NHS
Hull University Teaching Hospitals
NHS Trust

FRCR Nuclear Medicine

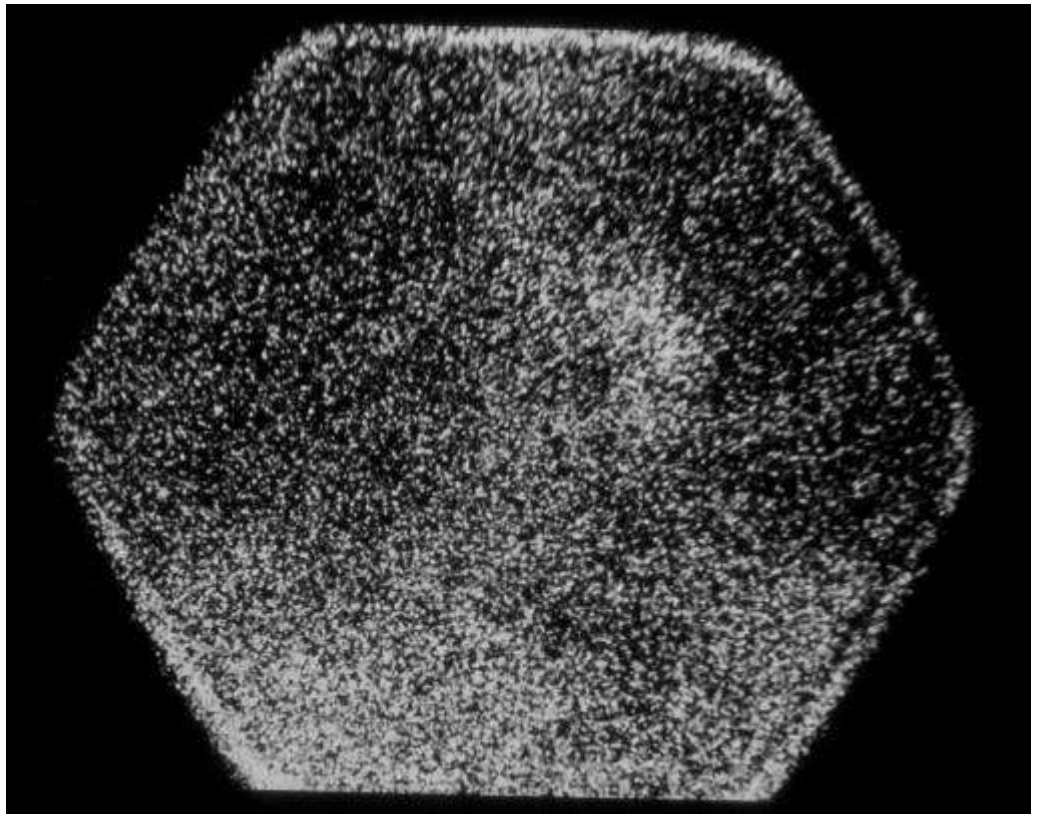
Lecture 1
The Gamma Camera and Image Formation

Today

1. What is Nuclear Medicine?
2. What are radiopharmaceuticals? What ideal properties do we require?
3. What is a gamma camera?
    - what are its components?
4. How do we form an image using a gamma camera?
5. What types of imaging can we do using the gamma camera?
6. Clinical examples of different types of scans using the gamma camera

Nuclear Medicine or…

Unclear Medicine ?



Can you spot the difference?

Alive

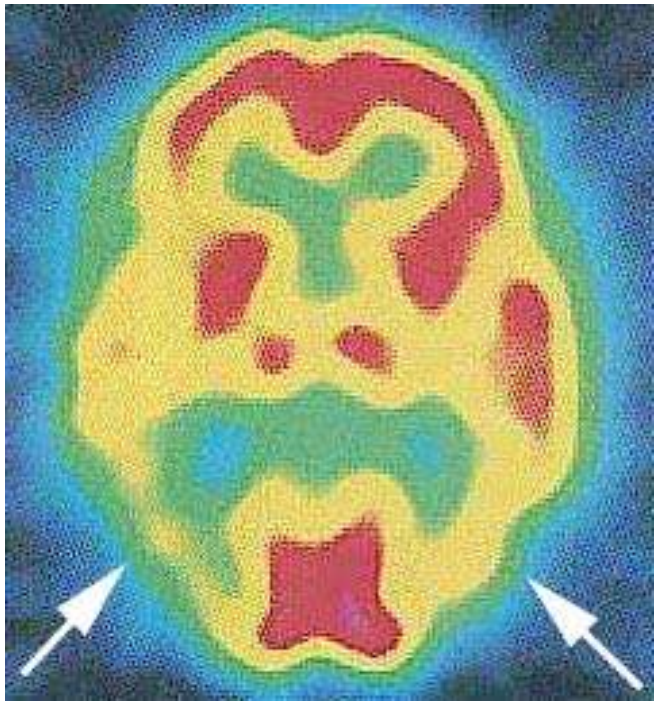


Dead

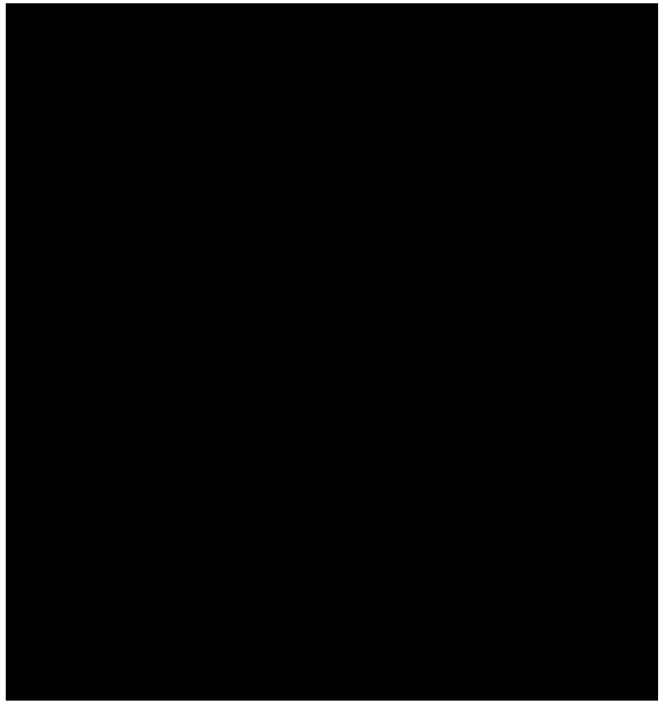


Nuclear Medicine Brain Imaging

Alive

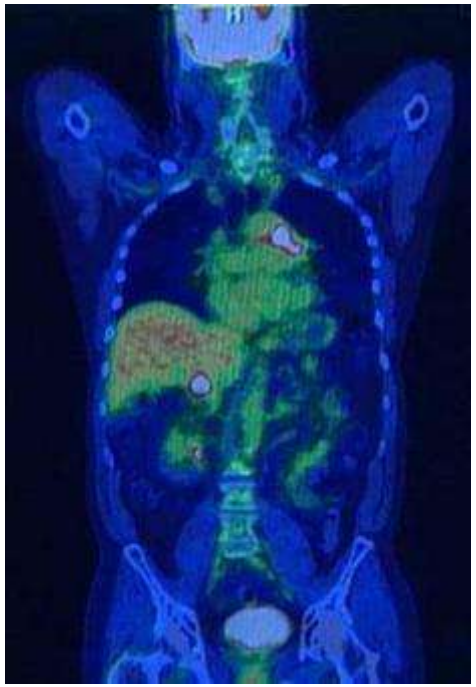


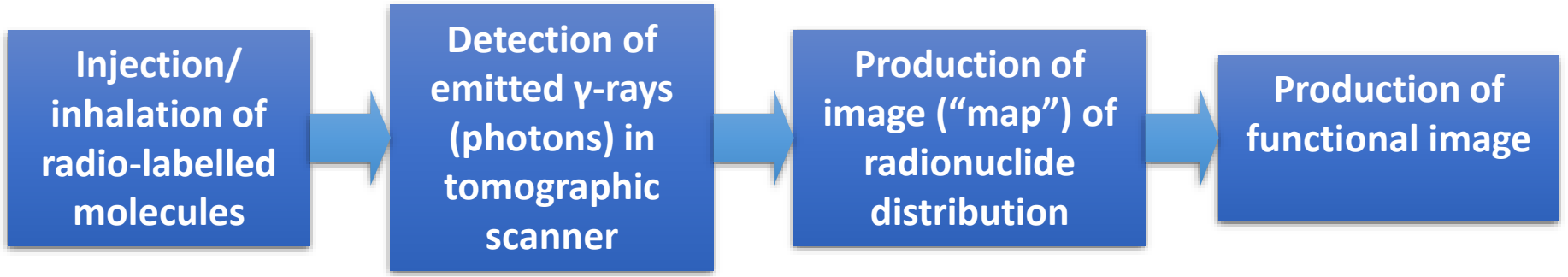
Dead



Functional Imaging

- To investigate regional tissue function
  - non-invasively
- Nuclear Medicine Imaging
  - SPECT, planar imaging
- Positron Emission Tomography
  - PET





Radiopharmaceuticals

Pharmaceutical	Radionuclide
Physiological properties determine distribution in-vivo	Radiation emitter
Rapid and complete absorption by biological system of interest	Allows location of tracer to be determined
e.g. MIBI, HDP, MAG3	e.g. $^{99}Tc^{m}$, ^{123}I, ^{201}Tl

Radiopharmacy



The Ideal Radiopharmaceutical

- Radionuclide should
  - have a half-life similar to length of test
  - emit γ or X-rays
  - have no charged particle emissions
  - have energy between 100-200keV
  - be chemically suitable
  - be readily available
- Pharmaceutical should
  - localise only in area of interest
  - elimination time similar to length of test
  - be simple to prepare





Commonly Used Radionuclides

Radionuclide	Production	Photon Energy (keV)	Half-life
^{67}Ga	Cyclotron	92, 182, 300, 390	78 hours
$^{99}Tc^{m}$	Generator	140	6 hours
^{111}In	Cyclotron	173, 247	2.8 days
^{123}I	Cyclotron	160	13 hours
^{131}I	Reactor	280, 364, 640	8 days
^{201}Tl	Cyclotron	68-80	73.5 hours

Radionuclide Generators

- Solution to the problem of supply
  - of short-lived radionuclides
- The principle is:

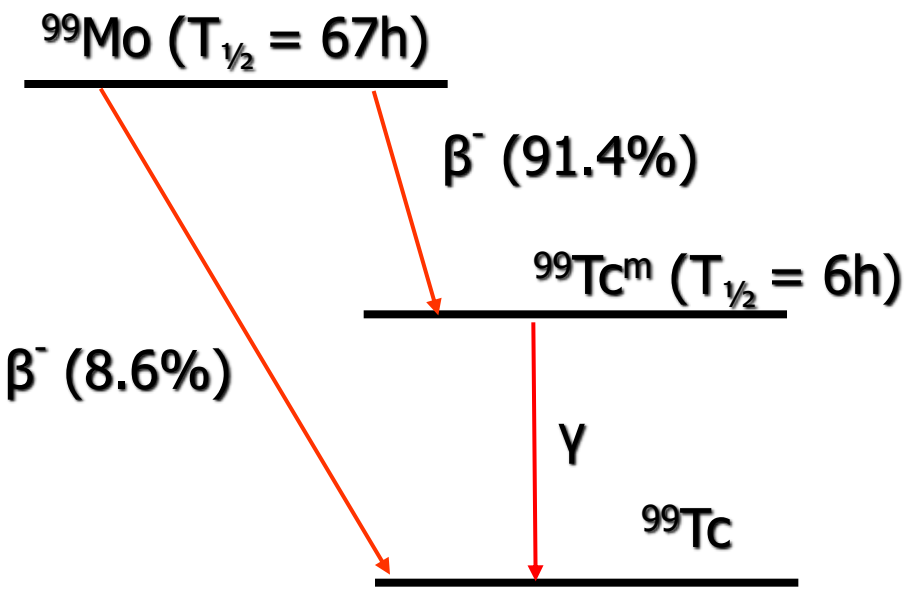
Relatively long-lived parent radionuclide

