Nuclear diagnostics and Magnetic Resonance Imaging
Week 1; Lecture 3; Gamma camera

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Contents

Section 1

Introduction

Overview

Exploit γs produced in decay of radiotracer, so, detectors must:

- Have good detection efficiency in range 50–600 keV
- Provide capability to measure γ energy:
  - To detect and reject γ that have undergone Compton scattering and so have lost pointing accuracy

"Gamma camera":

- Technique based on light production in a large-area crystal of sodium iodide (NaI)
- Scintillation light, produced by exciting atoms by absorption of radiation
- Light detection typically using 'photomultiplier tubes' (PMTs)

Generating scintillation light

Scintillation light is generated by relaxation of atomic electrons excited by ionising radiation.

scintillator   photodetector
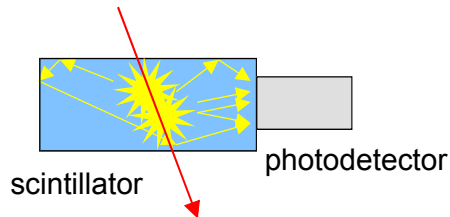
Properties of inorganic scintillators (e.g. NaI) include:

- Large range of Z and density; for medical application average and density Z of NaI and are favourable giving high probability that photon will be detected
- Large light yield; up to 40,000 photons per MeV
  - i.e. signal depends on energy of incident photon
- Single-decay times of from ns to μs

See for example Ambrosio, CERN Academic Training, April 2005
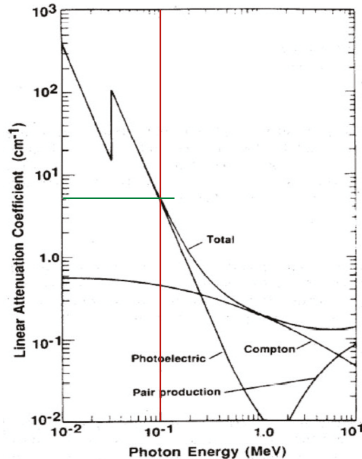
Generating scintillation light
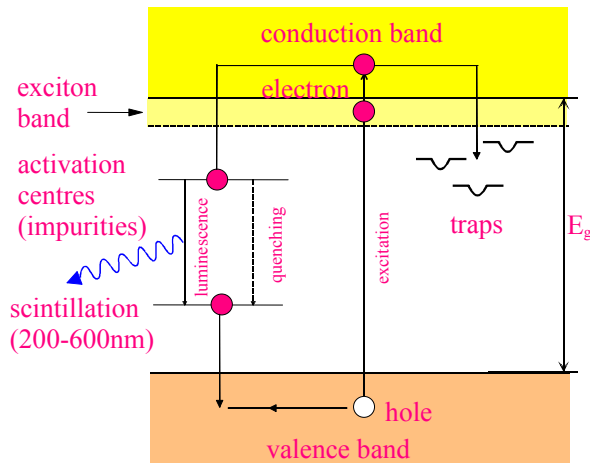
There can be more than one time constant:

- Fast recombination (ns–μs) from activation centres
- Delayed recombination due to trapping (μs–ms)
  - Traps arise due to dopants (wanted) and lattice imperfections (unwanted)

Chrystal preparation determines properties of scintillation light

See for example Ambrosio, CERN Academic Training, April 2005

Photon absorption in crystals

Intensity, I, function of depth traversed, d:

$$I = I_0 \exp(-\mu d)$$

μ is the "Linear attenuation coefficient"

For NaI, at the energies we are interested in, penetration depth is a few mm

Detecting scintillation light

Photo-electric effect used to convert light into electronic signal that can be digitised

Detector requirements:

- High sensitivity; i.e. high "quantum efficiency", QE:

$$QE = \frac{N_{\mathrm{pe}}}{N_\gamma}$$

where N_{pe} is the number of photo-electrons generated by N_γ photons impinging on detector

