Nuclear diagnostics and Magnetic Resonance Imaging

Lecture 3: Nuclear diagnostics III: gamma camera

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Outline

1. **The Gamma Camera**
    - Introduction
    - Gamma camera
    - Collimator
    - Scintillation detector
    - Gamma cameras and example images

Section 1

The Gamma Camera

Overview

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

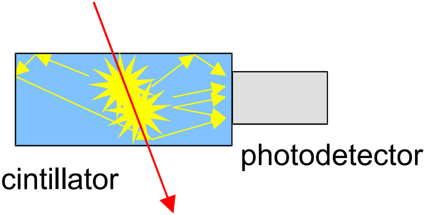
- Have good detection efficiency in range 80–300 keV
- Provide capability to measure γ energy:
    - To detect and reject γ that have undergone Compton scattering and so have lost pointing accuracy

"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.

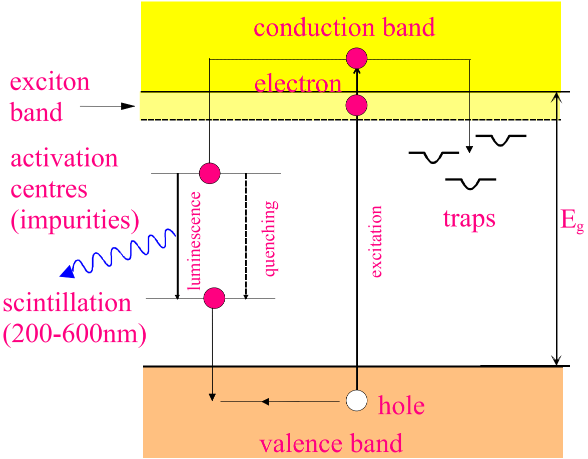


Properties of inorganic scintillators (e.g. NaI) include:

- 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



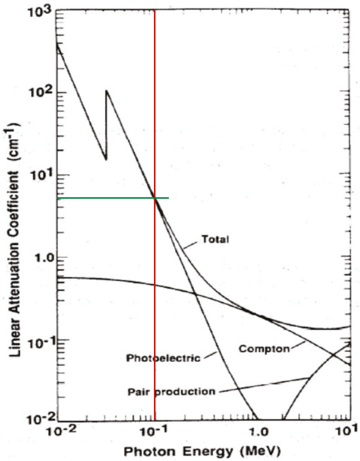
There can be more than one time constant:

- 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



DOI: http://dx.doi.org/10.5772/intechopen.8550

Intensity, I, function of depth traversed, d:

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

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:

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

  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

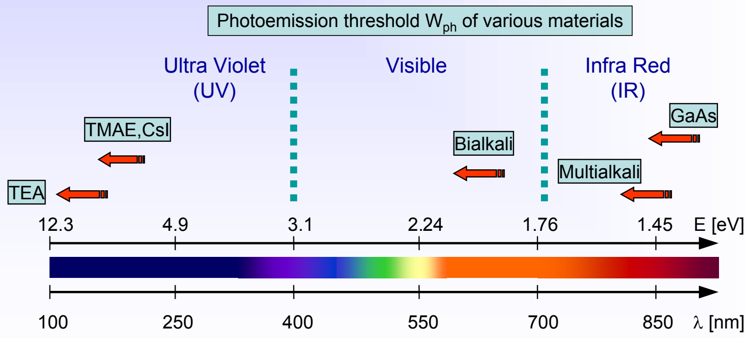
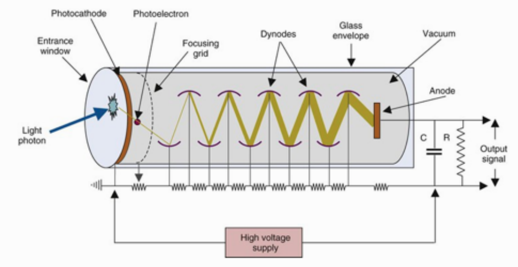
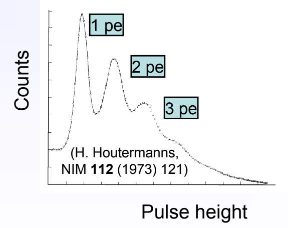


Photo-electric a 3-step process:

- 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





(H. Houtermanns, NIM **112** (1973) 121)

