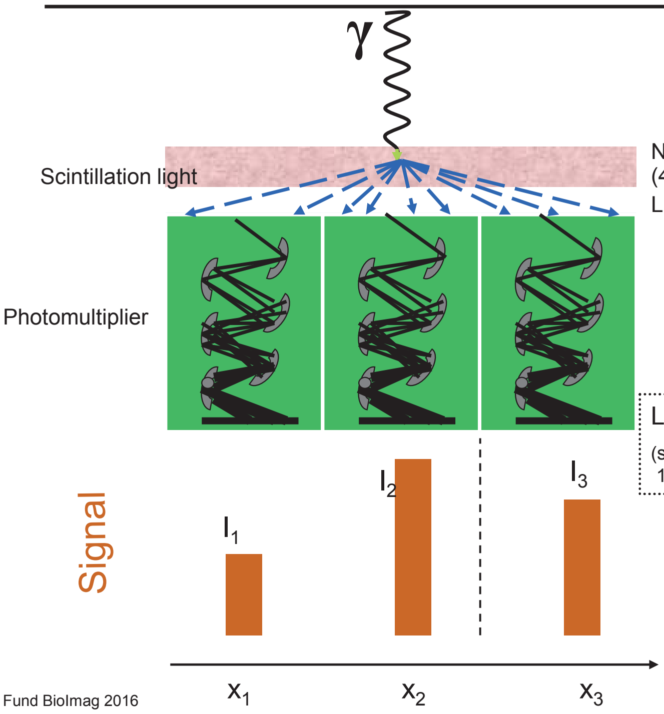


PMTs are bulky

Scintillator crystal

How to increase resolution beyond PMT dimensions ?

How to improve the spatial resolution of PMT ?
(Anger, 1964)



NaI-crystal
(40 cm x 40 cm)
Light-guide

$$x = \frac{\sum x_k I_k}{\sum I_k}$$

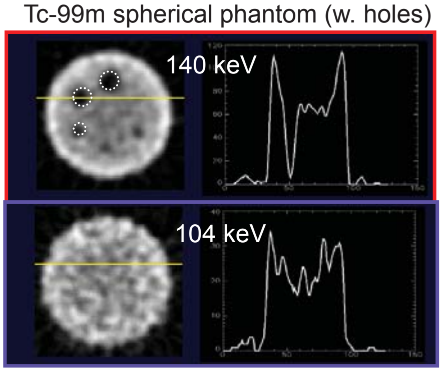
Looks familiar ?
(see center of mass
1st year Physics)

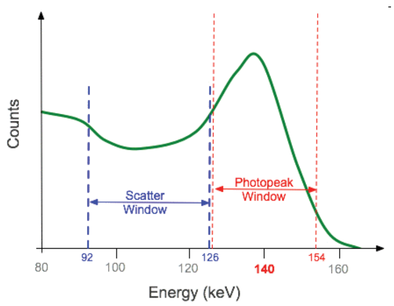
$$x_{CM} = \frac{\sum x_k m_k}{\sum m_k}$$

→ Location, Energy

5-5. How to discriminate scattered photons ?

Tc-99m spherical phantom (w. holes)



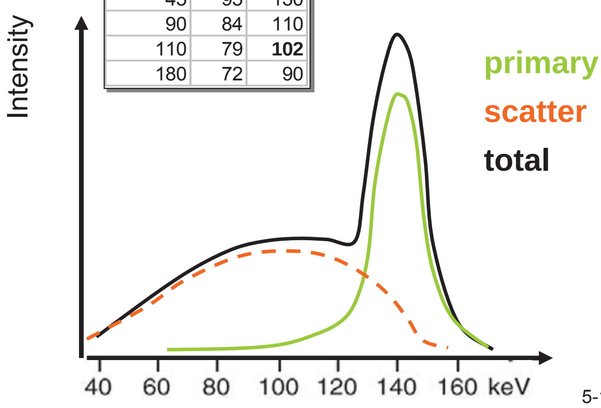


Most scattering is by Compton

$$E_f = \frac{E_i}{\left(1 + E_i \frac{(1-\cos\theta)}{m_e c^2}\right)_i}$$

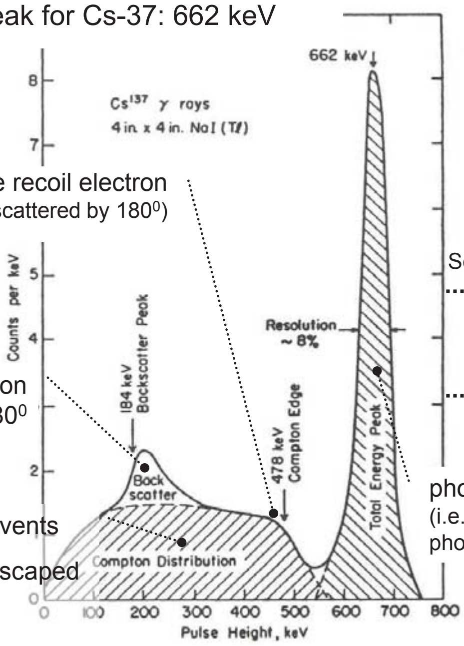
Measure E_f
→ identify severely scattered photons

theta/E_i	100	**140**
20	99	138
45	95	130
90	84	110
110	79	**102**
180	72	90



What processes contribute to the Scintillation light spectrum ?
scintillation signal depends on x-ray energy

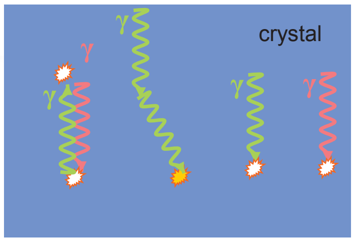
NaI (Tl) scintillation peak for Cs-37: 662 keV

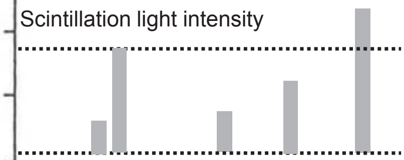


max. energy of the recoil electron
(i.e. 662 keV photon scattered by 180^0)

energy of 662 keV photon scattered by 180^0

- light from Compton events
- secondary photons escaped from crystal





Scintillation light intensity

photons that lose all energy
(i.e. Compton events + final photoelectric event)

SPECT summary
Single **P**hoton **E**mission **C**omputed **T**omography

1. Measurement of single photon emitters
   injected into subject
2. Collimation ensures x-ray directionality (⇒ backprojection)
3. Absorption is undesirable
4. Photon energies comparable to CT
   ⇒ SPECT-CT