- Low intrinsic noise
- Low gain fluctuations

See for example Gys, CERN Academic Training, April 2005

The photo-electric effect

Photoemission threshold W_{ph} of various materials

Ultra Violet (UV) — Visible — Infra Red (IR)

TMAE,CsI — Bialkali — GaAs — Multialkali — TEA

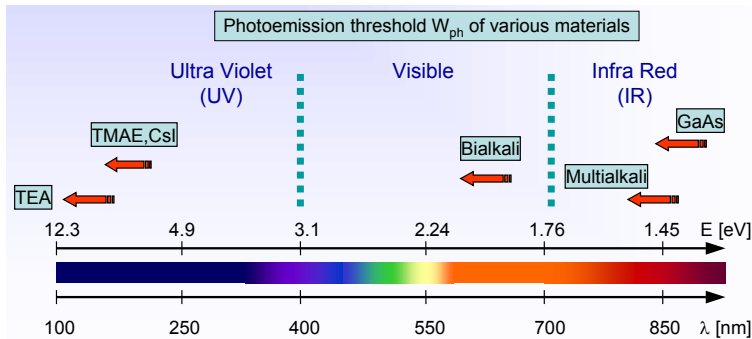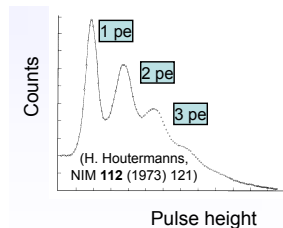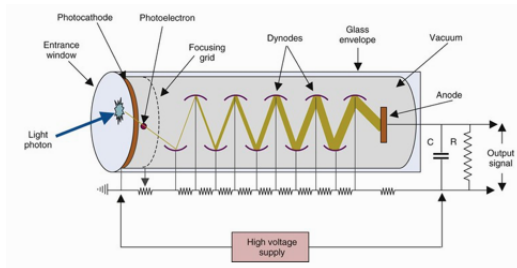| 12.3 | 4.9 | 3.1 | 2.24 | 1.76 | 1.45 | E [eV] |

| 100 | 250 | 400 | 550 | 700 | 850 | λ [nm] |

Photo-electric a 3-step process:

- Excite electrons in photocathode photon
- Excited electrons diffuse through material, losing some energy
- Electrons reaching surface with energy sufficient to escape may be detected

The photo-multiplier tube

- Photo-emission from photo-cathode
- Secondary emission from subsequent dynodes
- Dynode gain, $g_i = \frac{N_e^{\mathrm{sec}}}{N_e^{prim}}$, usually between $g_i = 3$ and $g_i = 50$
- Total gain $\mathcal{G} = \Pi_1^{N_{\mathrm{dynode}}} g_i$

See for example Gys, CERN Academic Training, April 2005

Summary of section 1

Gamma camera exploits scintillation light to detect photons produced in radionuclde decay

Scintillation light is:

- Generated in the relaxation of atomic electrons excited by the passage of ionising radiation
- Detected using photomupliplier tubes

Section 2

Gamma camera

The Gamma camera

"Imaging collimator" defines direction of detected γs

- Forms projected image on scintillator

Large, single-crystal NaI scintillator coupled to a clear plastic or glass light guide
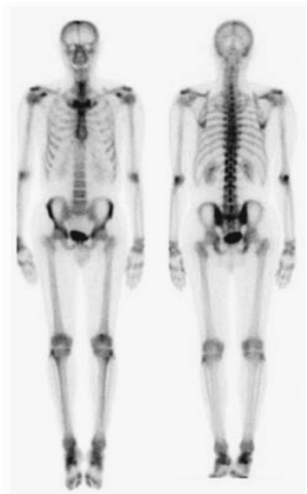
Light detected using PMT array

PMT readout by pulse-height-sensitive electronics; events are recorded if energy falls within the desired window

Many events are required for an image to be built up:

- x, y intensity map;
- γ-energy spectrum
- Possibly also the time evolution of the image
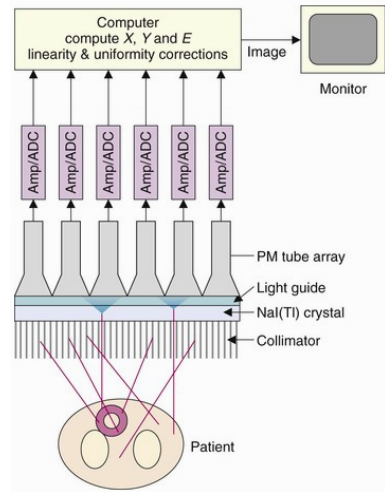
Example image

Example whole-body image taken using ^{99m}Tc-MDP
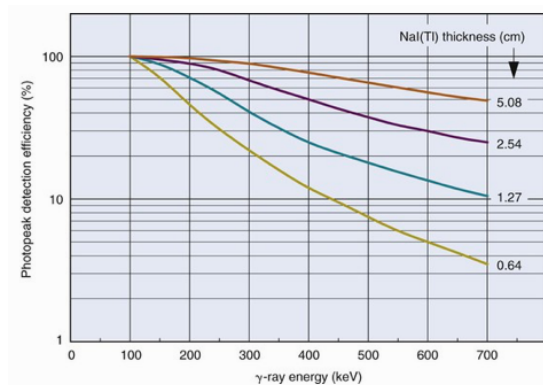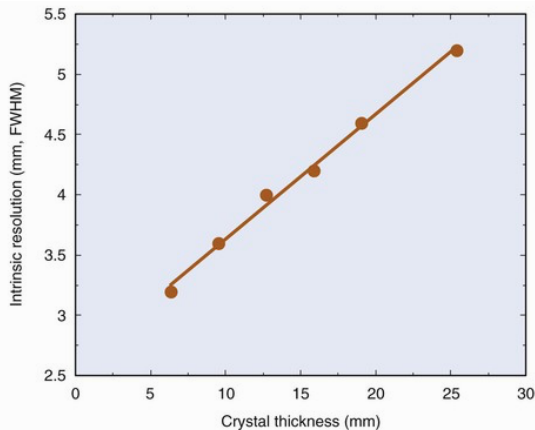
Resolution

Contributions to intrinsic resolution:

- Detector thickness (geometrical effect)
- Compton scattering on atomic electron:
  - $\gamma_i + e \rightarrow \gamma_o + e'$; γ_o not parallel to γ_i
  - Small effect: $< 10\%$ of γs displaced by $> 2.5\,\mathrm{mm}$ in $6.4\,\mathrm{mm}$ thick detector
- Statistical fluctuations in photon count:
  - Scintillation photons & photoelectrons Poisson distributed
  - If N photoelectrons expected, variance of number detected will be N
  - Consequence is that distribution of γs over surface of detector will fluctuate
- Intrinsic resolution degrades with decreasing E_γ:
  - Fewer scintillation photons expected for low-energy γs
  - So, RMS of fluctuations ($\propto \frac{\sqrt{N}}{N}$) grows as E_γ decreases

Intrinsic spatial resolution for $6.3\,\mathrm{mm}$ thick NaI(Tl) crystal.

Thallium (Tl) doping improves light production efficiency through recombination of electrons/holes at dopant site in lattice.
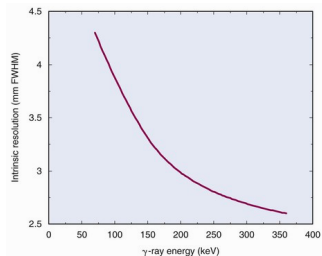
Trade off between resolution and efficiency

For practical sources (e.g. ^{99m}Tc), $100 \lesssim E_\gamma \lesssim 200$ keV. Motivates thickness of 5–6 mm to get high efficiency and good resolution.