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

See for example Gys, CERN Academic Training, April 2005

The Gamma camera

“Imaging collimator” defines direction of detected γs

- Forms projected image on scintillator

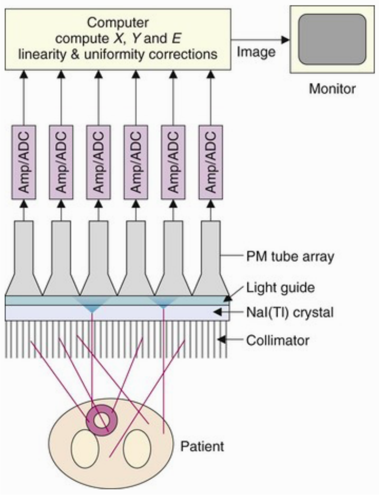
Large, single-crystal NaI scintillator coupled to a clear plastic or glass light guide

Light detected using PMT array

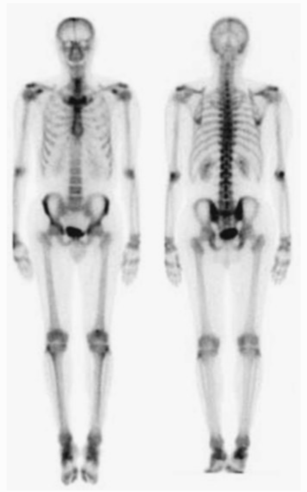
PMT readout by pulse-height-sensitive electronics; events are recorded if energy falls within the desired window

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

- 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

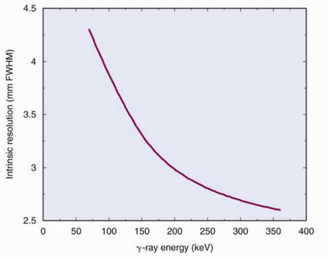
Resolution

Contributions to intrinsic resolution:

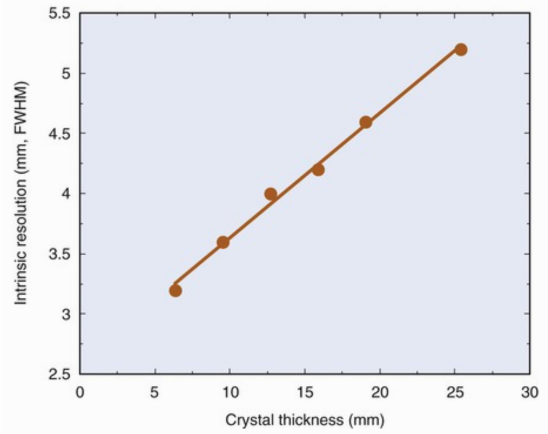
- Detector thickness (geometrical effect)
- Compton scattering on atomic electron:
  - $\gamma_i + e \to \gamma_o + e'$; γ_o not parallel to γ_i
  - Small effect: $< 10\%$ of γs displaced by > 2.5 mm in 6.4 mm thick detector
- Statistical fluctuations in photon count:
  - Scintillation photons & photoelectrons 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

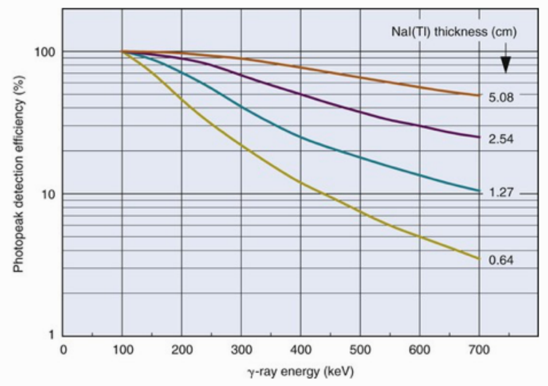
Intrinsic spatial resolution for 6.3 mm thick NaI(Tl) crystal.

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



Trade off between resolution and efficiency

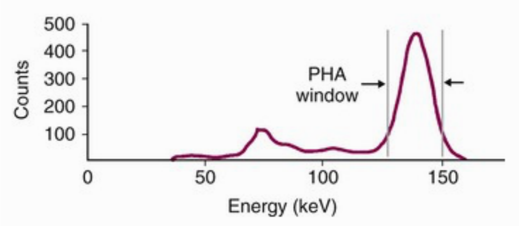




For practical sources (e.g. ^{99m}Tc), $100 \lesssim E_\gamma \lesssim 200$ keV. Motivates thickness of 5–6 mm to get high efficiency and good resolution.