Decay

Daughter radionuclide with shorter half-life

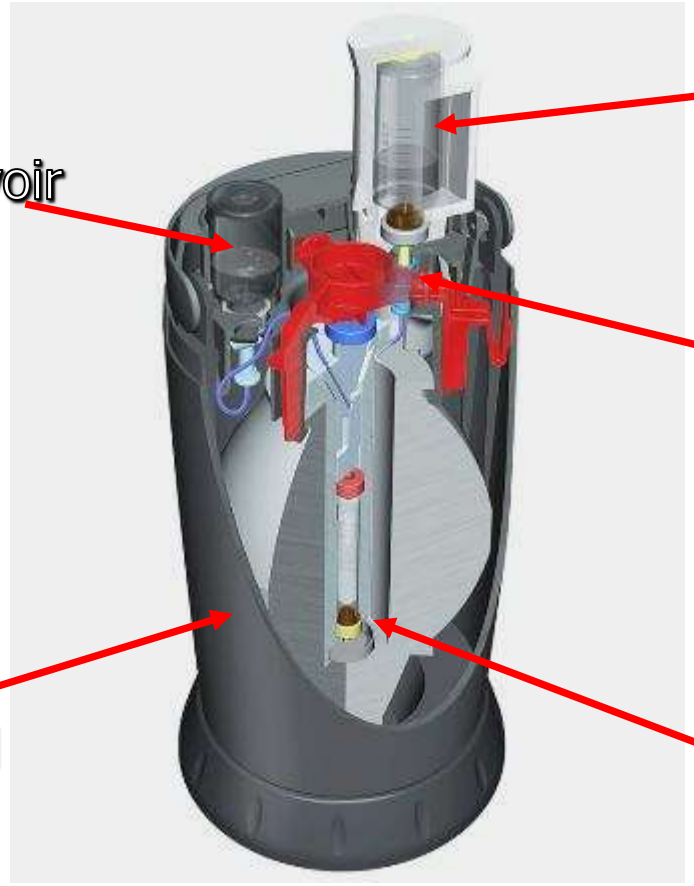


^{99}Mo Decay Scheme



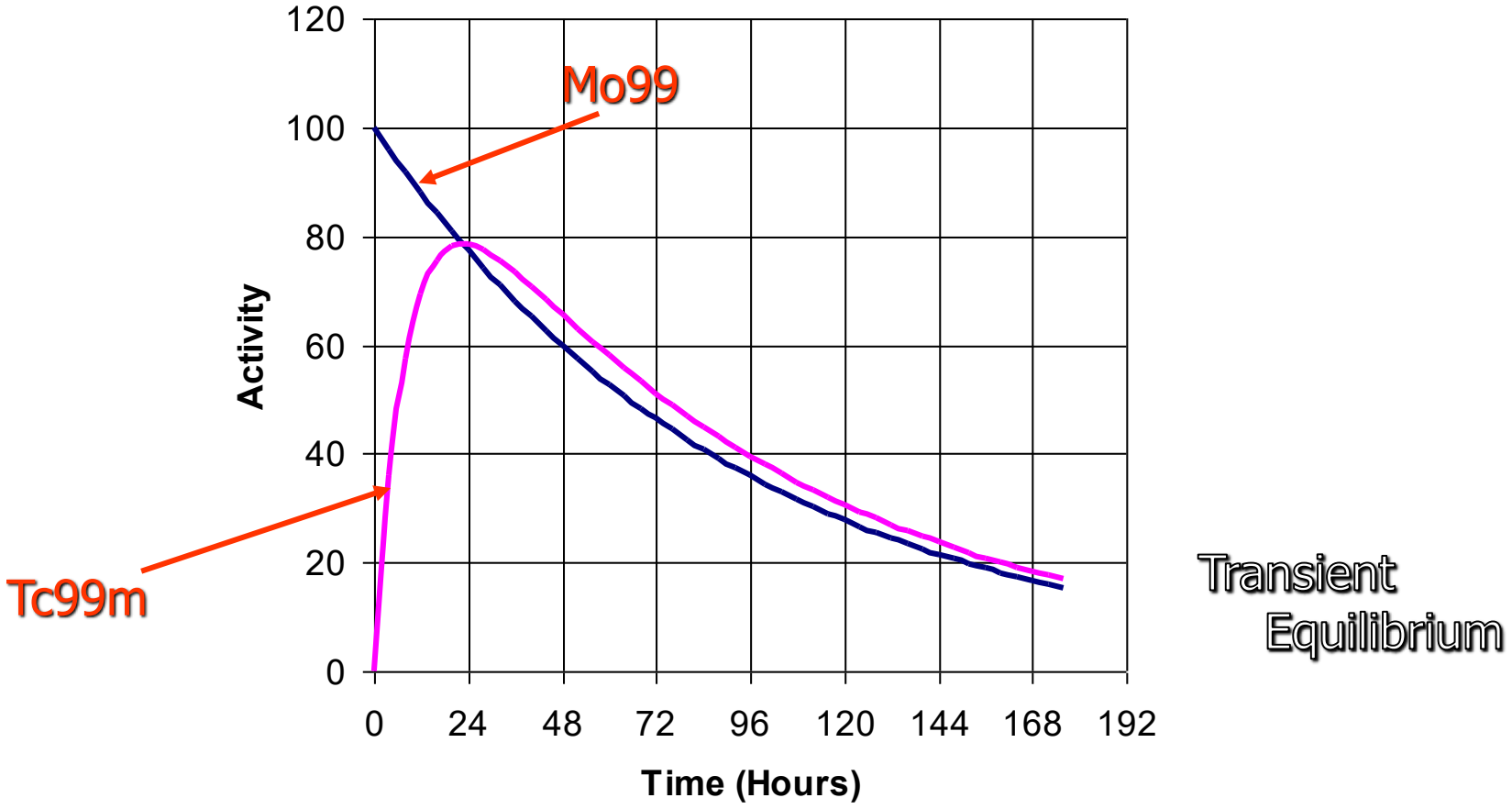
$^{99}Mo/^{99}Tc^{m}$ Generator



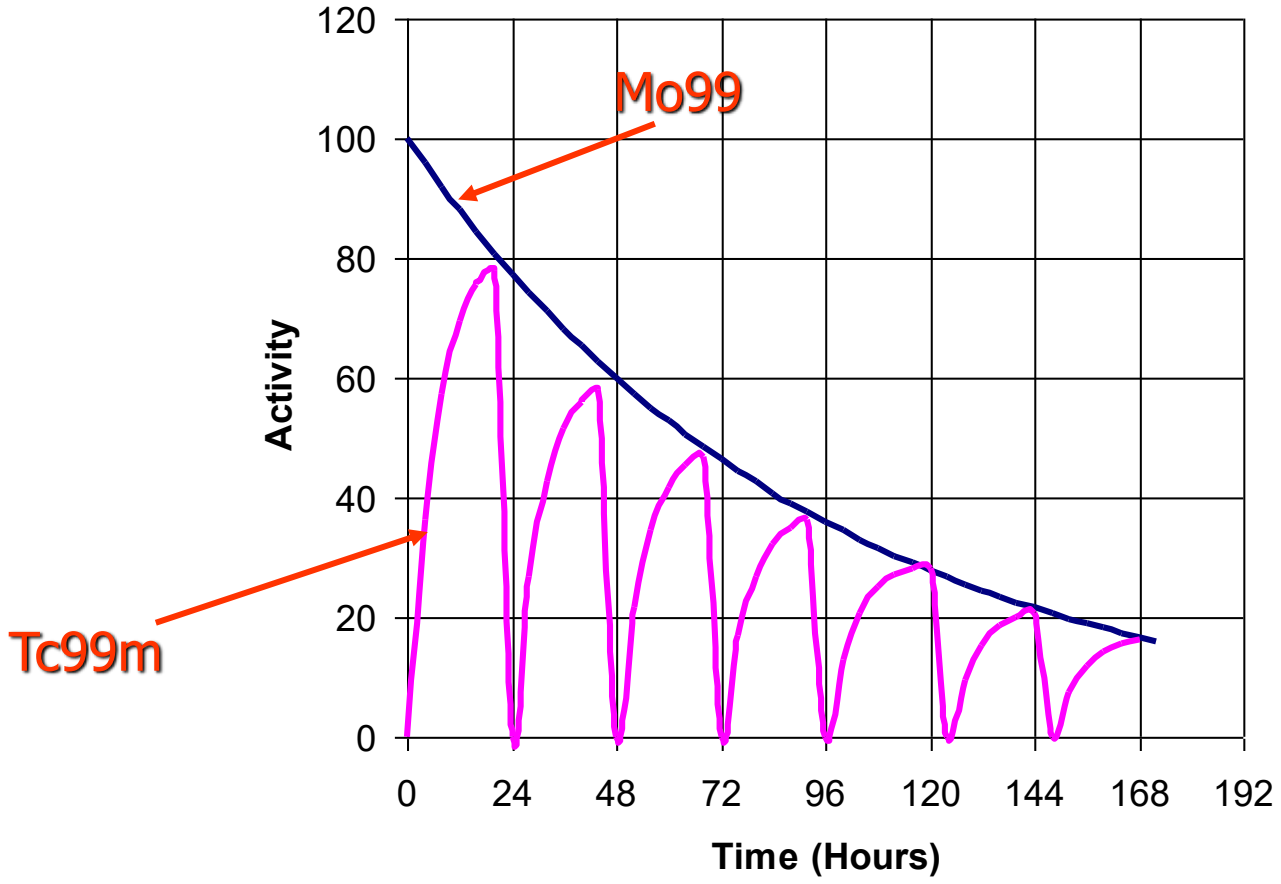


$Na^{+}Cl^{-}$ → Generator → $Na^{+}(TcO_4)^{-}$

$^{99}Mo/^{99}Tc^{m}$ Generator



$^{99}Mo/^{99}Tc^{m}$ Generator with Elution



Radiolabelling with $^{99}Tc^{m}$

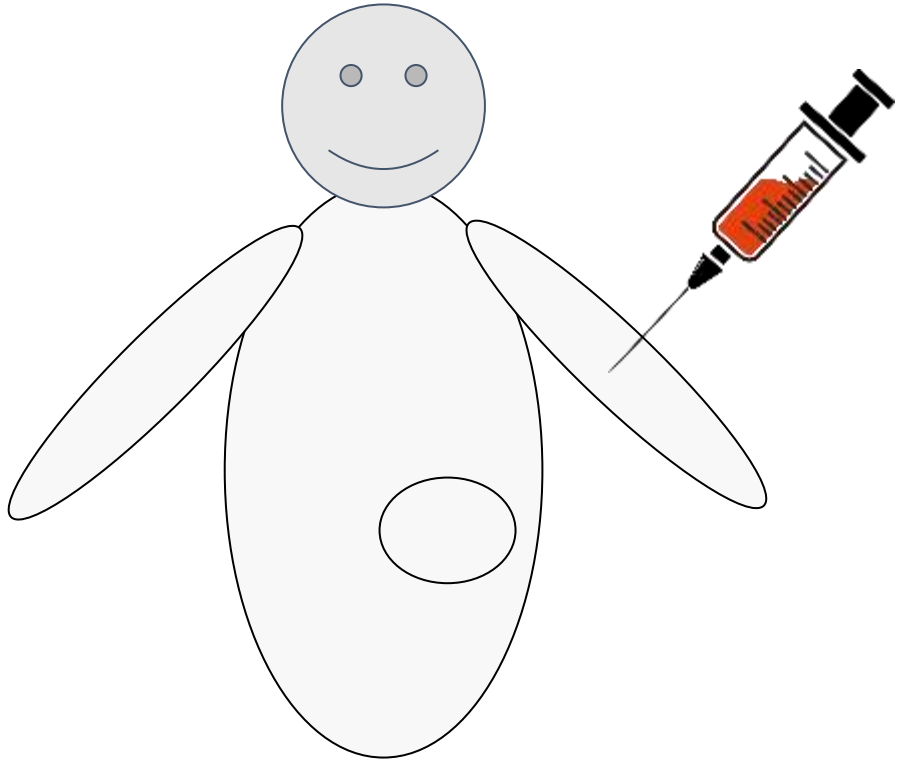
- ‘Cold kits’ – non-radioactive vials used to produce the radiopharmaceutical
- Pre-packed set of sterile ingredients designed for the preparation of a specific radiopharmaceutical
- The generator will be eluted and the cold kit radiolabelled with the Tc99m
- Preparation will vary depending on the radiopharmaceutical. Some require agitating (shaking), others boiling etc

Radionuclide Calibrator

- Confirms correct activity prior to patient administration
- Well-type ionisation chamber
  - pressurised argon gas (increases efficiency)
- Electrometer
  - measures small ionisation currents
- Protective sleeve
  - removable if activity spilt
- “Dipper”
  - reduces finger dose
  - ensures fixed geometry
- Shielding
  - reducing background radiation
  - protects the user

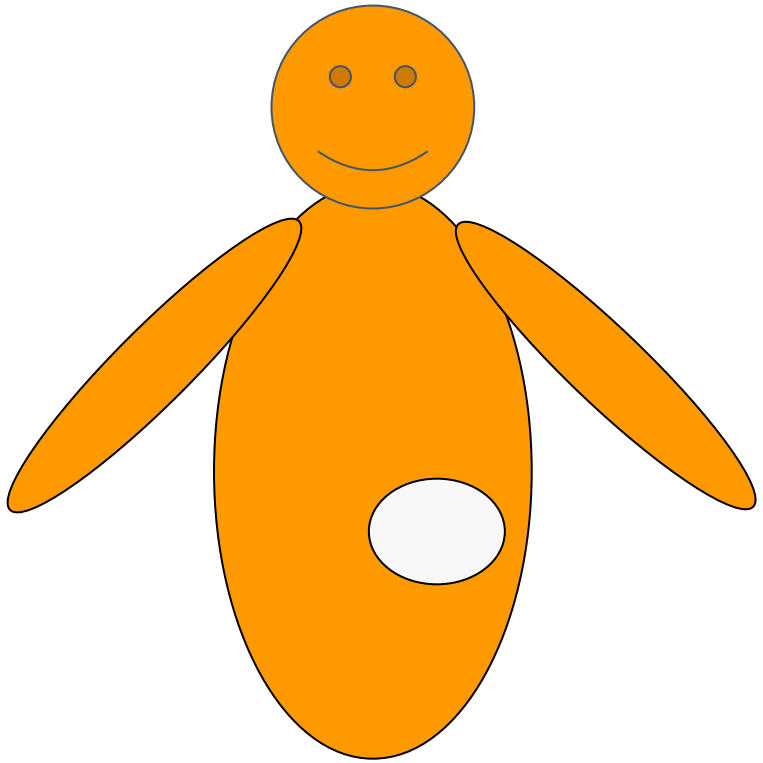


Nuclear Medicine Administration



- IV most common administration
- Others include :
  - Oral
  - Inhalation
  - Subdermal
  - Subcutaneous

Nuclear Medicine
Localisation and Uptake

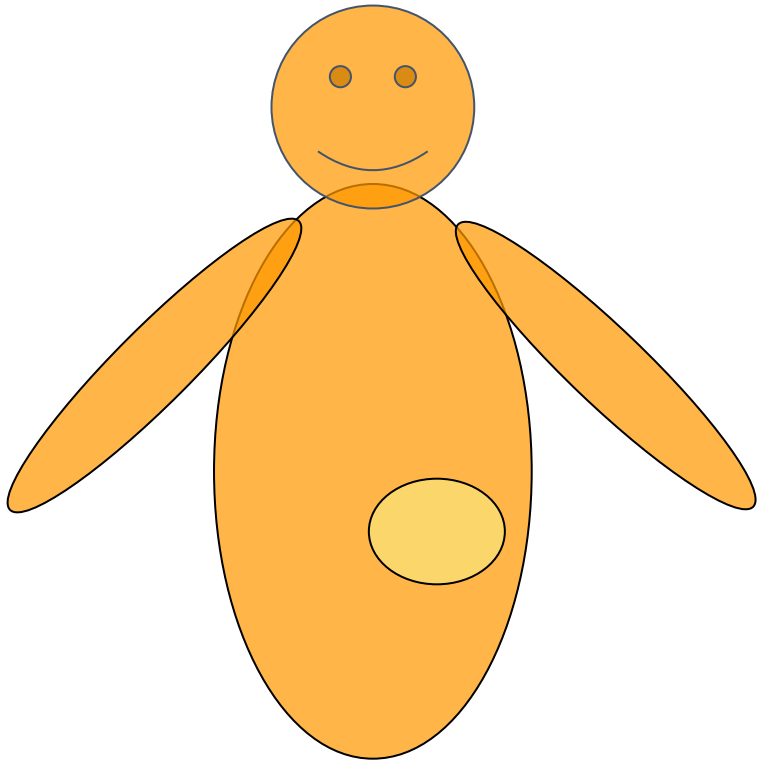


Initially

- Tracer circulates in the vasculature

- No physiological uptake in the organ/area of interest

Nuclear Medicine
Localisation and Uptake

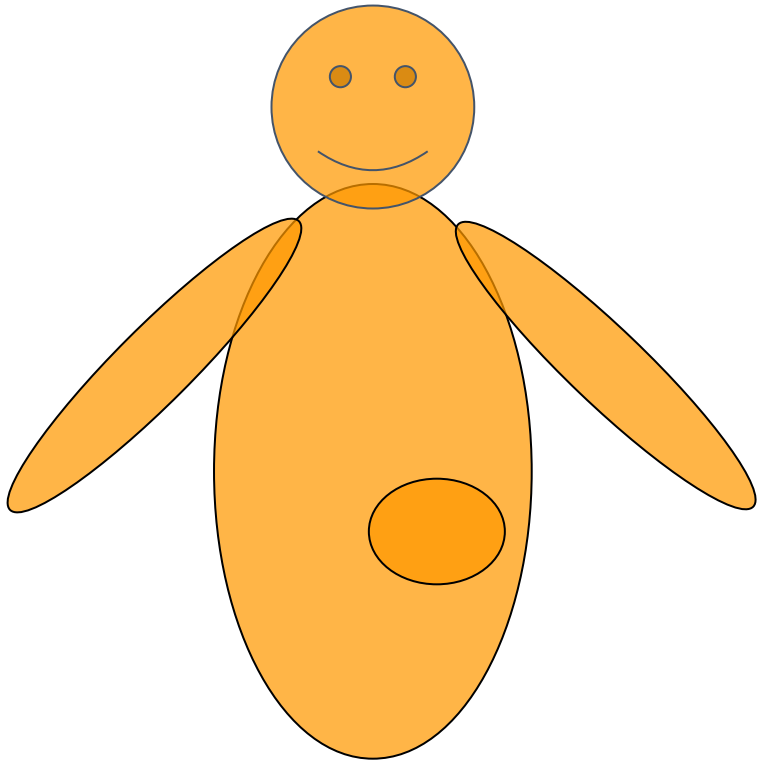


After a time

- Physiological uptake occurs

- Organ/area of interest becomes more radioactive.

Nuclear Medicine
Localisation and Uptake

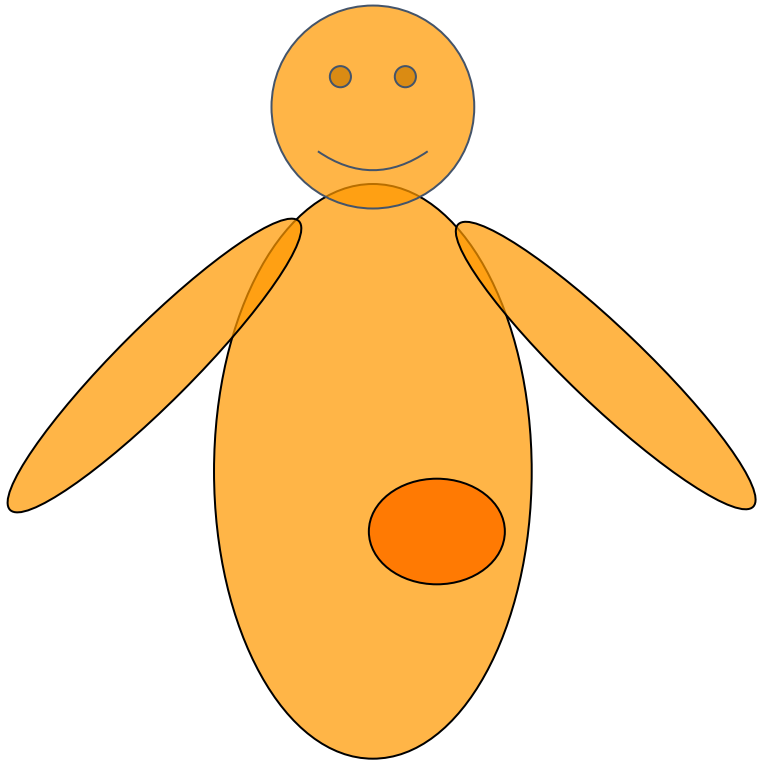


At some point

- Organ/area of interest indistinguishable

- Relatively equal amounts of radiopharmaceutical in all areas of body

Nuclear Medicine
Localisation and Uptake

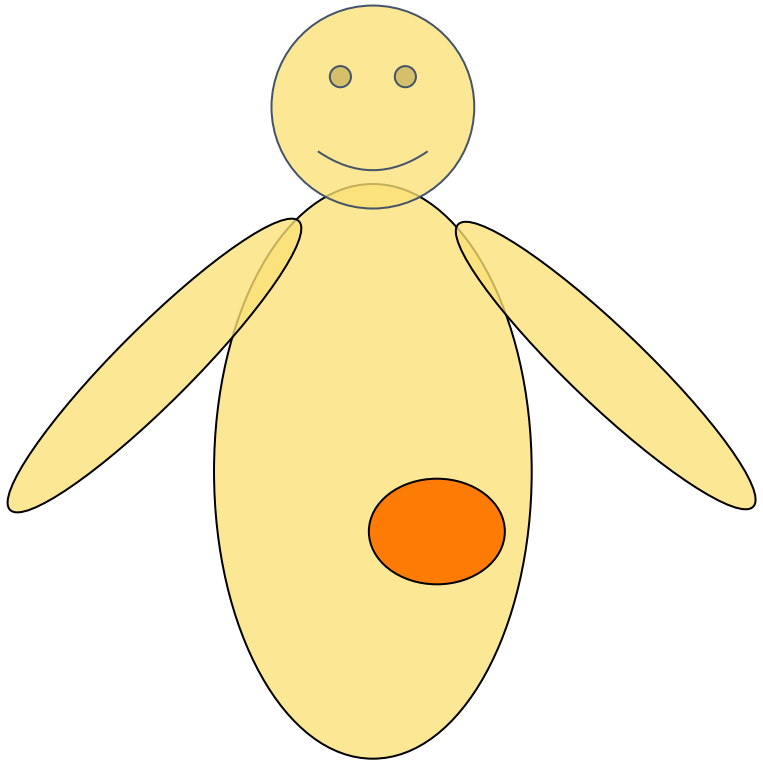


Organ/area detectability

- Organ of interest indistinguishable

- Relatively equal amounts of radiopharmaceutical in all areas of body

Nuclear Medicine
Localisation and Uptake

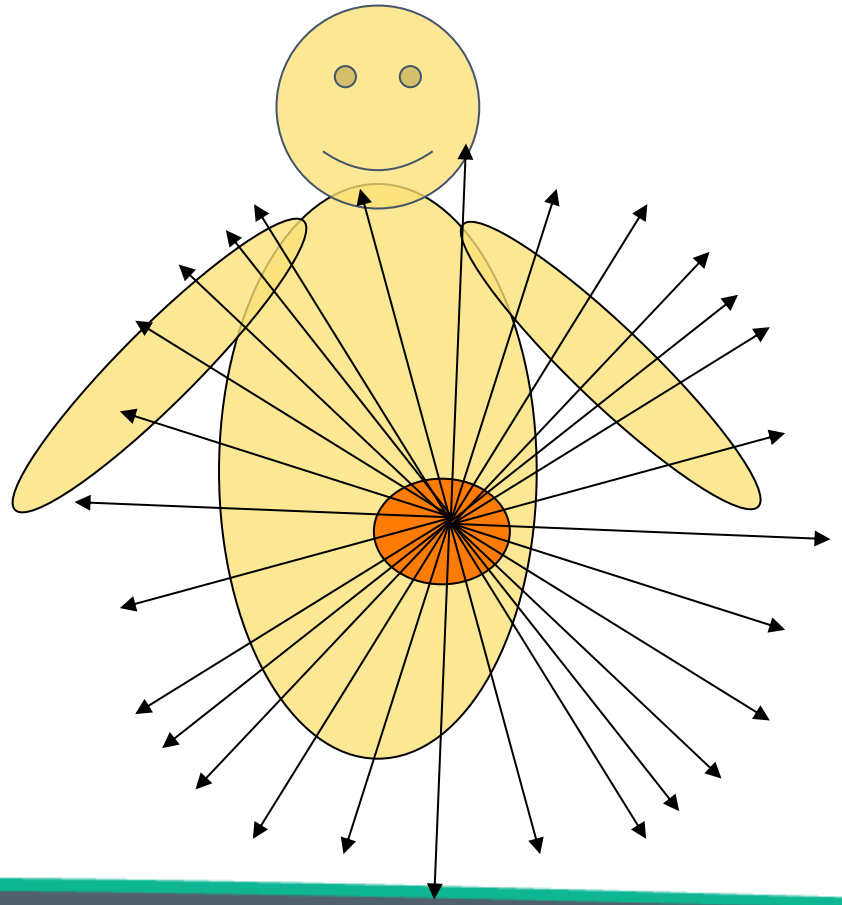


Enhanced contrast

- Between organ/area and rest of body

- Time window to image

Nuclear Medicine
Imaging Location of Tracer



- Image formed from gamma-rays emitted by radiopharmaceutical
- Gamma rays emitted in all directions from the patient
- The whole patient is radioactive including ALL bodily fluids