Decay γ selection

Compton-scattered photons have an energy lower than that of the decay photons.
Atomic transitions from electrons excited in the lead shield or the NaI detector also contribute low-energy photons.
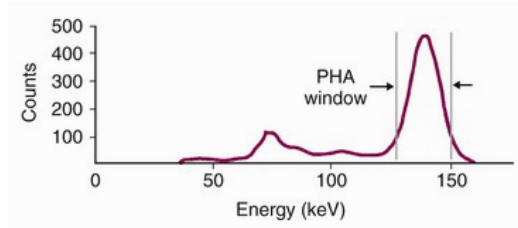
PHA: pulse height analyser

Exploit energy resolution to select γs that emerge without scattering:
- Energy resolution $\propto \frac{1}{E_\gamma}$.
- Typical energy resolution, $\frac{\Delta E_\gamma}{E_\gamma}$, is $\sim 10\%$ at 140 keV.

Types of event

A: Good event

B: Scatter in detector:

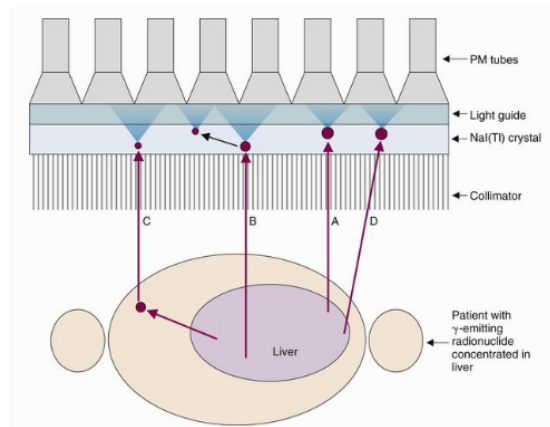- Full energy is recorded, but
- Position information is distorted

C: Scatter in patient

- γ arriving at detector has reduced energy, but may still fall within the detection window
- Unwanted event

D: Septal penetration

- Unwanted event

Summary of section 2

The gamma camera exploits a large NaI crystal viewed using and array of photomultipliers to generate an image of the take-up of a gamma-emitting radionuclide

A collimator is used to define "pointing" accuracy

The intrinsic resolution of the gamma camera is related to the thickness of the scintillator; it improves with photon energy

Selection of high-energy photons reduces the contribution from photons that have undergone Compton scattering

Section 3

Collimator

Image formation

Image is formed using an "absorptive" collimator:

- The collimator absorbs "unwanted" γs

Collimator selects direction of observed γs:

- This determines the "pointing geometry"
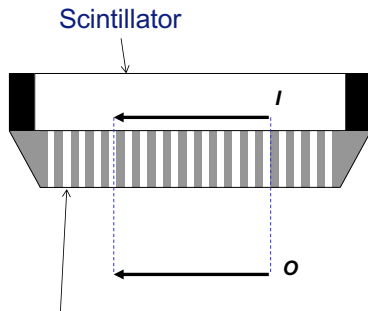- Wasteful of γs, most are absorbed in collimator

Absorptive collimator made from lead or tungsten:

- High probability of absorption in moderate thickness of material

Four main types:

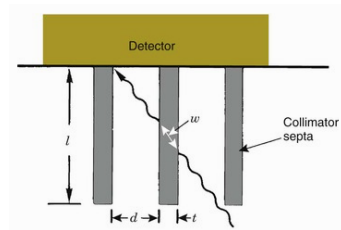- Parallel, pin-hole, converging, diverging

Parallel-hole collimator

Scintillator

I

Pinholes

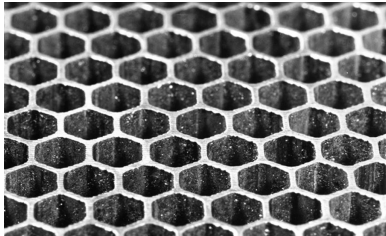Magnification, M, given by:
$$M = \frac{I}{O} = 1$$