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

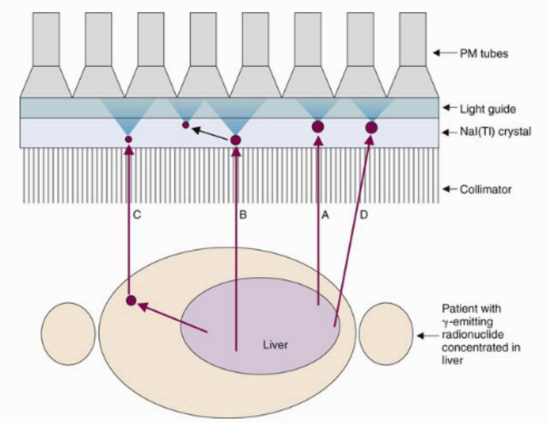


Image formation

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

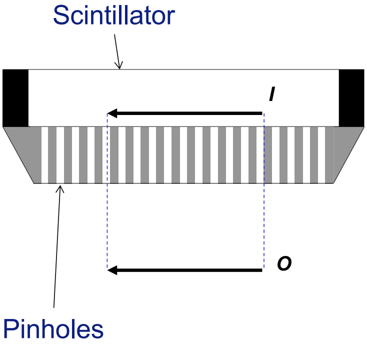
Absorptive collimator made from lead or tungsten:

- High probability of absorption in moderate thickness of material

Four main types:

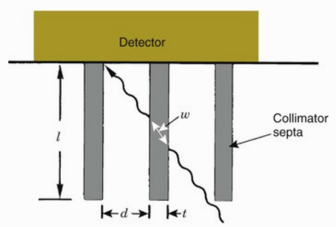
- Parallel, pin-hole, converging, diverging

Parallel-hole collimator



Magnification, M, given by:

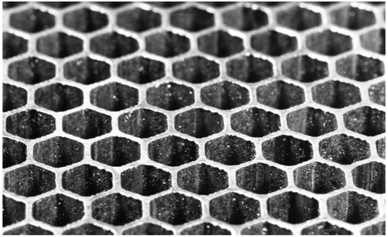
$$M = \frac{I}{O} = 1$$



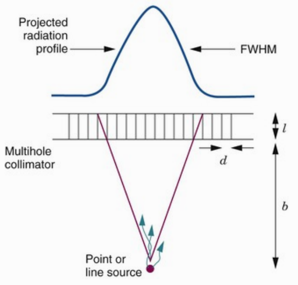
Septal thickness: $t = \frac{2dw}{l-w}$
To generate contrast, require low transmission of off-axis γs. Specify, septal penetration $< 5\%$. Then, for medium with linear attenuation coefficient, μ:

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

Parallel-hole collimator: contribution to resolution



Example: hexagonal holes to maximise area of detector exposed



Resolution, $\delta r_{\rm col}$, is FWHM spread of radiation from point source.

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

Independent of t

Parallel-hole collimator: geometrical efficiency

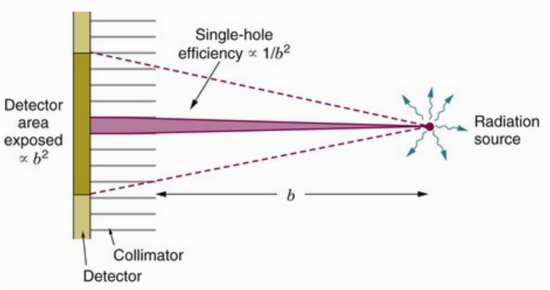
Geometric efficiency, g, defined as fraction of emitted γs that are transmitted by collimator

Example, for square-hole collimator:

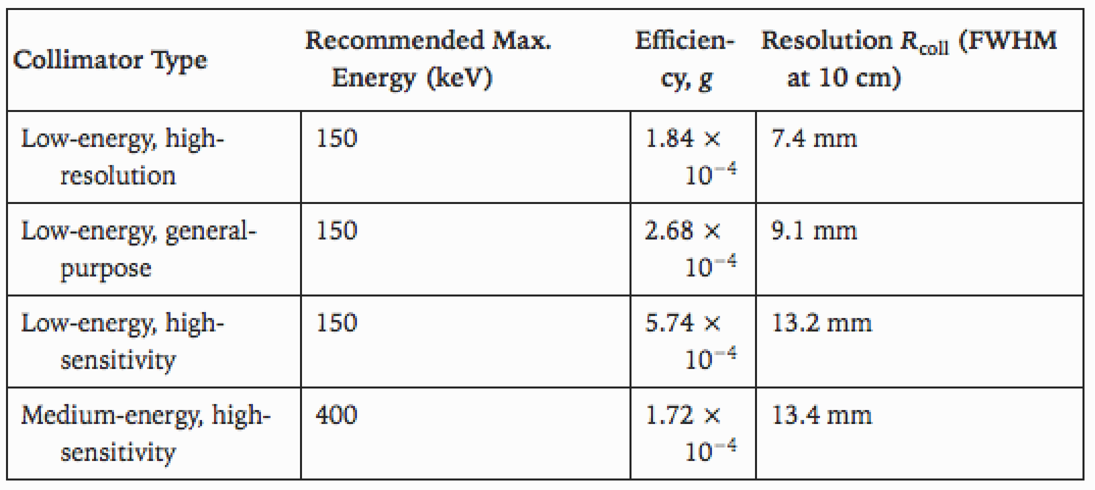
$$g = \frac{d^4}{12 l^2 \left(d + t\right)^2}$$

Independent of b, because:

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

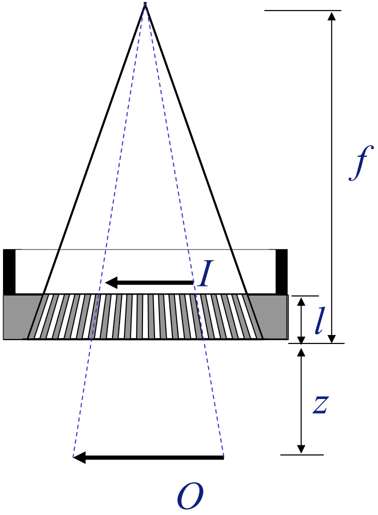


Parallel-hole collimator: summary



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

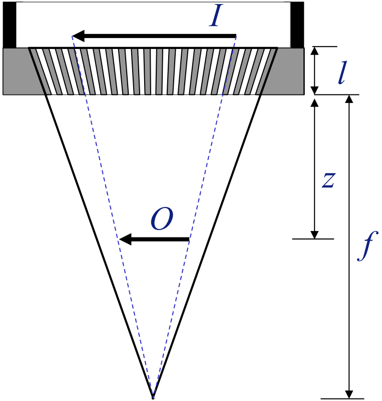
Magnified image that is:

- 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

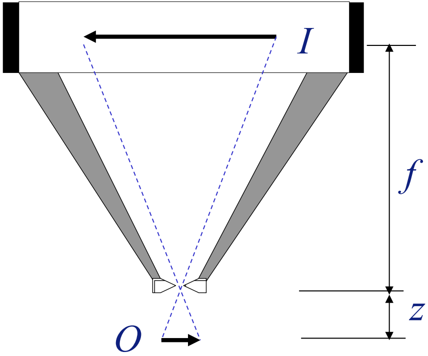
Image is:

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

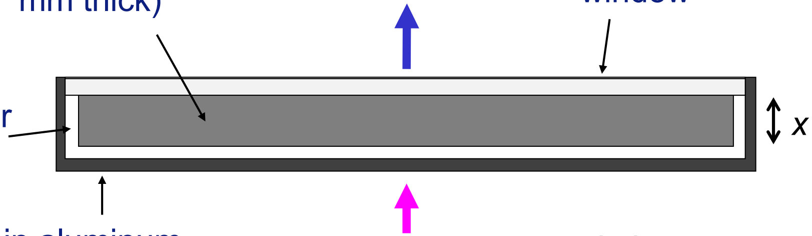
Image size depends on distance (z) leading to distortion

Magnification:

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



Crystal assembly



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

Scintillation light exits to PMTs

Glass window

Reflector material

Thin aluminum casing to hermetically seal crystal

Gamma rays enter from this side

NaI(Tl):