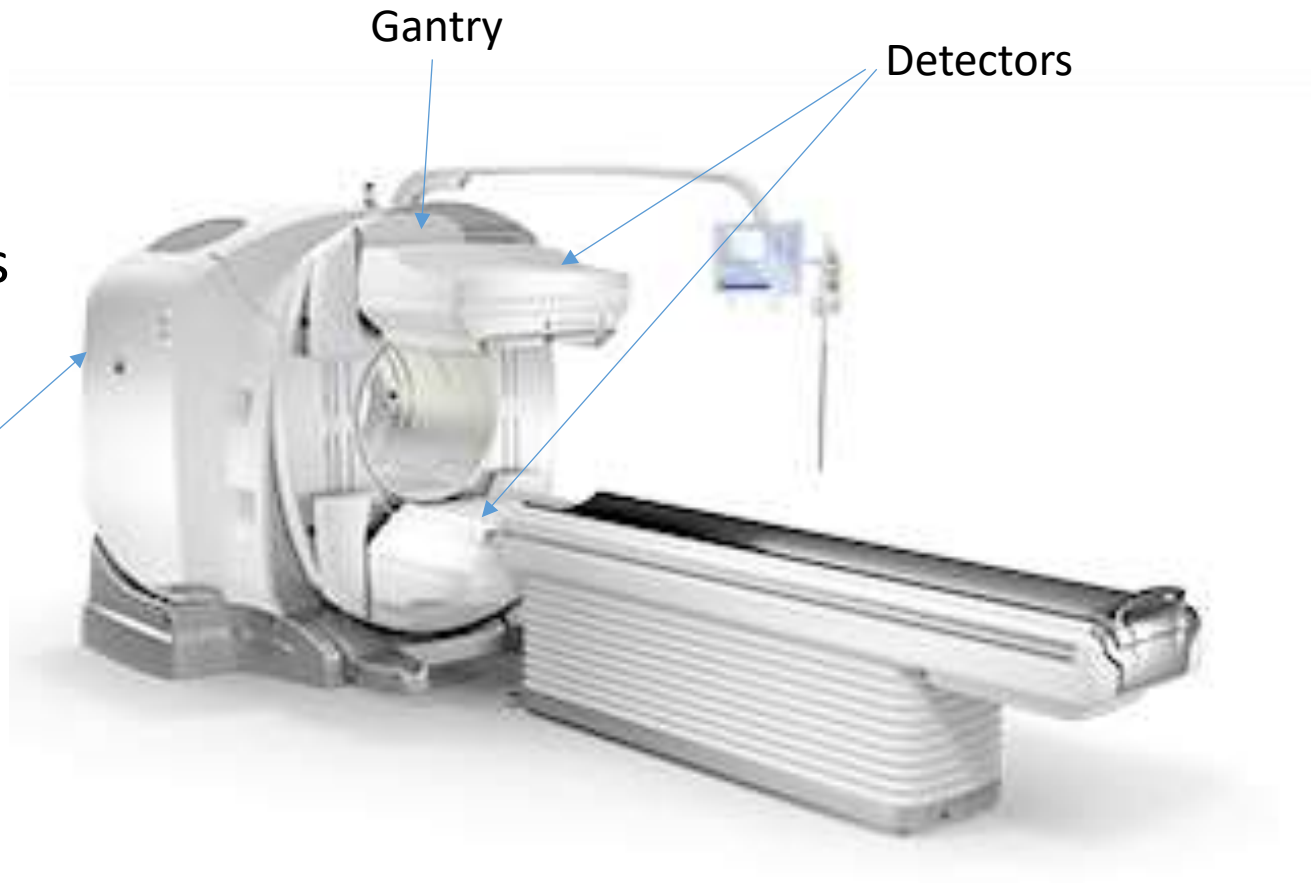


The Gamma Camera

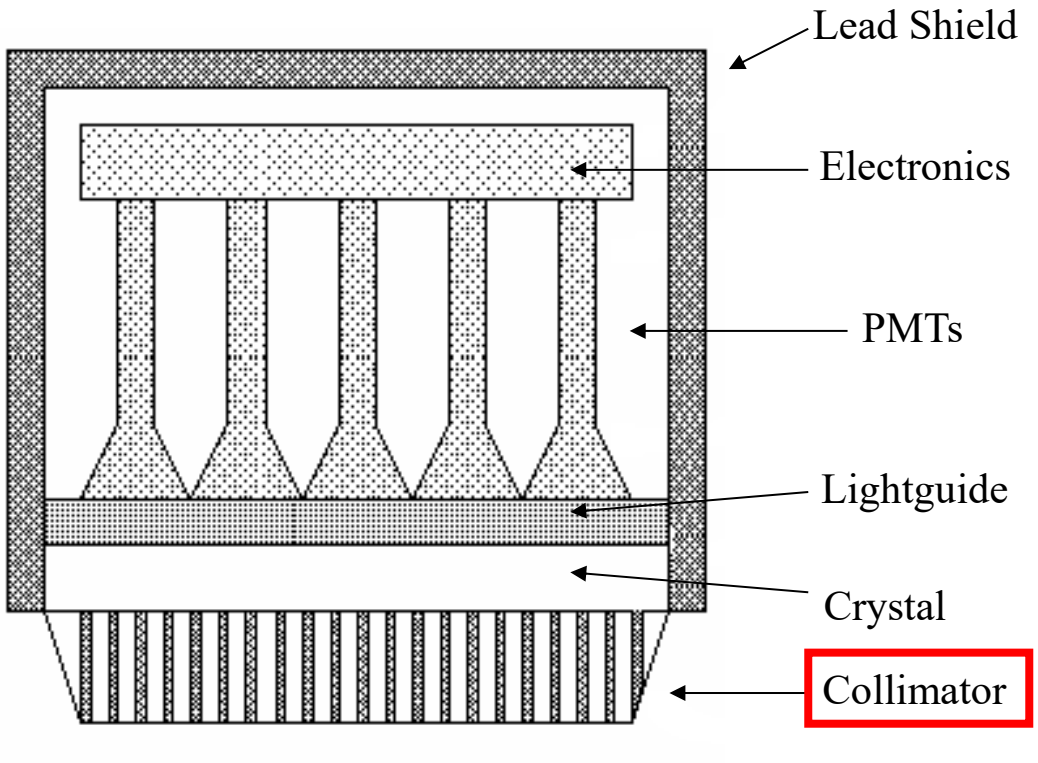


The Gamma Camera

- Key instrument in Nuclear Medicine
- Images distribution of radiopharmaceuticals

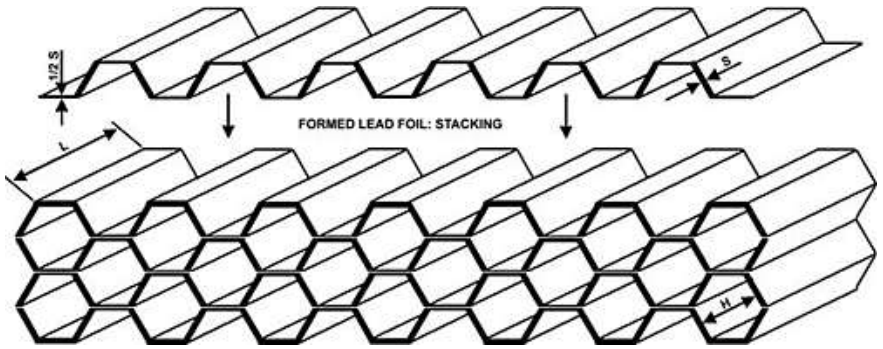


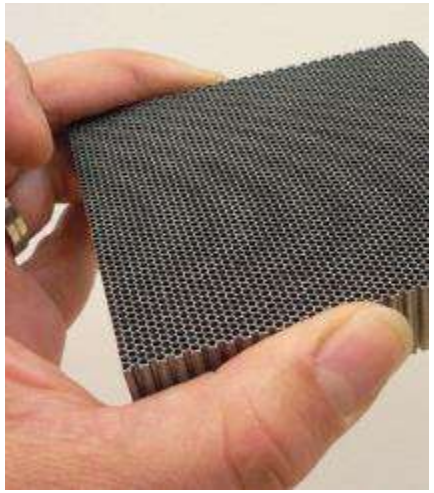
The Detector



The Collimator

- Lead plate with array of thousands of holes
- Honeycomb structure to maximise holes
- Made by casting hot lead or folding lead foils
- Purpose – only photons travelling in same direction as holes are let through



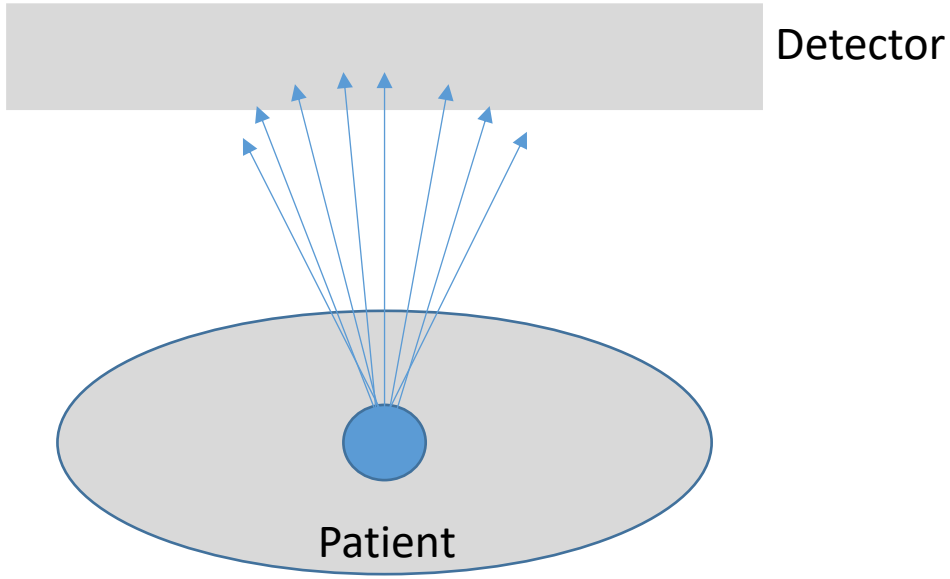


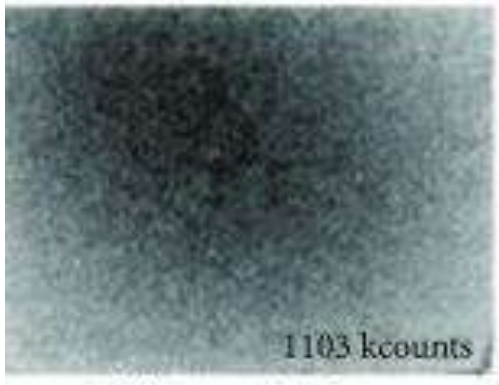
The Collimator

- Without collimator:
  - no positional information but lots of counts in image

- With collimator:
  - image formation with positional information possible with only photons travelling parallel to collimator accepted (gain in resolution, loss in counts)

Note: most studies use collimator but a couple don't when the camera is used only as a counter and image resolution not required e.g. SeHCAT





Uncollimated Image

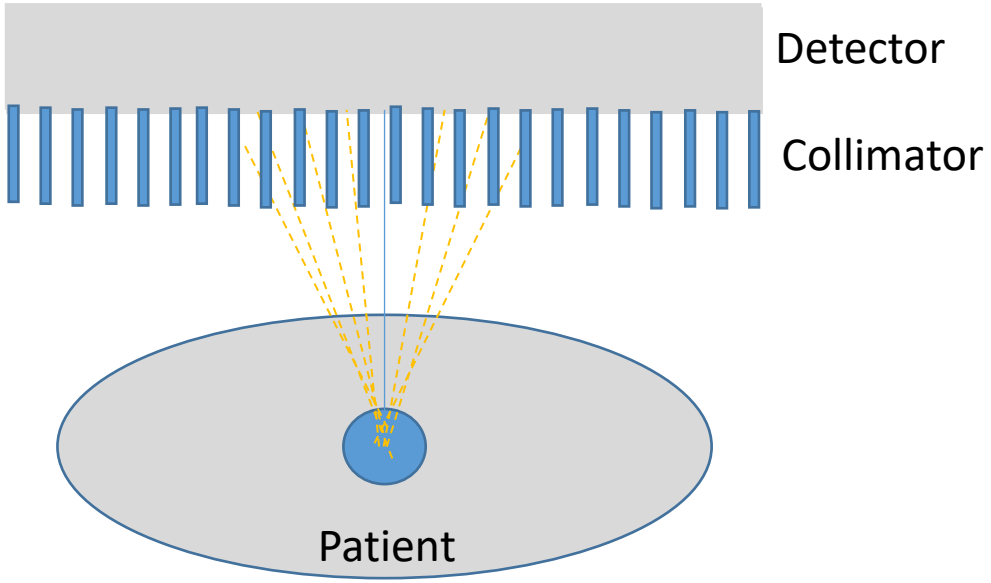


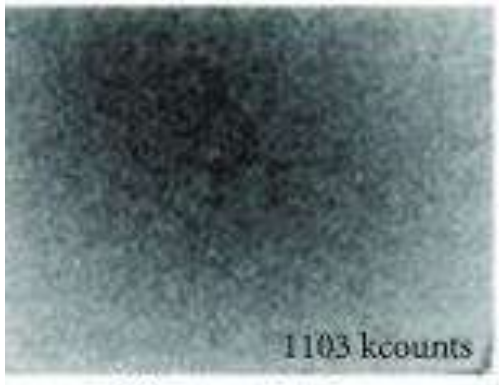
Collimated Image

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Uncollimated Image

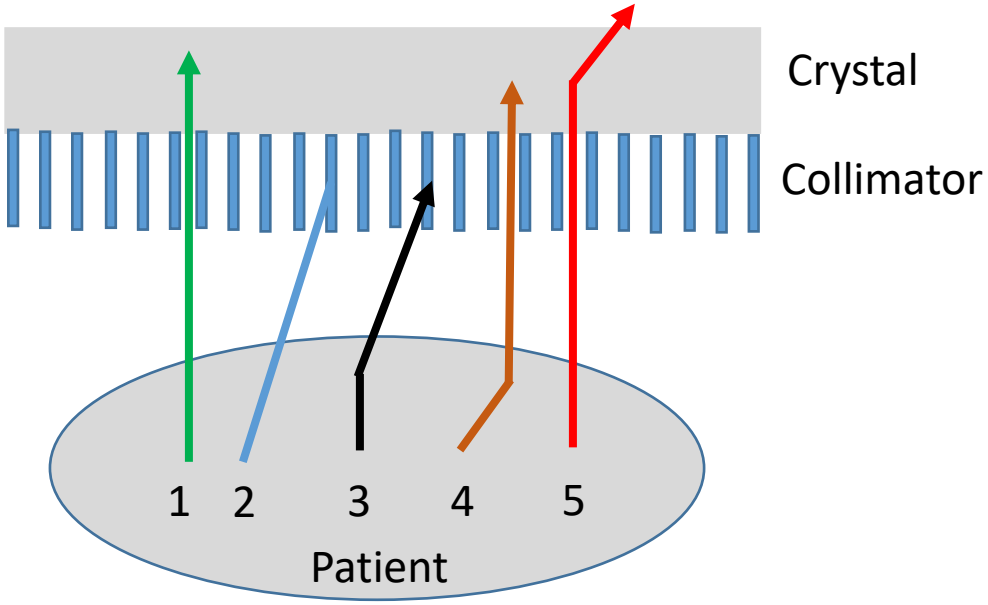


Collimated Image

The Collimator

Types of events:

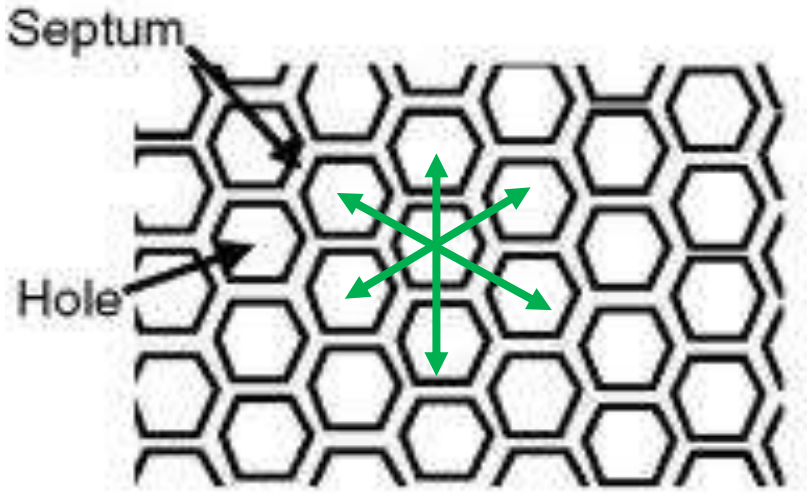
1. Perpendicular gamma ray gets through
2. Non-perpendicular gamma stopped by collimators
3. Scattered and blocked
4. Scattered and gets through
5. Gets through and scattered in crystal – collimator makes no difference

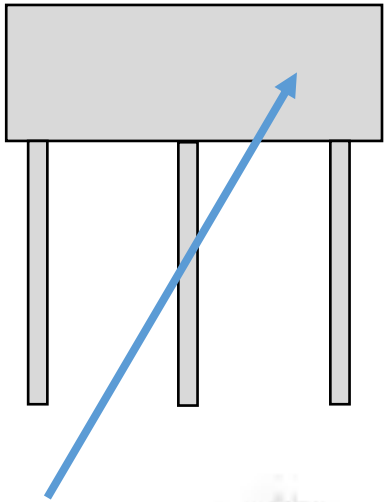


Selection dependent on direction **not** scatter.
Some scatter still present in image

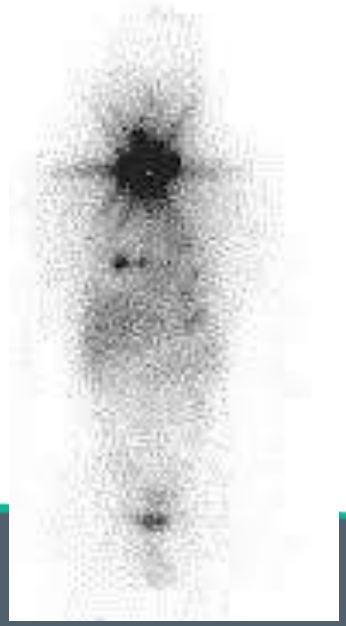
The Collimator – Septal Thickness

- Different collimator types
- What can change in collimator design?
  - Septal thickness – septal penetration





Collimator septa must be thick enough to stop highest energy gamma emitted by source

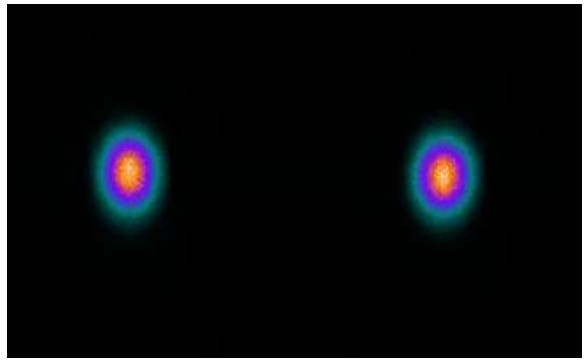


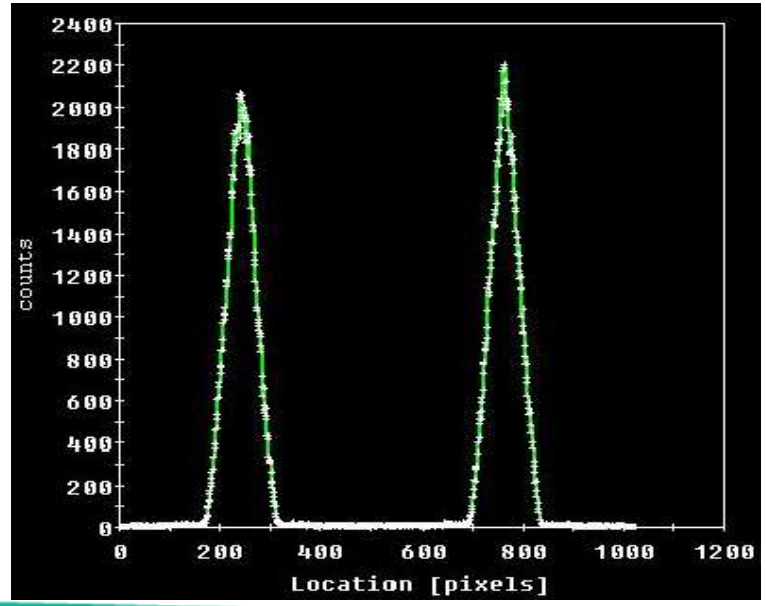
If not, gammas will be detected through collimator holes away from source position and resolution will be impacted.

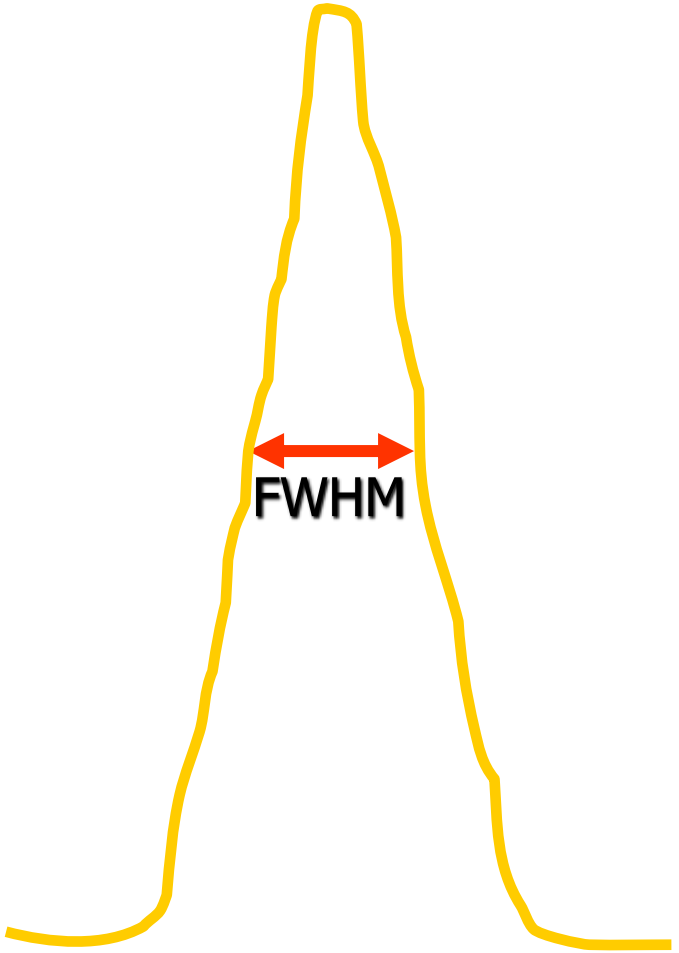
Collimator Parameters

- Spatial Resolution (FWHM)
  - a measure of the sharpness of an image
- Sensitivity (cps/MBq)
  - the proportion of those photons incident on the collimator which pass through to the detector