γ incidence minimizing material shown. Hence: $t = \frac{2dw}{l-w}$

Specify, septal penetration $\lesssim 5\%$; i.e., for medium with linear attenuation coefficient, μ, $\ln \frac{I}{I_0} \lesssim \ln(0.05) = -\mu w \approx 3$:

$$t \gtrsim \frac{6d}{\mu l - 3} \approx 3\,\text{mm for Pb collimator and } E_\gamma = 140\,\text{MeV}$$

Parallel-hole collimator: contribution to resolution

Example: hexagonal holes to maximise area of detector exposed
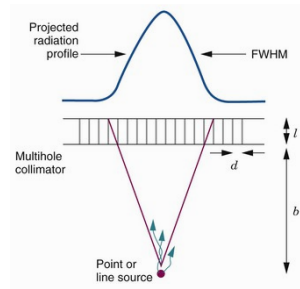
Resolution, δr_{col}, is FWHM spread of radiation from point source.

$$\delta r_{\mathrm{col}} \approx d \frac{l + b}{l}$$

Independent of t

Parallel-hole collimator: geometrical efficiency

Geometric efficiency, g, defined as fraction of emitted γs that are transmitted by collimator
Example, for square-hole collimator:

$$g = \frac{d^4}{12 l^2 \left(d + t\right)^2}$$

Independent of b, because:

- Efficiency for a particular hole falls as $\frac{1}{b^2}$, but
- Number of holes illuminated groups as b^2

Single-hole efficiency $\propto 1/b^2$

Detector area exposed $\propto b^2$

Radiation source

b

Collimator
Detector
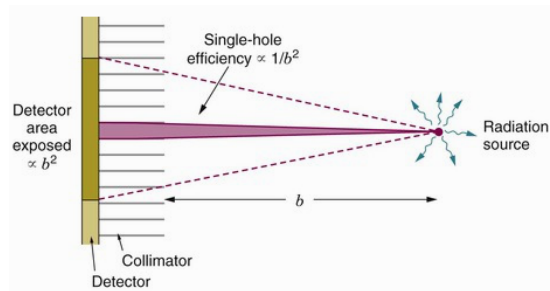
Parallel-hole collimator: summary

Collimator Type	Recommended Max. Energy (keV)	Efficiency, g	Resolution R_{coll} (FWHM at 10 cm)
Low-energy, high-resolution	150	1.84×10^{-4}	7.4 mm
Low-energy, general-purpose	150	2.68×10^{-4}	9.1 mm
Low-energy, high-sensitivity	150	5.74×10^{-4}	13.2 mm
Medium-energy, high-sensitivity	400	1.72×10^{-4}	13.4 mm

Diverging collimator

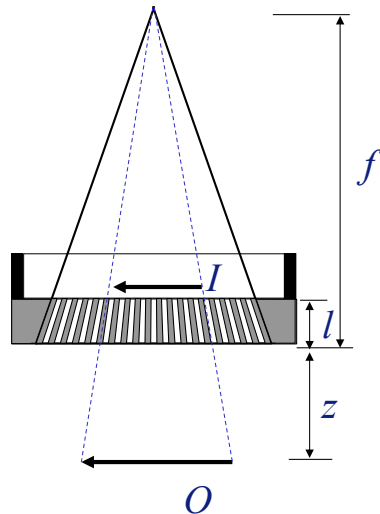Focal point typically 40–50 cm behind collimator