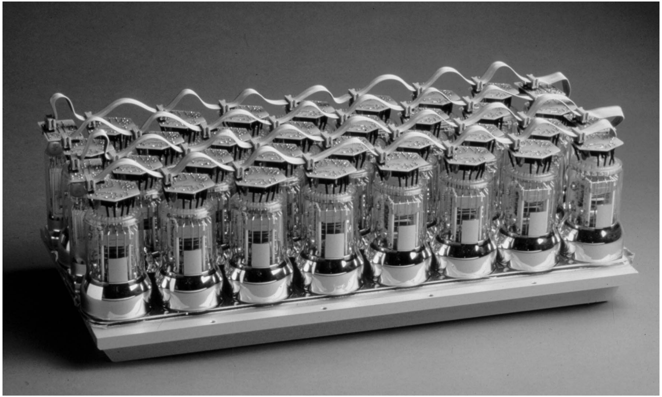
- peak emission 415 nm
- 38 photons per keV
- decay time 230 ns

Head

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

PMT diameter: typically 50 mm

30–100 PMTs per head



Position reconstruction

In linear approximation:

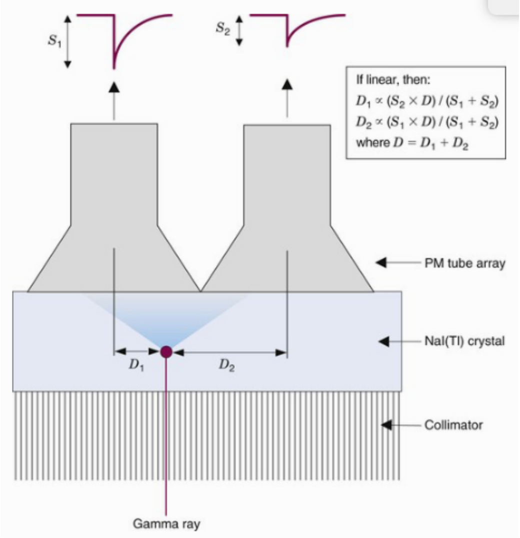
$$D_1 = \frac{S_2 \times D}{S_1 + S_2}$$

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

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



Detection efficiency

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

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

where:

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

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

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

Spatial resolution

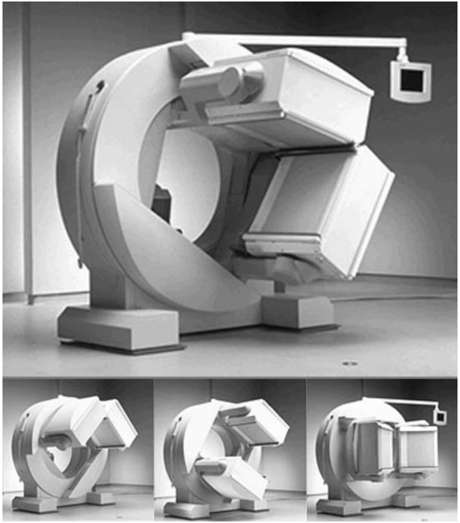
Three major contributions to the spatial resolution:

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

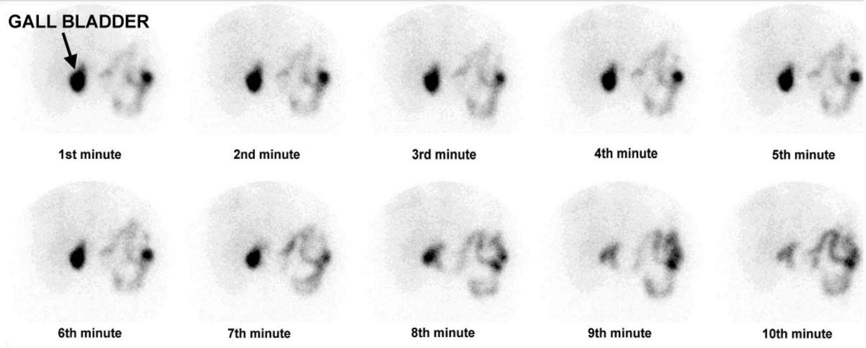
System resolution is given by:

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

Gamma cameras



Dynamic imaging study



- ^{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