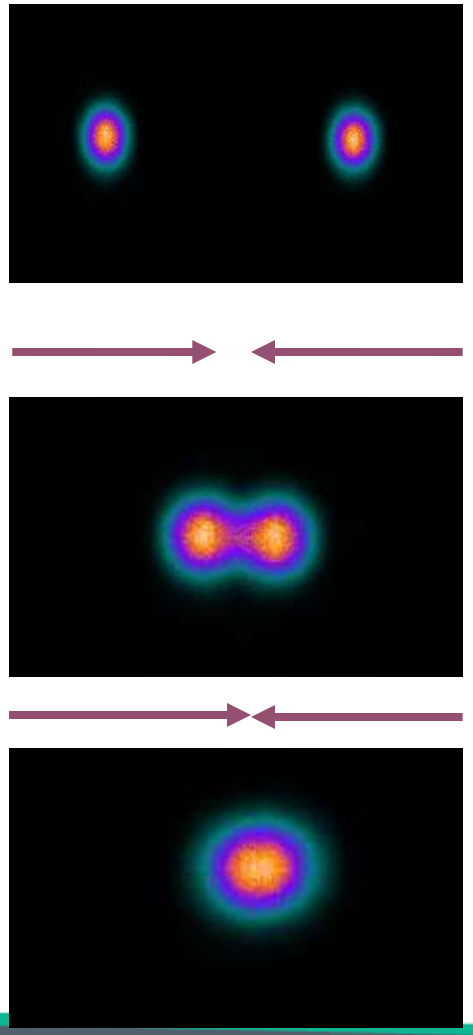
Spatial Resolution

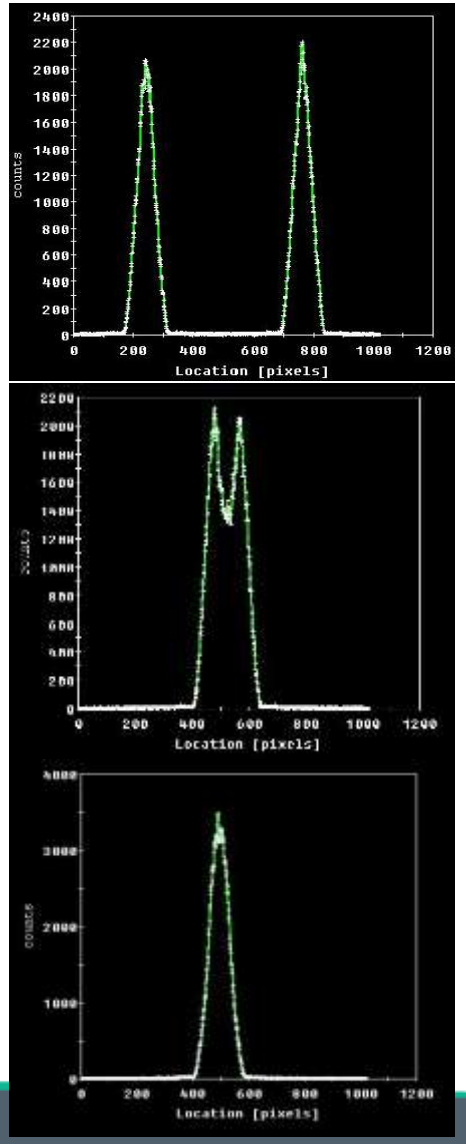




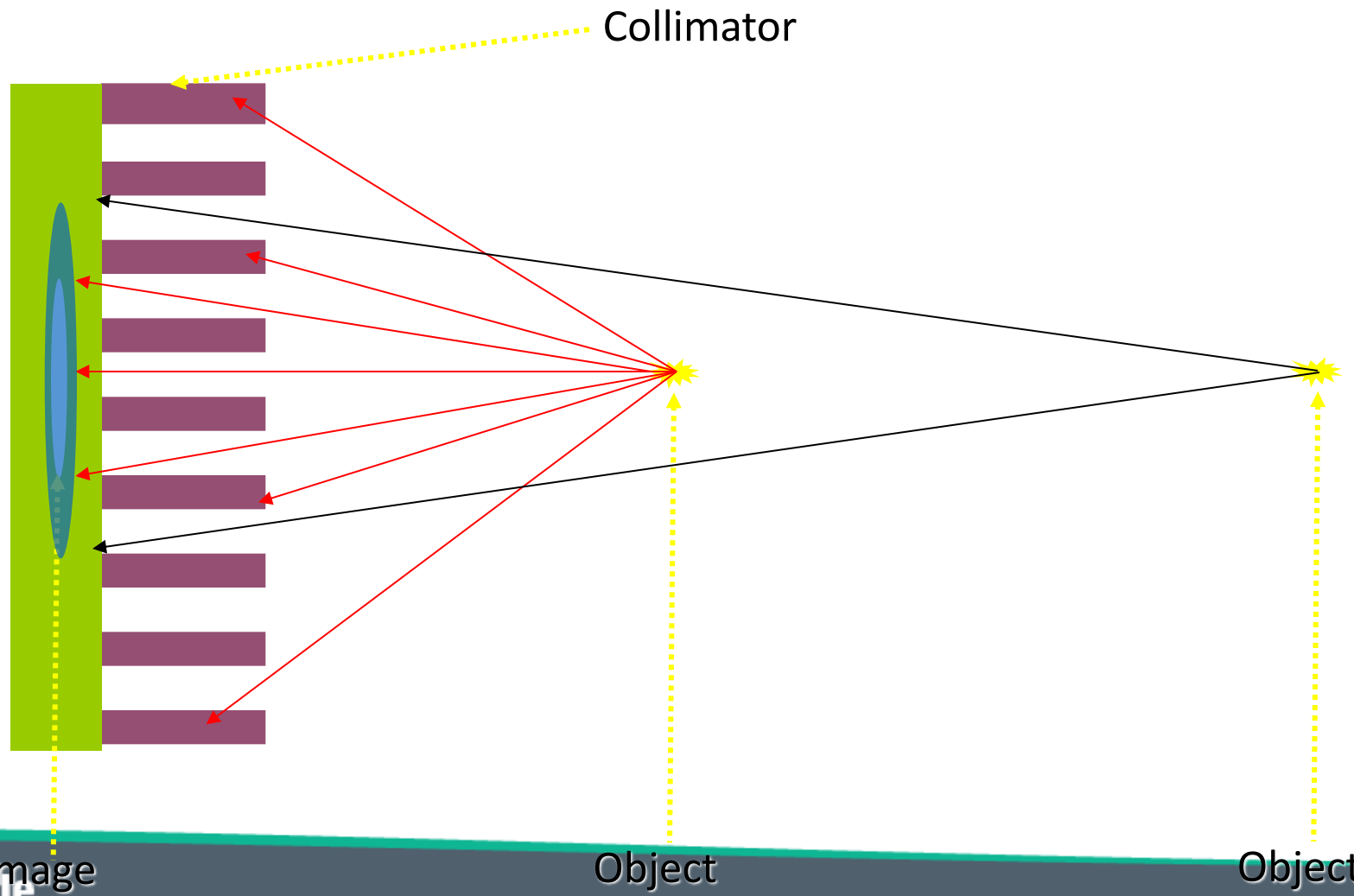


Significance of FWHM

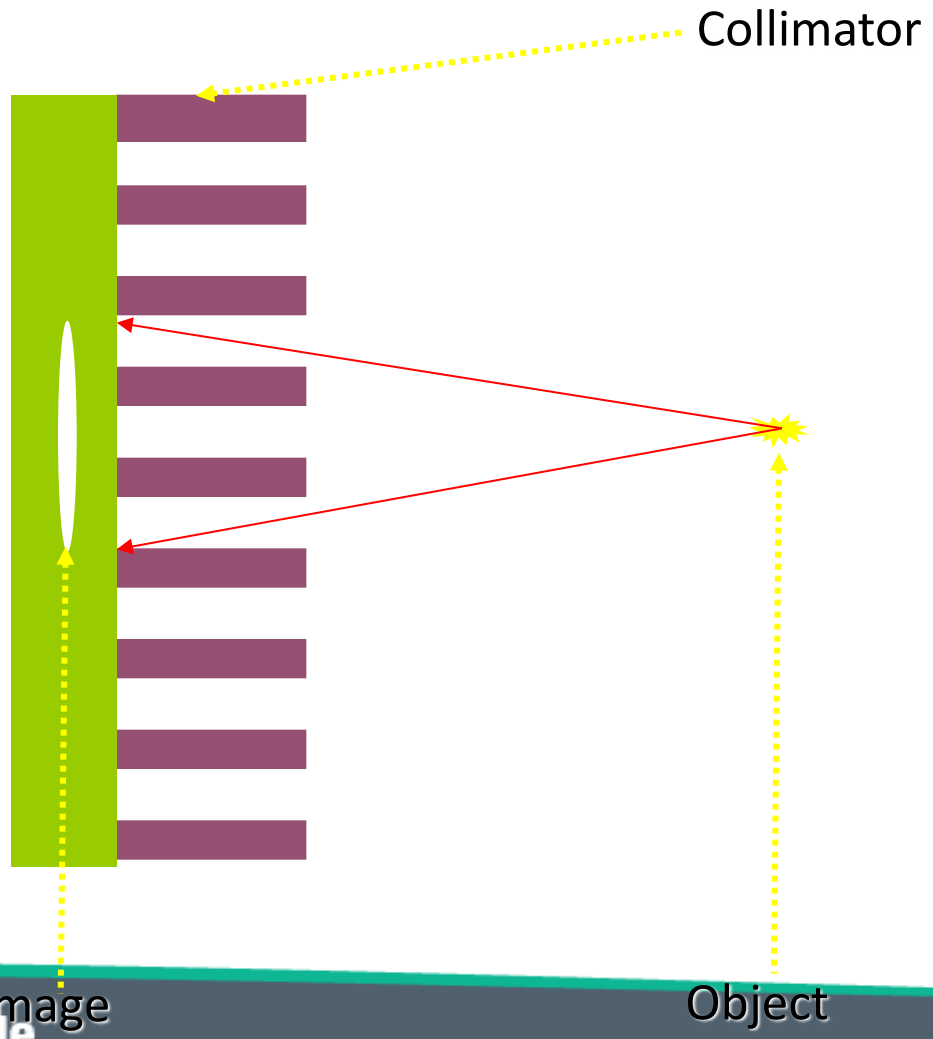




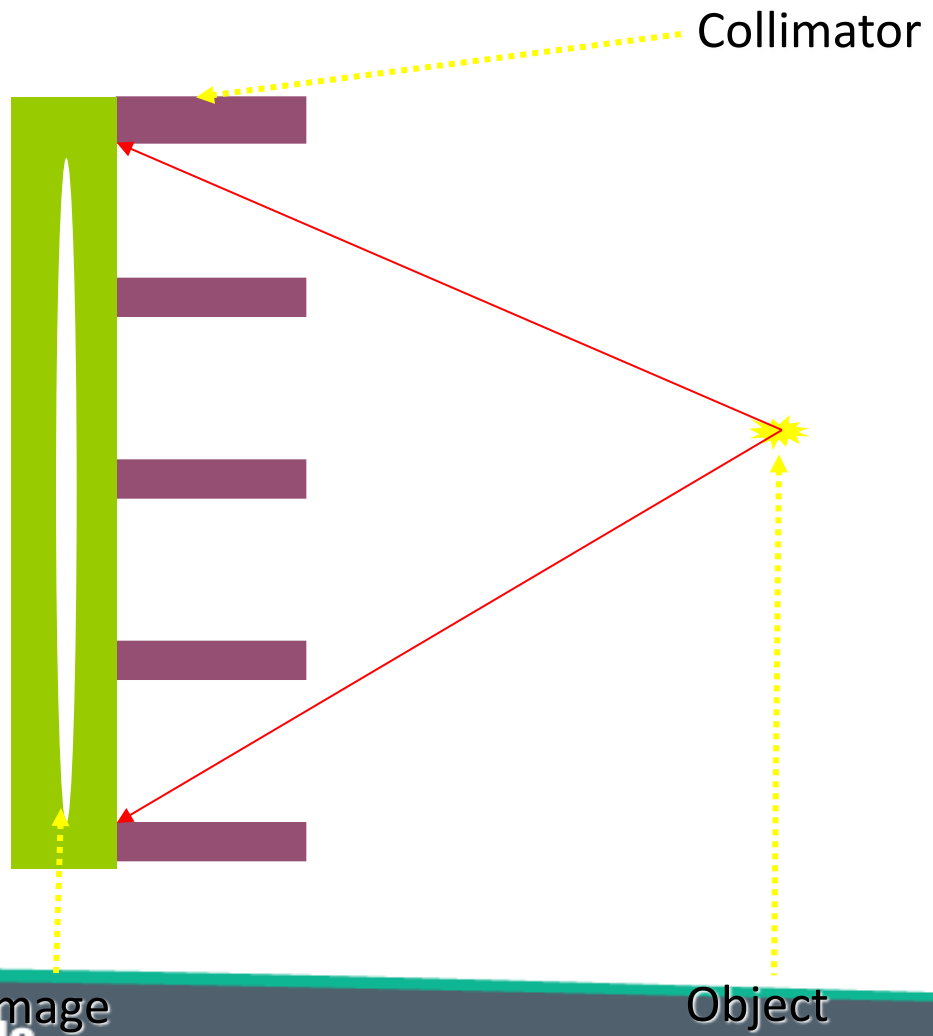
Distance from Collimator



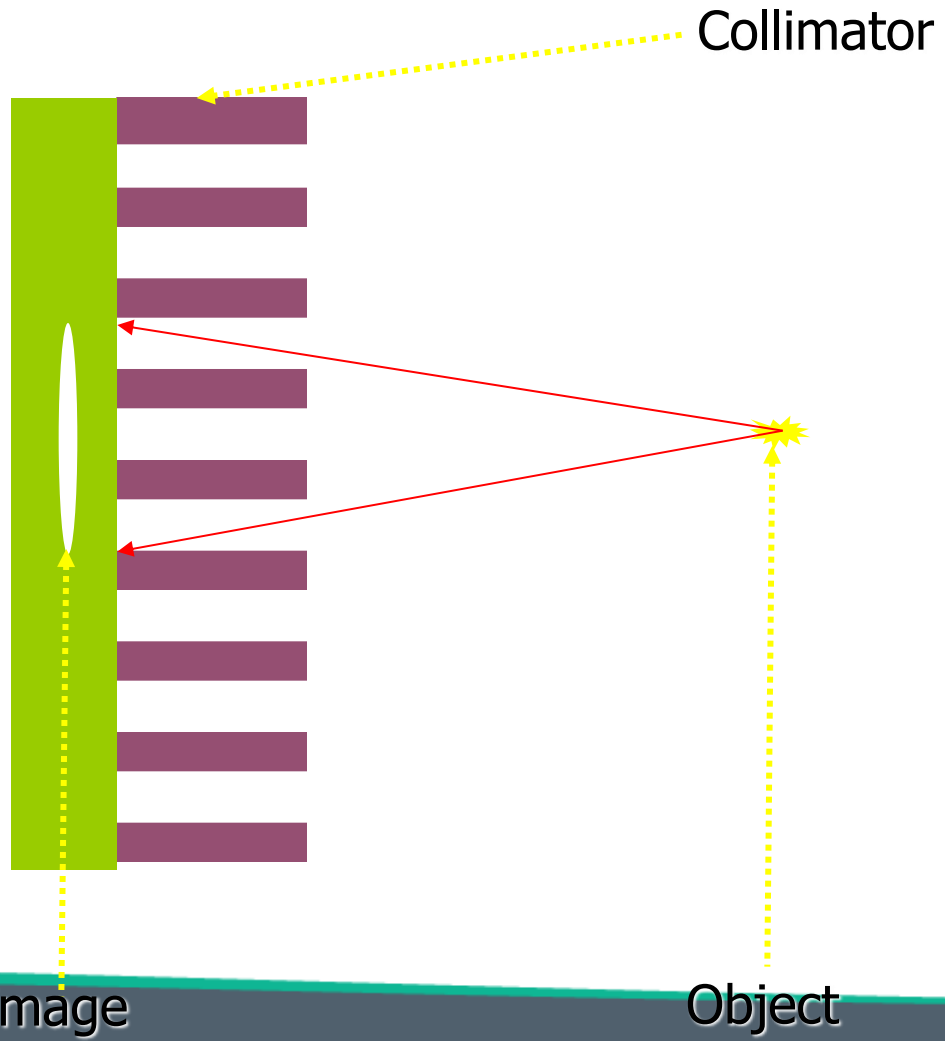
Hole Size



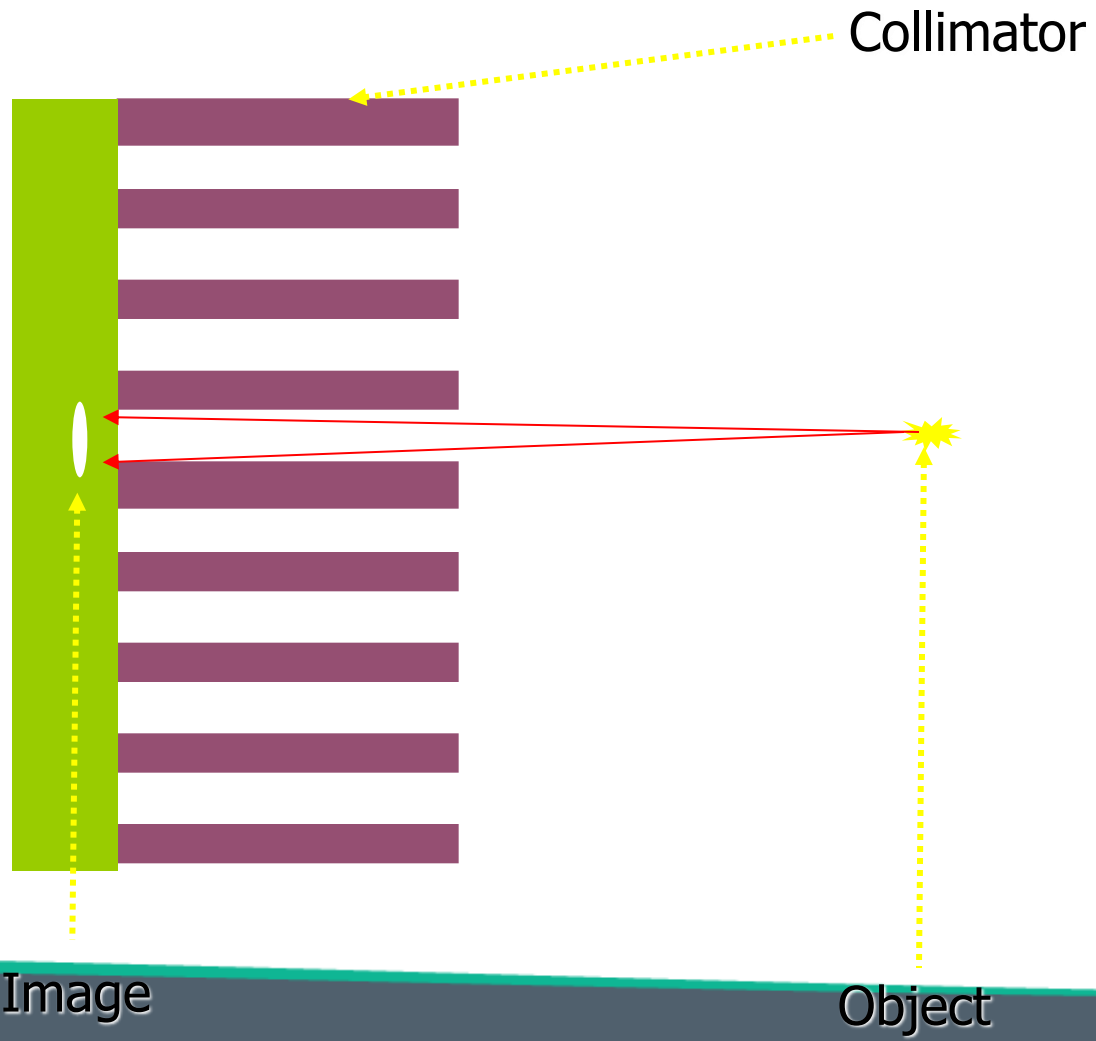
Hole Size



Hole Length



Hole Length



Collimators: Performance Factors

Type	Hole Size (mm)	Number of Holes	Hole Length (mm)	Septal Thickness (mm)
LEHR	1.5	86,300	35	0.20
LEGP	1.9	56,560	35	0.20
MEGP	3.0	15,210	58	1.05
HEGP	4.0	7,410	66	1.80

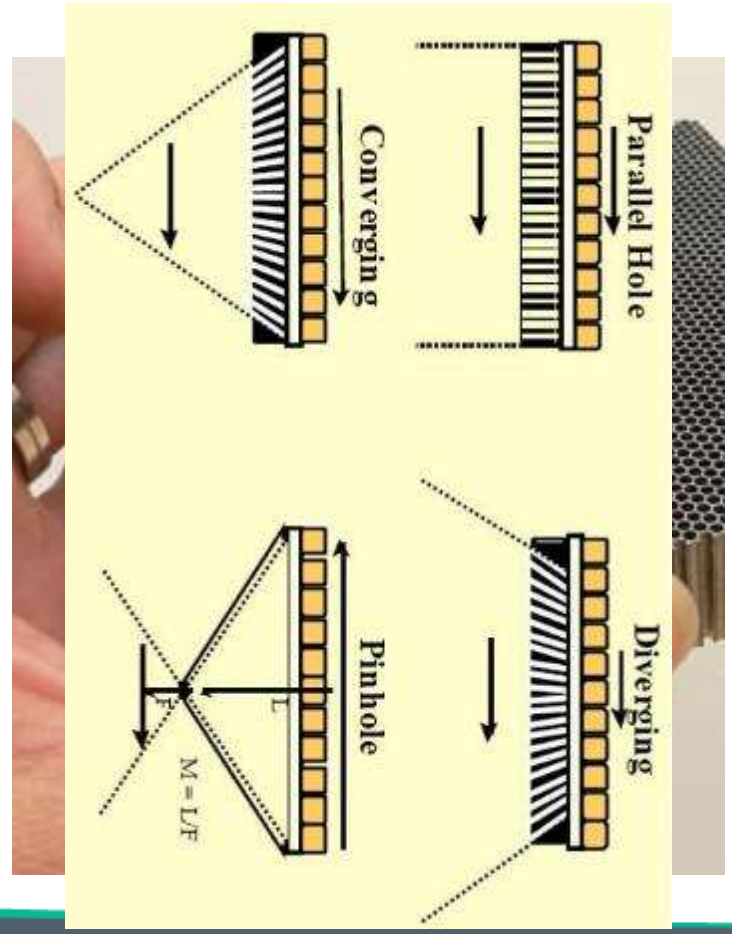
Collimators: Performance Factors

Type	Resolution* (mm)	Sensitivity (cps/MBq)
LEHR	7.4	72.0
LEGP	9.0	121.5
MEGP	9.4	64.8
HEGP	10.7	65.25

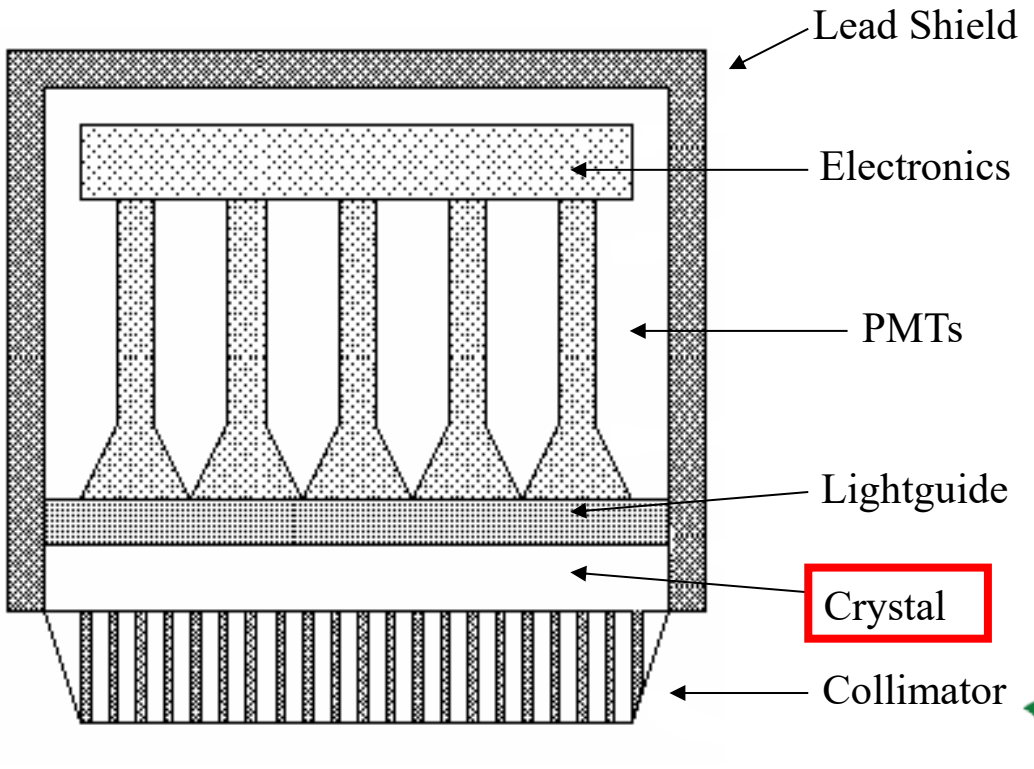
*spatial resolution at 10 cm from collimator face

Types of Collimators

- There are several types of collimators:
  - Parallel-Hole collimator
  - Converging collimator
  - Diverging collimator
  - Pin-Hole collimator
- Depending on the energy:
  - LE: 0 keV < energy < 200 keV
  - ME: 200 keV < energy < 300 keV
  - HE: 300 keV < energy < 400 keV

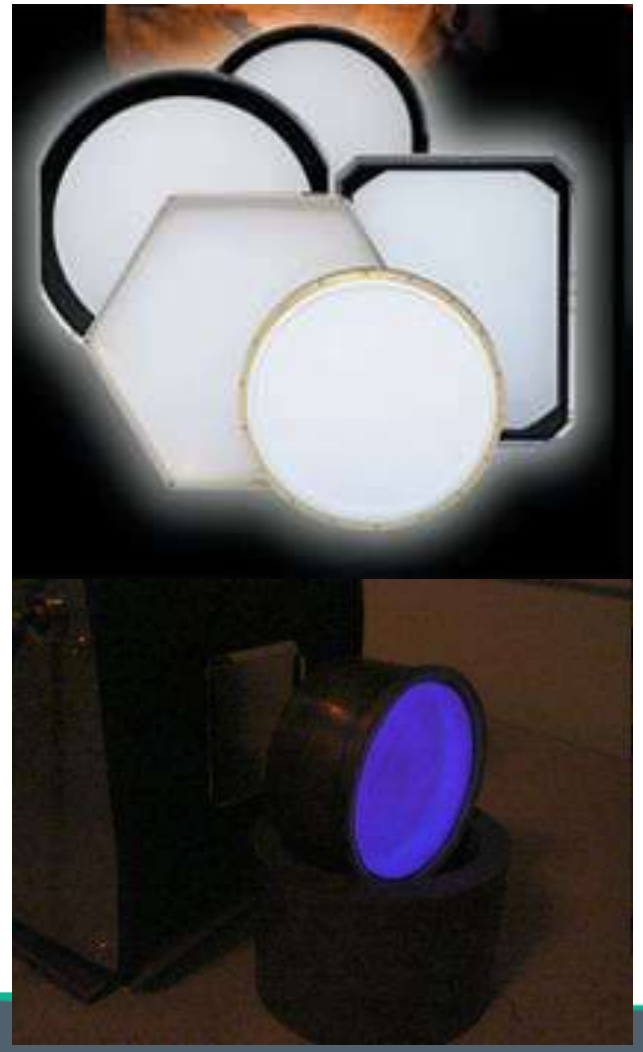


The Detector



The Scintillation Crystal

- γ-ray photon
  - detected by interacting with crystal
  - converted into scintillations
- Crystal shape:
  - Circular
  - rectangular
- The crystal size
  - ~ 60 x 45 cm^2
  - FOV ~ 54 x 40 cm^2
- Crystal thickness
  - ~ 9.5 mm (3/8 inch)