Large field of view

Reduced image that is not inverted

Image size depends on distance (z) leading to distortion

Magnification:

$$M = \frac{I}{O} = \frac{f - l}{f + z} < 1$$

Converging collimator

Focal point typically 40–50 cm in front of collimator

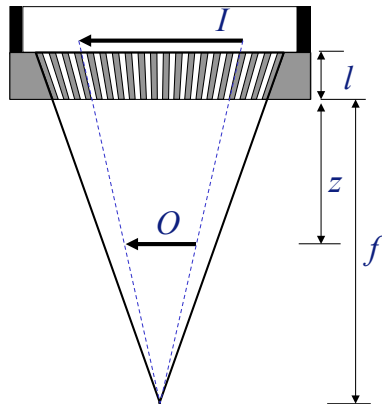Reduced field of view

Magnified image that is:

- Not inverted if $z < f$
- Inverted if $z > f$

Image size depends on distance (z) leading to distortion

Magnification:

$$M = \frac{I}{O} = \frac{f + l}{f - z} > 1$$

Pinhole collimator

Pinhole size $\sim$ mm

Field of view depends on z
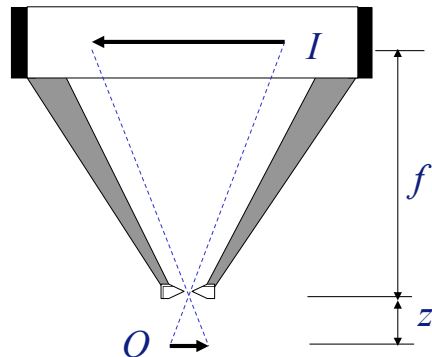
Image is:

- Magnified and inverted if $z < f$
- Reduced and inverted if $z > f$

Image size depends on distance (z) leading to distortion

Magnification:

$$M = \frac{I}{O} = \frac{f + I}{f - z} > 1$$

Summary of section 3

Collimator geometry is chosen based on application.

Contribution to overall resolution of gamma camera and its efficiency depend on collimator thickness and size of holes

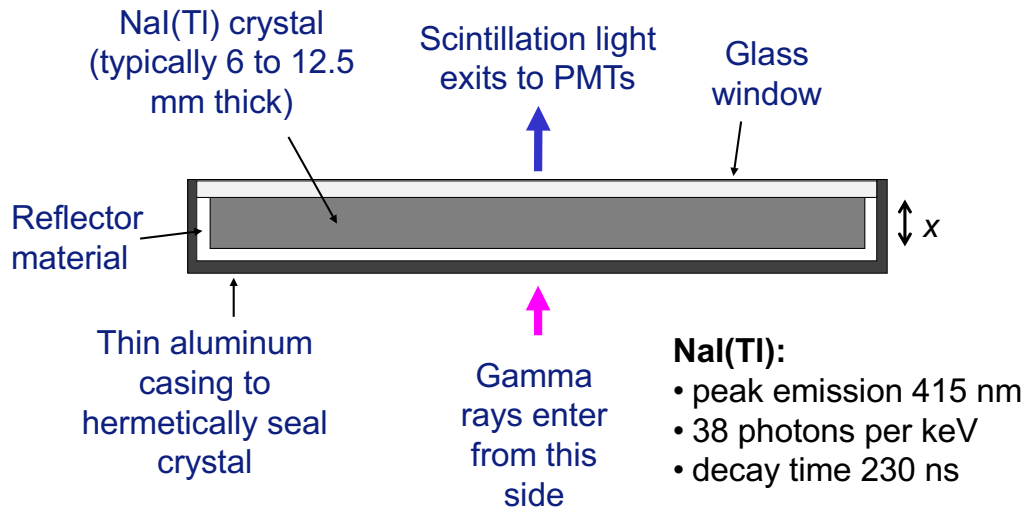Four types of collimator were considered:

- Parallel-hole collimator:
- Diverging collimator: produces a reduced image (magnification, $M < 1$)
- Converging collimator: produces a magnified image (magnification, $M > 1$)
- Pin-hold collimator: produces a magnified image (magnification, $M > 1$)

Section 4

Scintillator

Crystal assembly

NaI(Tl) crystal (typically 6 to 12.5 mm thick)

Scintillation light exits to PMTs

Glass window

Reflector material

x

Thin aluminum casing to hermetically seal crystal

Gamma rays enter from this side

NaI(Tl):
• peak emission 415 nm
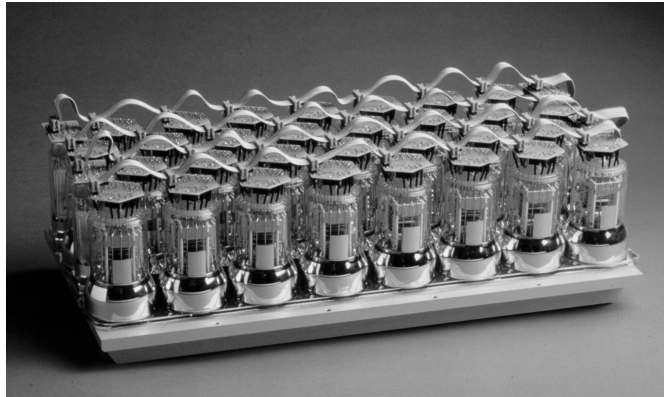• 38 photons per keV
• decay time 230 ns

Head

Area: typically $60 \times 40 \, \text{cm}^2$

PMT diameter: typically $50 \, \text{mm}$

30–100 PMTs per head

Position reconstruction
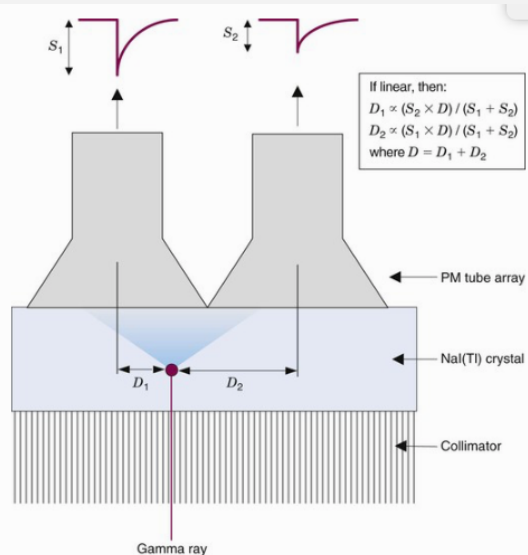
In linear approximation:

$$D_1 = \frac{S_2 \times D}{S_1 + S_2}$$

$$D_2 = \frac{S_1 \times D}{S_1 + S_2}$$

where $D = D_1 + D_2$

Event position is calculated as the centroid ("centre of mass") of the PMT signals

More complex algorithms that account for distortions are also employed

If linear, then:
$D_1 \propto (S_2 \times D) / (S_1 + S_2)$
$D_2 \propto (S_1 \times D) / (S_1 + S_2)$
where $D = D_1 + D_2$

PM tube array

NaI(Tl) crystal

Collimator

Gamma ray

Detection efficiency

Can now define detection efficiency of the system:, $\mathcal{E}$:

$$\mathcal{E} = g\epsilon F_{\mathrm{elec}}$$

where:

- g is the geometrical efficiency
- ϵ is the ratio of the number of γs recorded divided by the the number of γs incident:

$$\epsilon = 1 - \exp\left(-\mu_{\mathrm{scint}} t_{\mathrm{scint}}\right)$$

  where μ_{scint} is the linear attenuation coefficient of the scintillator and t_{scint} its thickness
- F_{elec} is the fraction of the γs accepted by the discriminators (front-end of the electronics)

Spatial resolution

Three major contributions to the spatial resolution:

- **Collimator resolution**, δr_{col}, defined above, usually dominates
- Intrinsic resolution, δr_{int} – ability of PMTs to localise event
- Residual impact of Compton scattering, δr_{Compt} in tissue resulting in non-colinearity of deetected γ with the γ that which left the decay site