Scintillation Crystal Properties

- **Desirable Properties of the scintillation crystal**:
  - High stopping efficiency for γ-rays
  - Stopping should be without scatter
  - High conversion of γ-ray energy into visible light
  - Wavelength of light should match response of PMTs
  - Crystal should be transparent to emitted light
  - Crystal should be mechanically robust
  - Thickness of scintillator should be short

Properties of NaI(Tl) Scintillator

- **The crystal – NaI(Tl)**
  - emits blue light at 415 nm
  - high attenuation coefficient
  - intrinsic efficiency:

    90% at 140 keV
  - conversion efficiency:

    10-15%



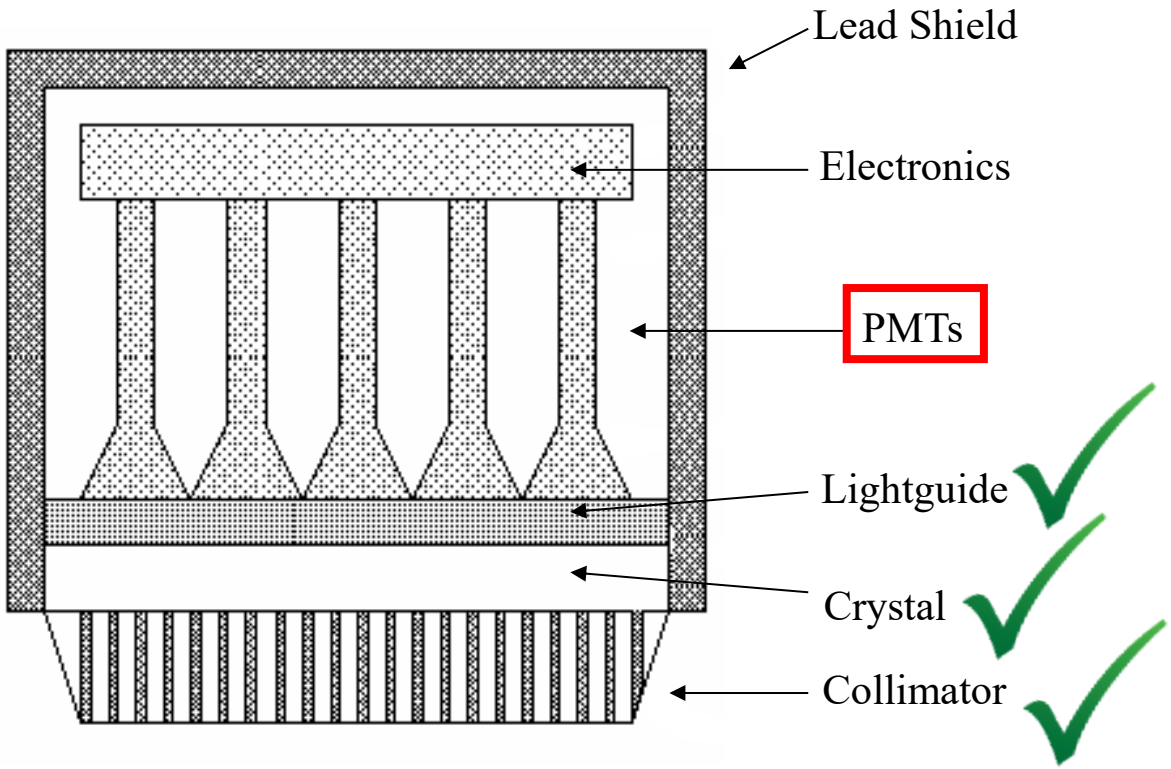
Disadvantages of NaI(Tl) crystal

- **NaI(Tl) crystal suffers from the following drawbacks**:
  - Expensive (approximately £50,000)
  - Fragile
    - sensitive against mechanical stresses
    - sensitive against temperature changes
  - Hygroscopic
    - encapsulated in aluminium case

Lightguide and Optical Coupling

- Lightguide
  - acts as optical coupler
  - usually quartz doped plexiglass (transparent plastic)
  - should be as thin as possible
  - should match the refractive index of scintillation crystal
- Silicone grease between
  - exit window of scintillation crystal and lightguide
  - lightguide and the PMTs
- No air bubbles trapped in the grease
  - photon reflections
  - reduced light transmission

The Detector

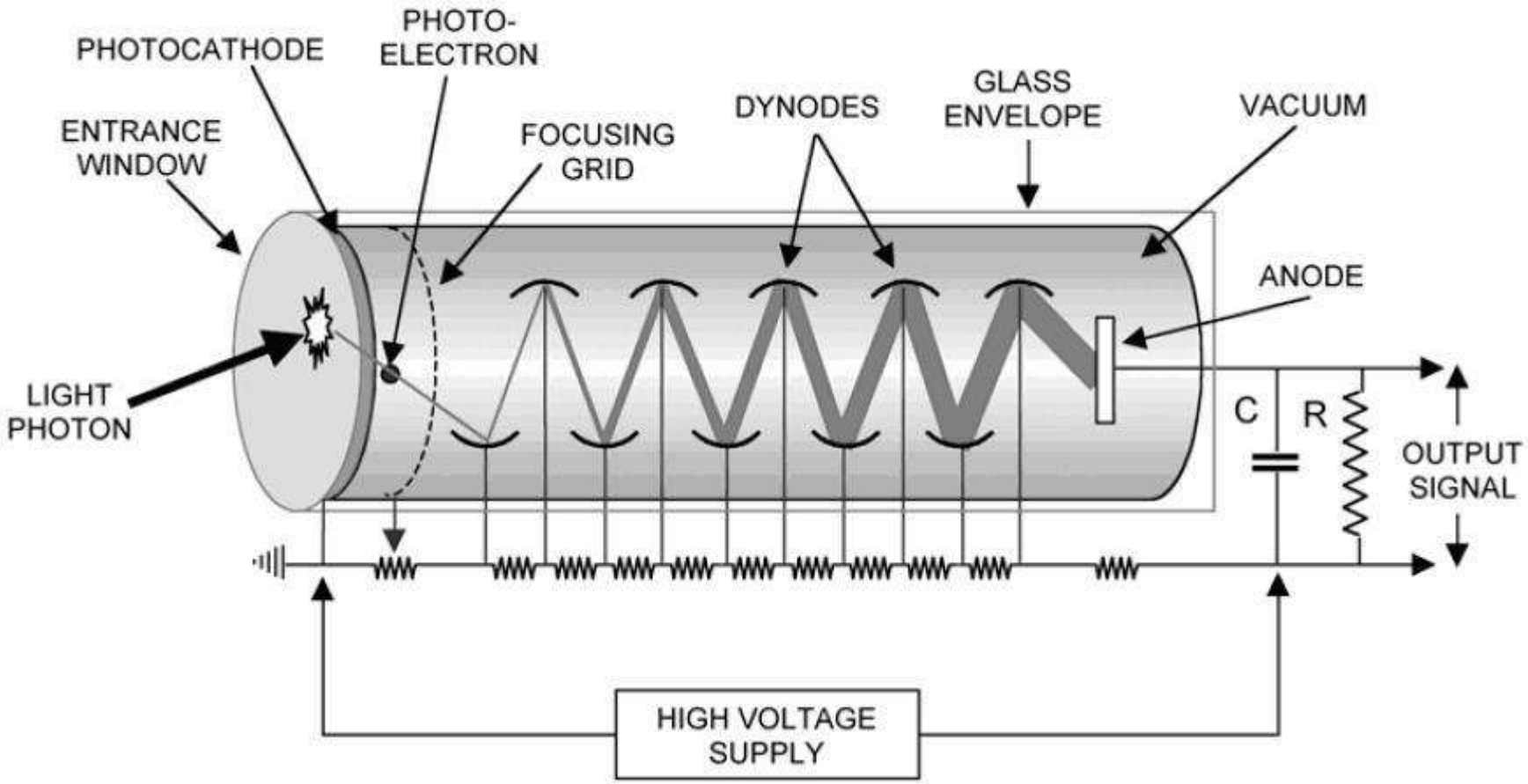


The Photomultiplier Tube

- A PMT is an evacuated glass envelope
- It consists of:
  - a photocathode
  - an anode
  - ~ 10 dynodes

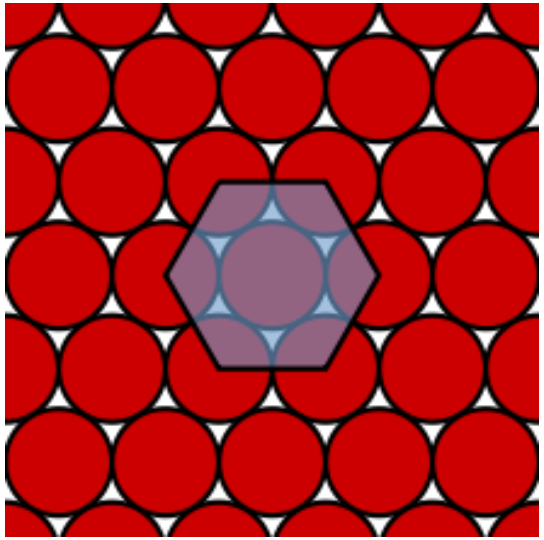


The Photomultiplier Tube



The Photomultiplier Tube

- Hexagonal array of detectors
- PMTs mounted on the crystal
- Cross Section of PMT
  - **Circular** or hexagonal
- Arrays of 7, 19, 37, 61 and 91
- The number of PMTs affects the spatial resolution of the camera
  - smaller diameter – improved resolution
  - increased number – uniformity problems



The Photomultiplier Tube Array







The Detector

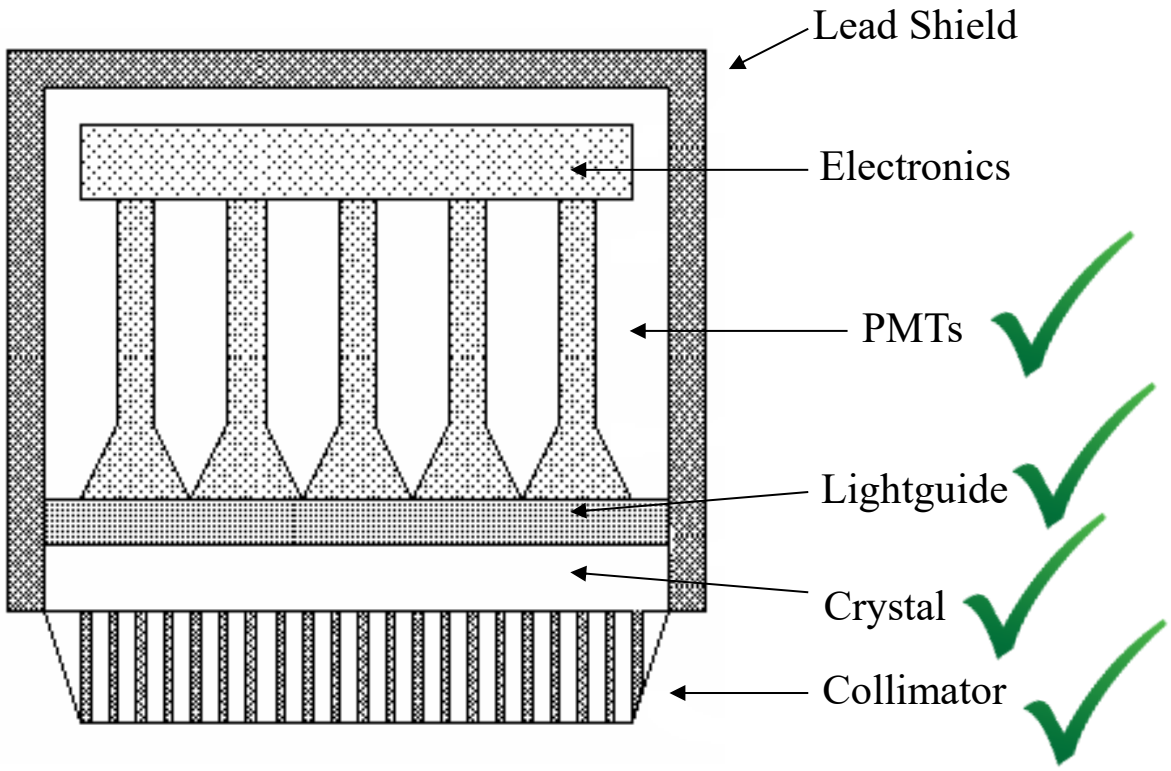
But how do we know that it is not scatter?

How do we know that it is the correct radionuclide?

Energy Discrimination

How do we know where the gamma came from? Where to put it in the image?

Localisation

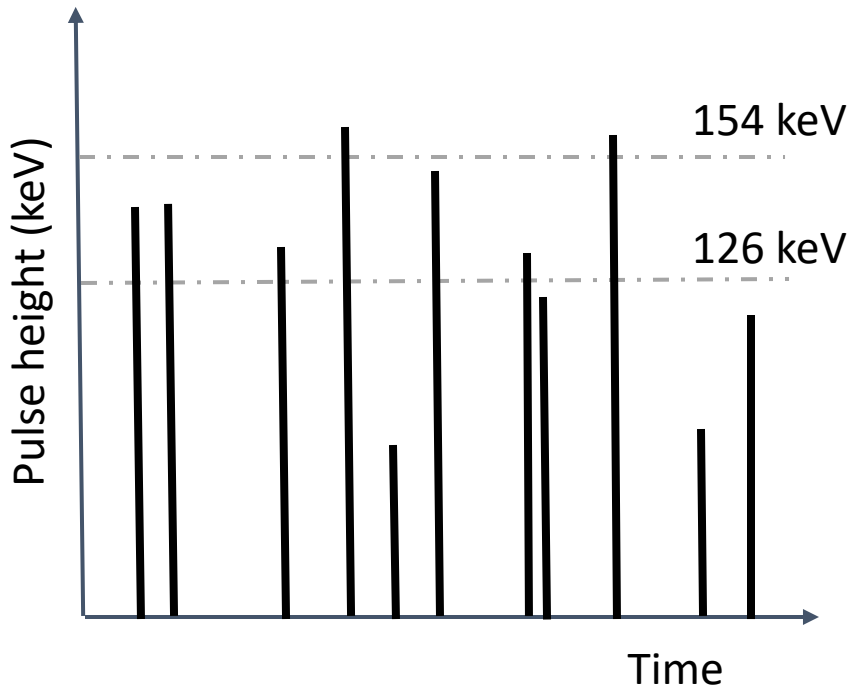


Pulse Height Analysis

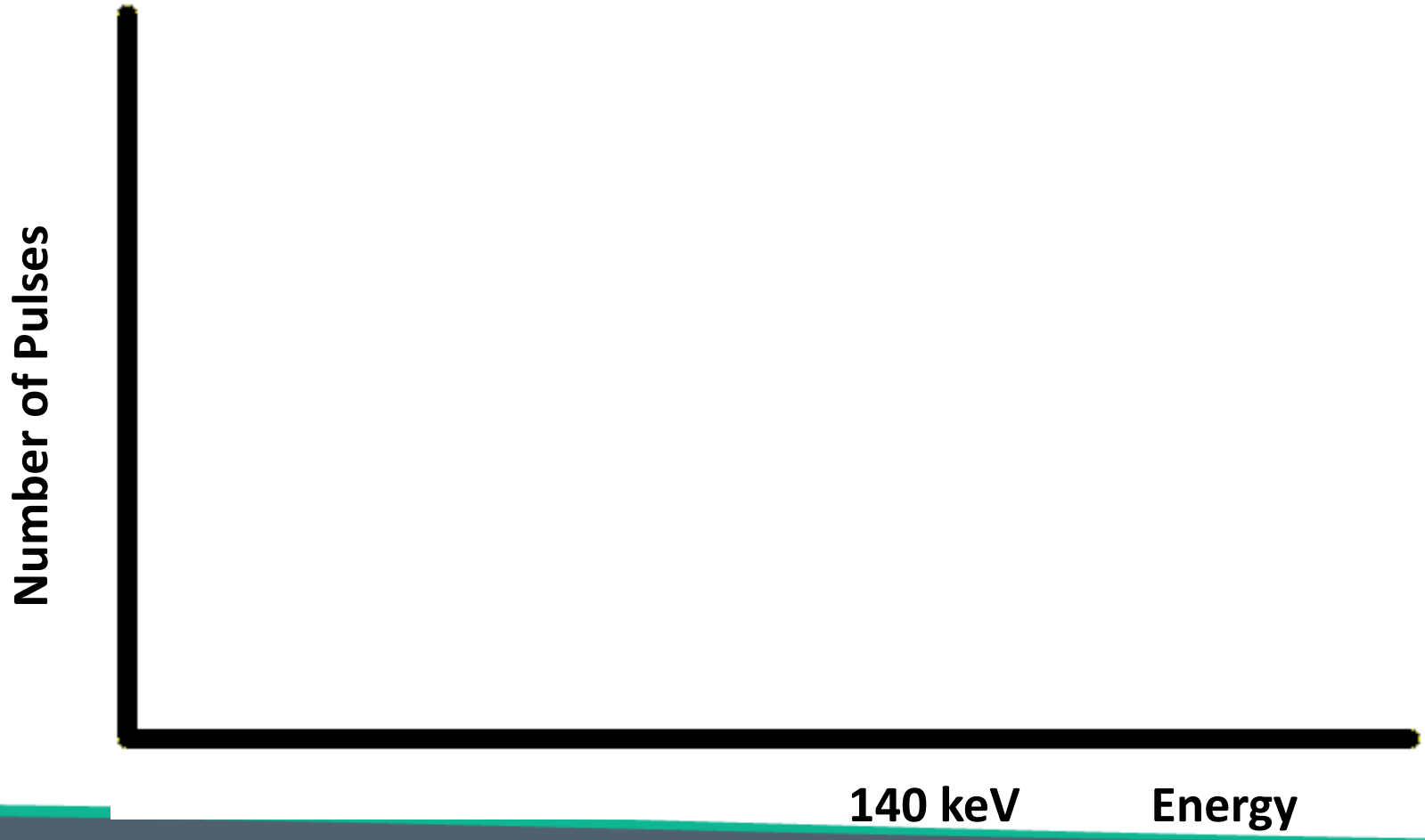
- Gamma photons scatter
  - In the patient
  - Compton scatter in the crystal

Z-signal goes to PHA

- PHA sets
  - energy window
- PHA checks
  - the energy of the γ-ray
- If Z-signal acceptable
  - γ-ray is detected
  - position determined by X and Y signals

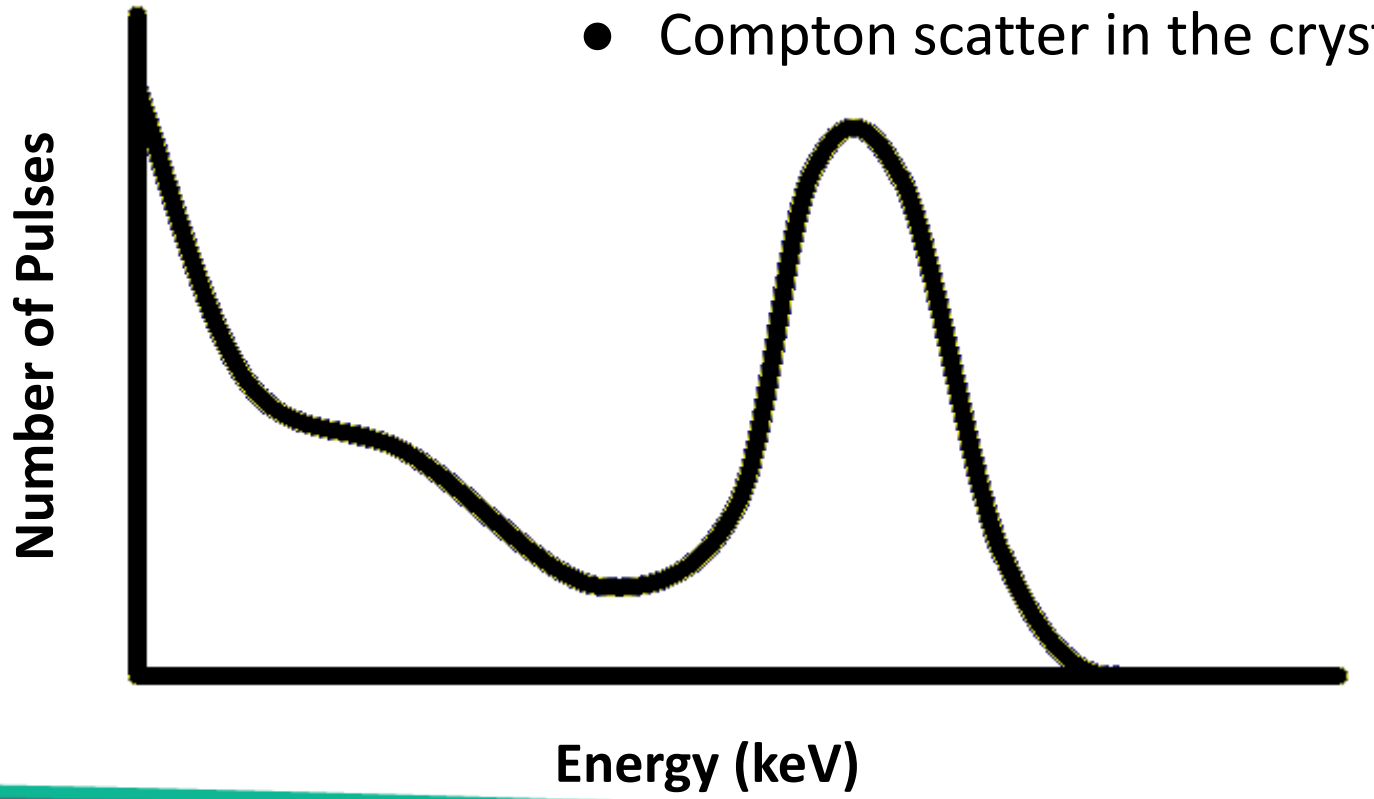


Idealised ^{99m}Tc Spectrum

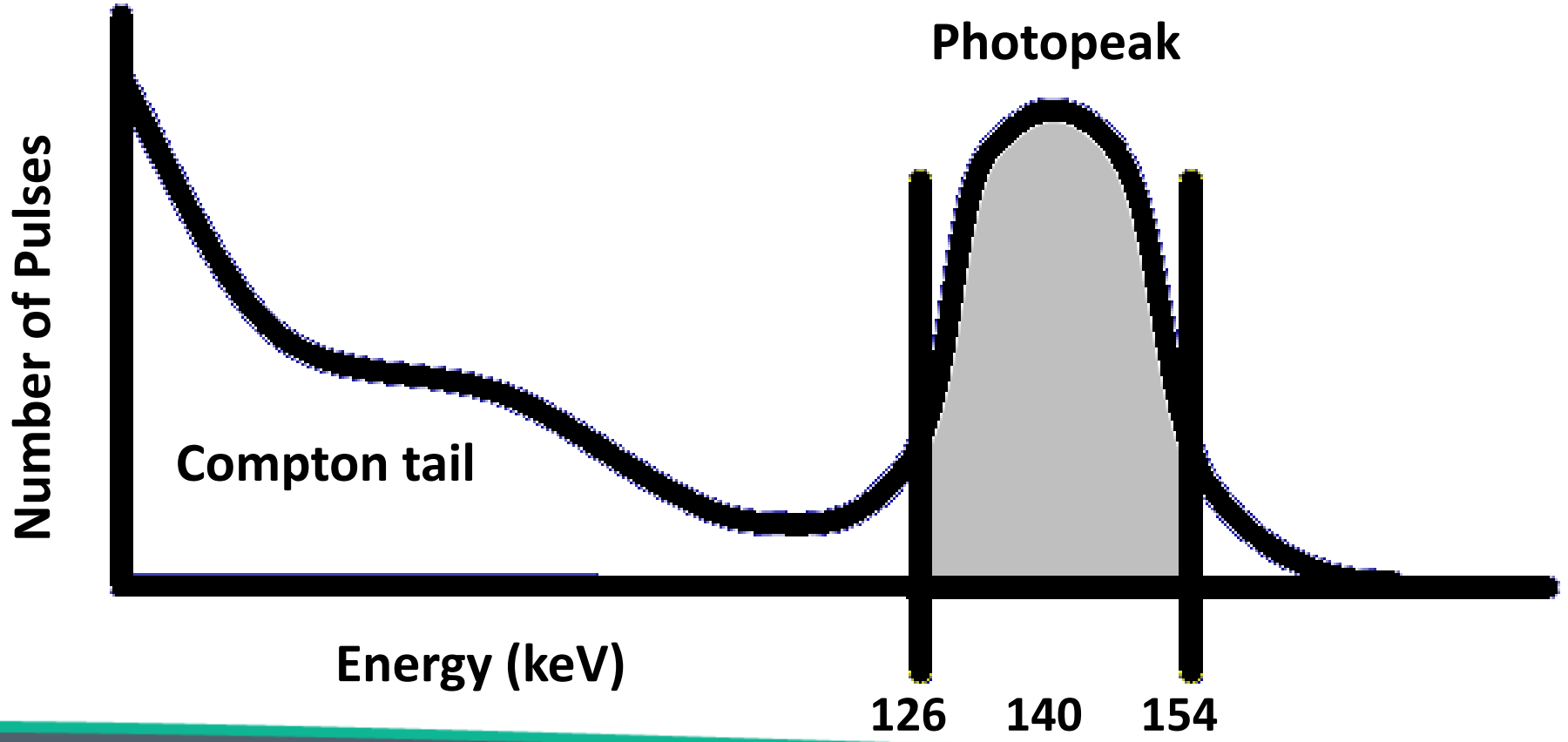


Actual ^{99m}Tc Spectrum

- Scatter within the patient
- Compton scatter in the crystal



Energy Windows



Positional and Energy Co-ordinates

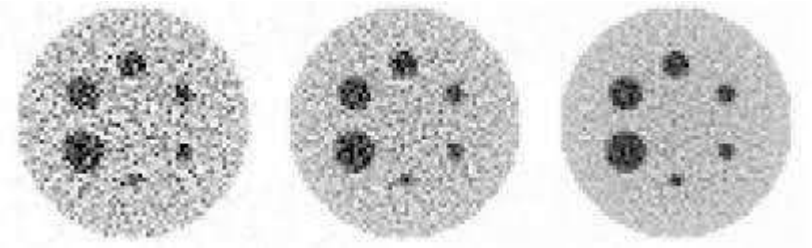
- PMT array detects light pulses from crystal
  - spatial (positional) information – X and Y signals
  - energy information – Z signal
- Z signal – the sum of the outputs of all PMTs
  - proportional to the total light output of the crystal



So we have a signal from the patient and we are ready to look at the images….

Image Quality in Nuclear Medicine

- What can impact Image Quality in Nuclear Medicine?
- Noise – statistical uncertainty in the number of counts recorded
  - Square root of number of counts – more counts = less noise
- More counts (think of sensitivity cps/MBq):
  - Higher activity of radiopharmaceutical given
  - Dependent on uptake and radiopharmaceutical
  - Attenuation in patient will reduce measured counts
  - Longer acquisition time = more counts (but can the patient withstand this?)
- Patient motion or physiological motion - gating
- Scatter

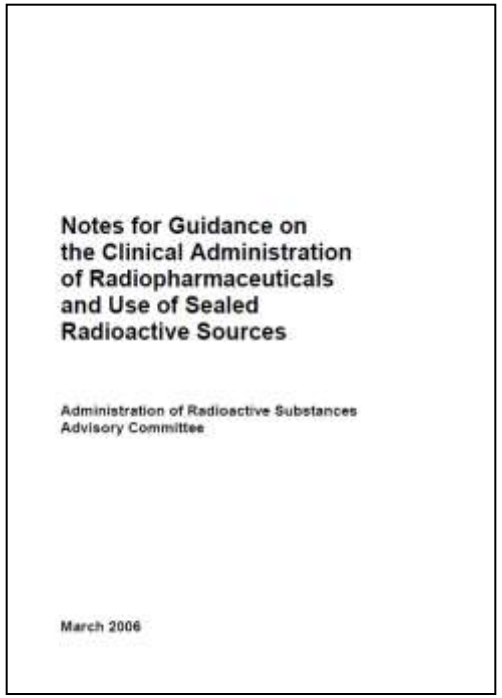


more noise

less noise

Image Quality: Recorded Counts

- Administered Activity
  - diagnostic reference levels – ARSAC
- Uptake
  - radiopharmaceutical properties
- Attenuation
  - patient size
- Acquisition Time
  - typical imaging times: 3-60 minutes


Notes for Guidance on the Clinical Administration of Radiopharmaceuticals and Use of Sealed Radioactive Sources

Administration of Radioactive Substances Advisory Committee

March 2006

Image Quality: Patient Motion

- Long imaging times
  - limit to time patient can remain still
- Physiological motion
  - cardiac gating
  - respiratory gating

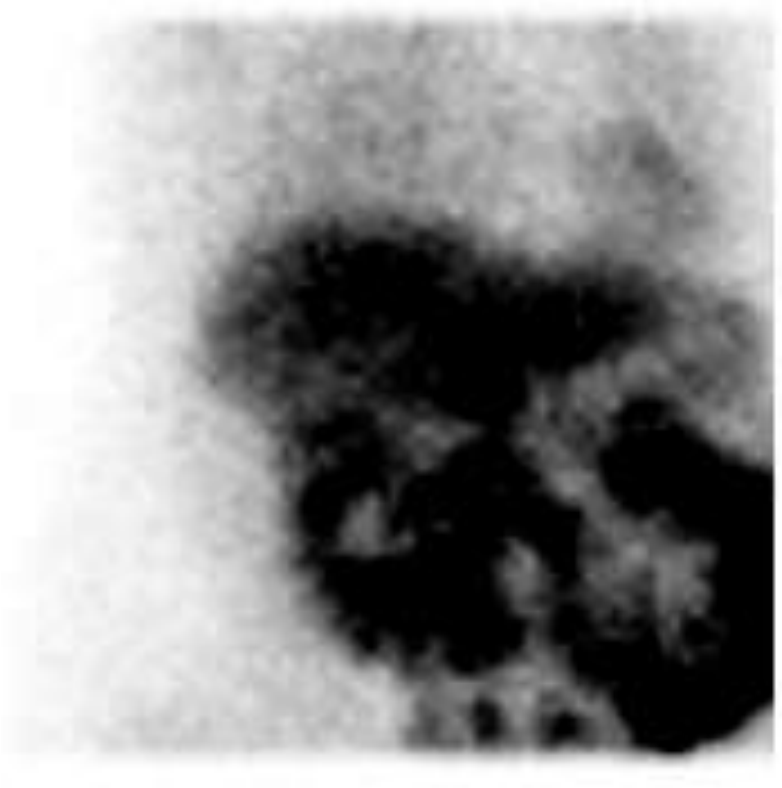


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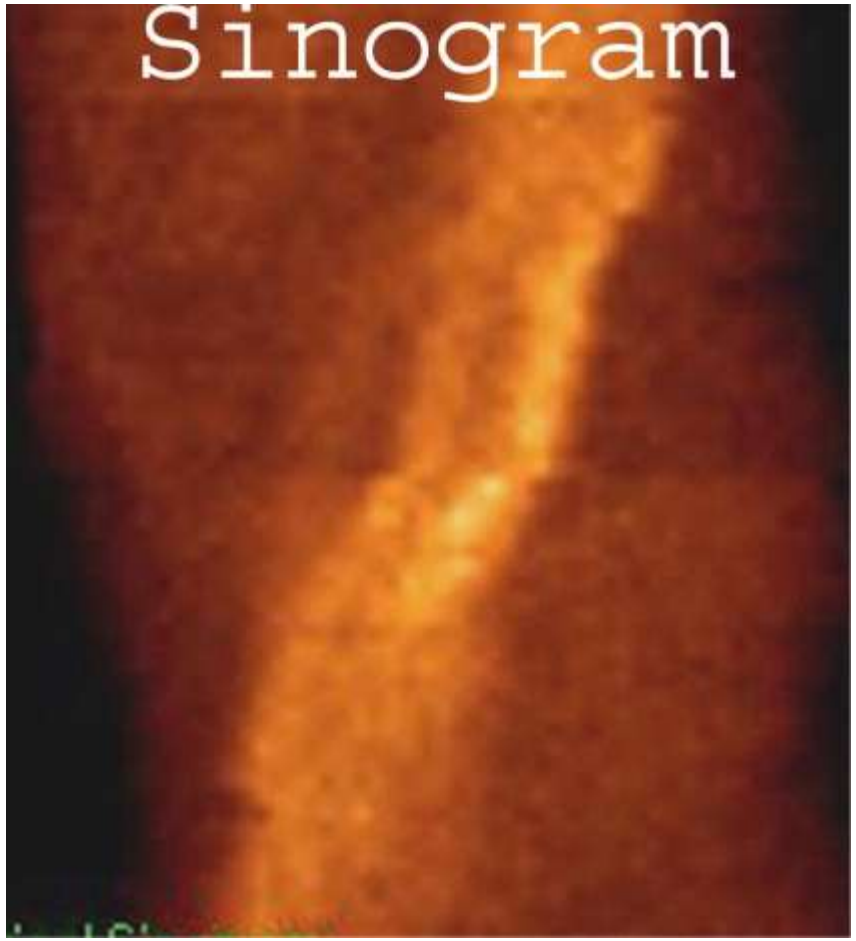


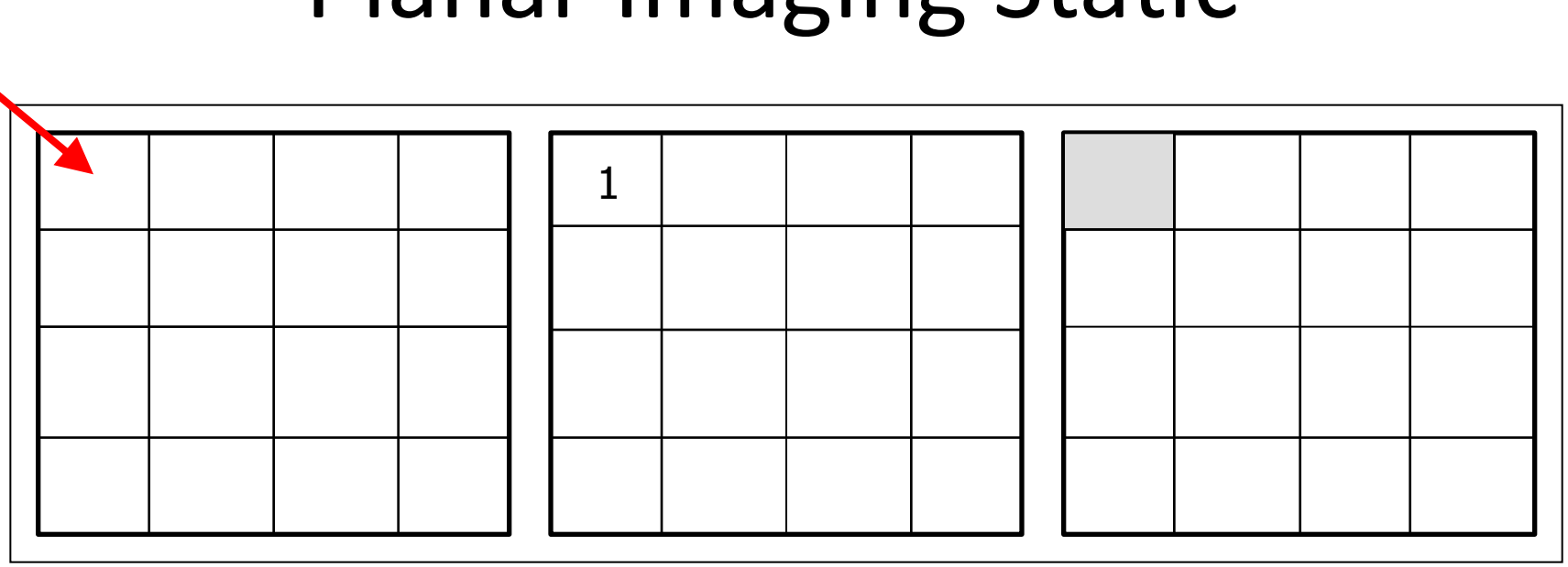
Image Acquisition Techniques

- Planar Imaging
  - Static
  - Dynamic
  - Multiple Gated (MUGA)
  - Whole Body
- Tomographic Imaging
  - Single Photon Emission Tomography (SPECT)
  - Positron Emission Tomography (PET)