System resolution is given by:

$$\delta r_{\text{sys}} = \left[\delta r_{\text{col}}^2 + \delta r_{\text{int}}^2 + \delta r_{\text{Compt}}^2 \right]^{\frac{1}{2}}$$

Summary of section 4

The gamma camera head is composed of the "crystal assembly" and the PMT array

The pulse-height measured in adjacent PMTs is used in a weighted mean to determine the position at which the γ struck the scintillator
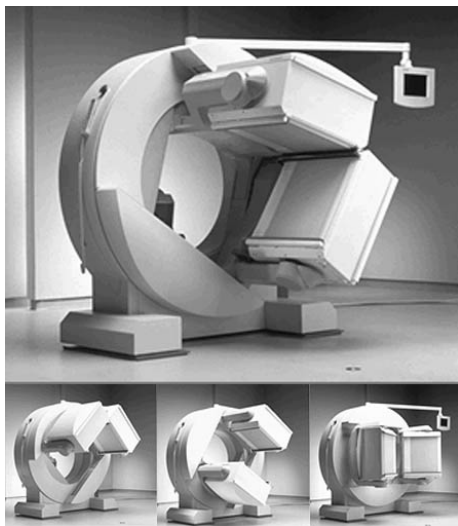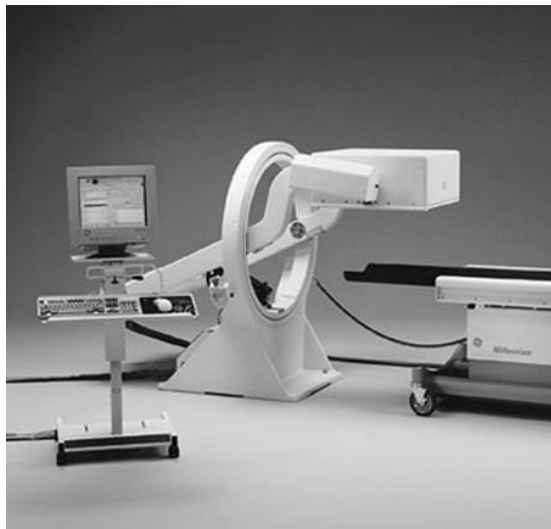
The detection efficiency is determined by the geometrical efficiency of the collimator, the attenuation coefficient of the scintillator, and the signal threshold applied in the front-end electronics

The spatial resolution is determined by the quadratic sum of the collimator resolution, the intrinsic resolution of the scintillator, and the contribution to the resolution due to Compton scattering
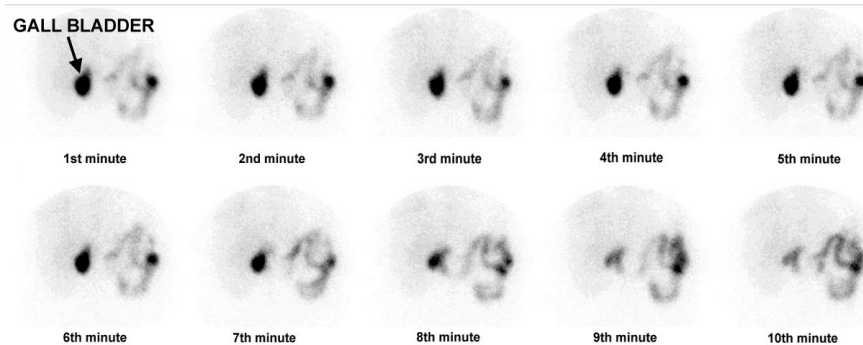
Section 5

Examples

Gamma cameras

Dynamic imaging study

GALL BLADDER

1st minute   2nd minute   3rd minute   4th minute   5th minute

6th minute   7th minute   8th minute   9th minute   10th minute

- ^{99m}Tc-HIDA
- At $t - 7$ mins, cholecystkinin was administered to simulate emptying of the gallbladder
- Rate of emptying can be measured from the sequence