Image Acquisition Techniques

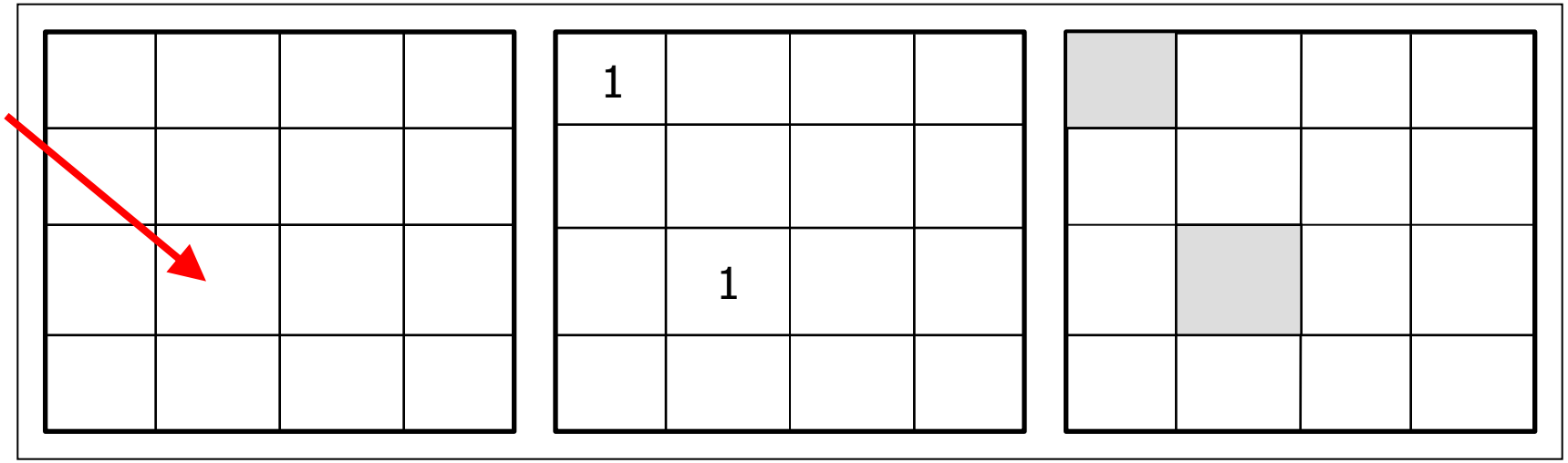
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Planar Imaging Static



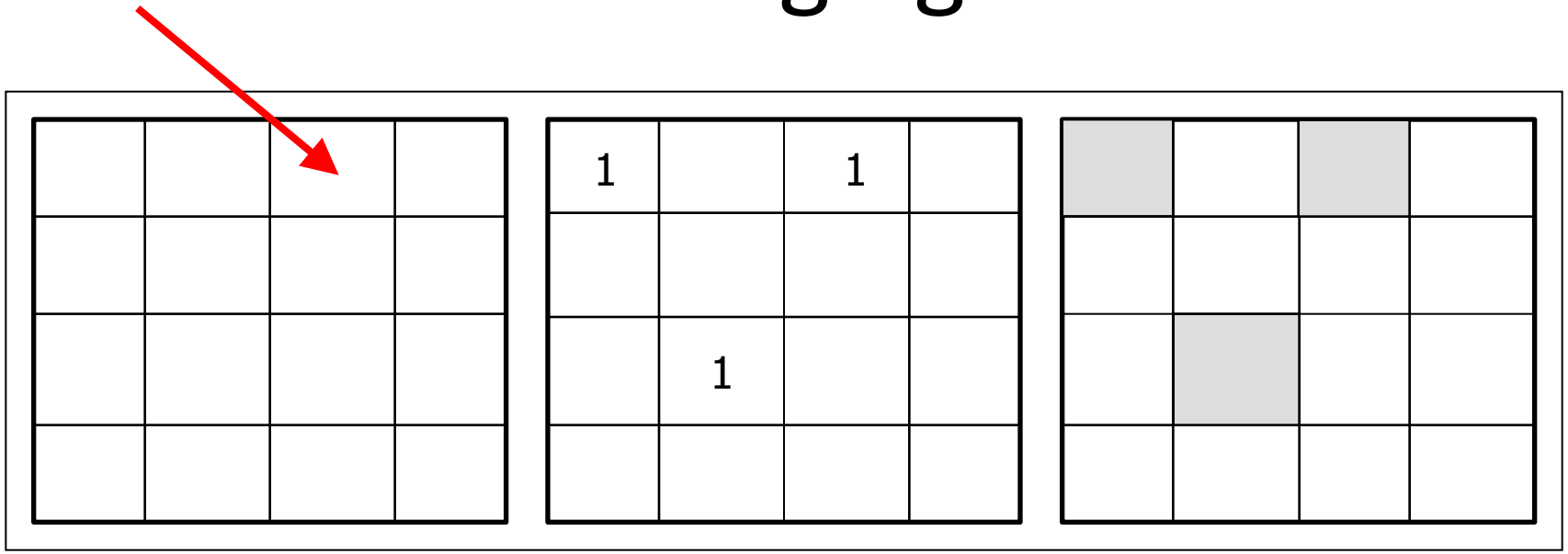
- Camera FOV divided into matrix of pixels
- Each pixel stores number of gamma rays detected at corresponding location on detector in the memory.

Planar Imaging Static



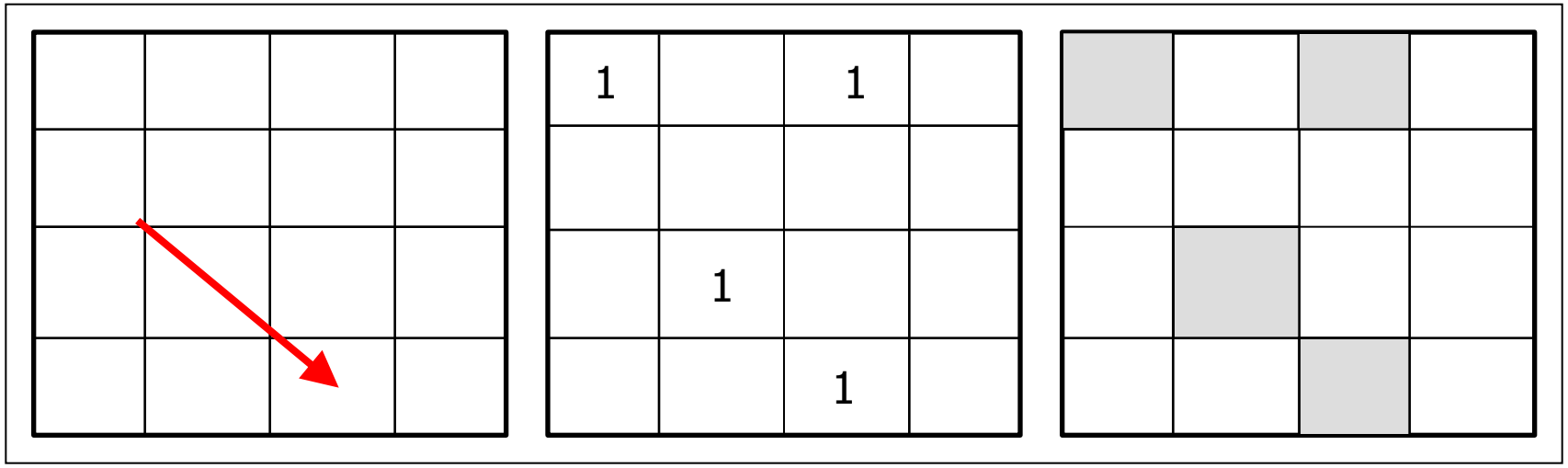
- Image is built up over time

Planar Imaging Static



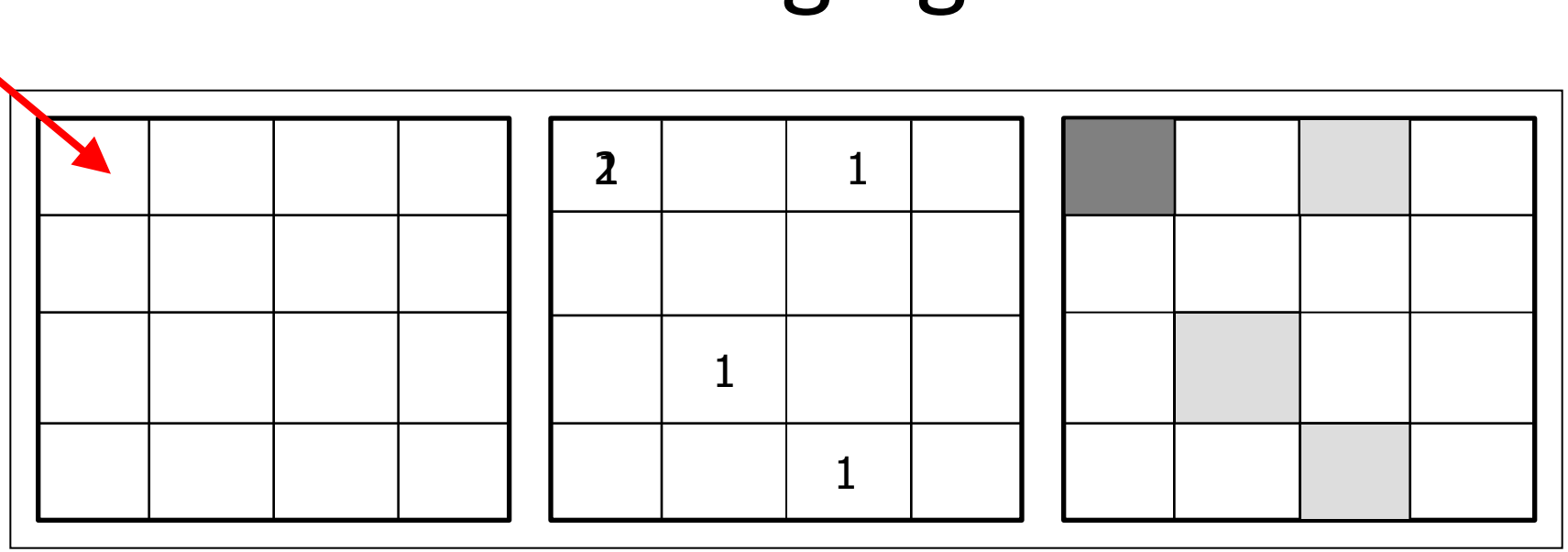
- Typical matrix sizes: 256^2, 128^2, 64^2

Planar Imaging Static



- Pixels darker that have detected more events

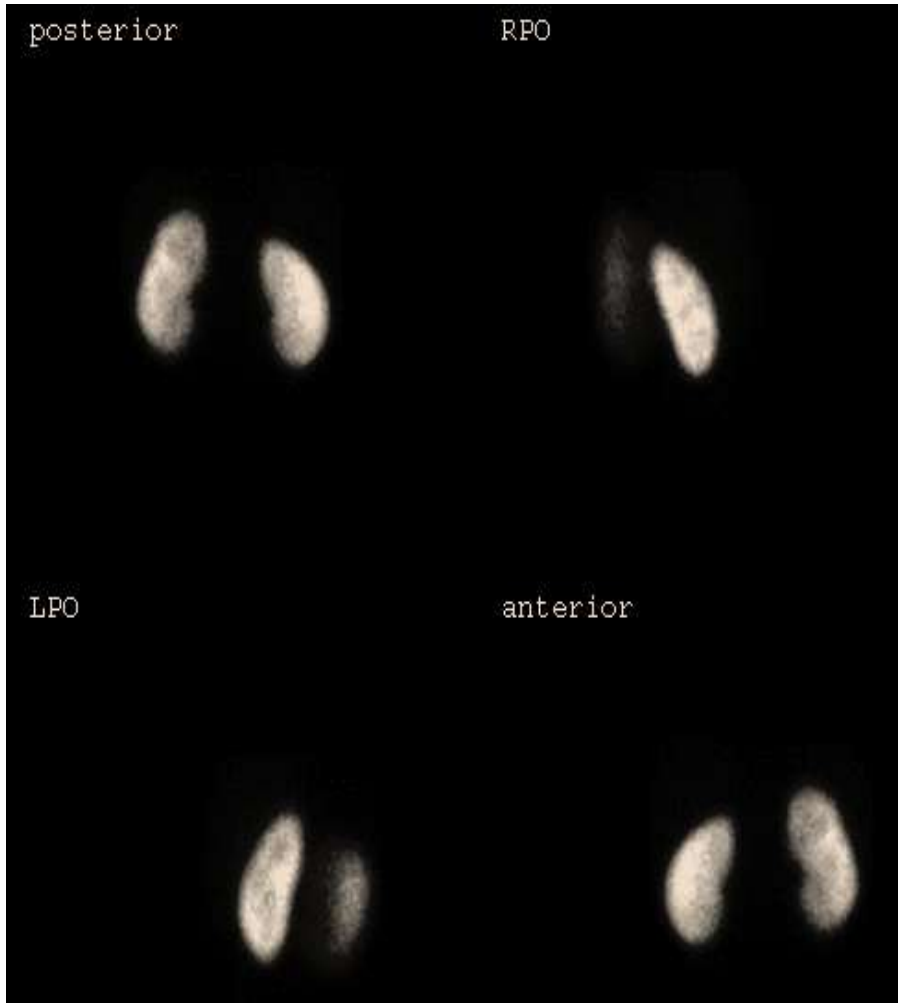
Planar Imaging Static



- Areas of increased uptake ‘hot spots’

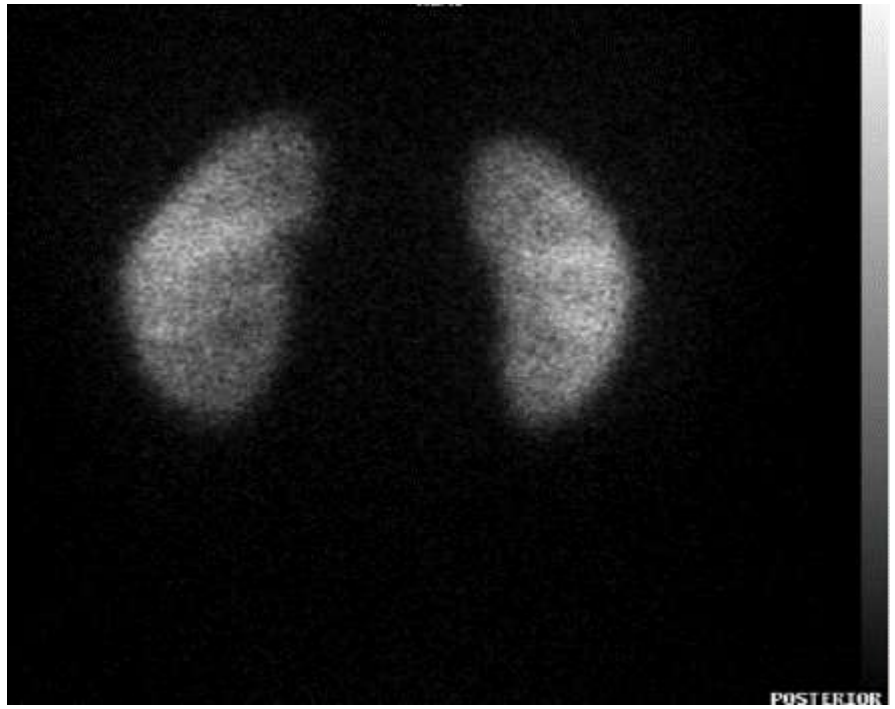
Renal Imaging - DMSA

- Radiopharmaceutical
  - ^{99m}Tc-DMSA
- Imaged at 3-4 hours
- Effective dose
  - 0.7 mSv
- Investigates
  - renal scarring
  - non-functioning tissue
  - divided renal function
- Useful post UTIs



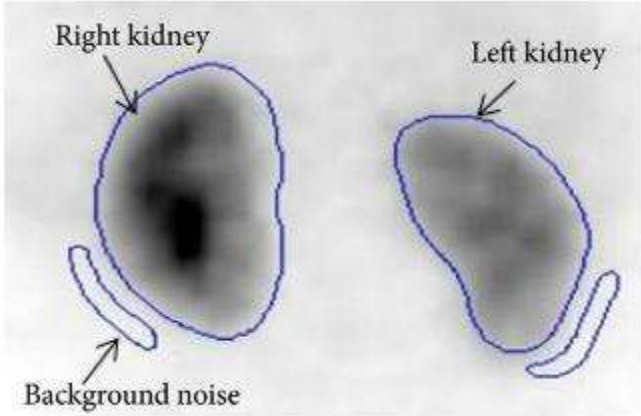
Case 1 – Normal Scan

- Divided function
  - Normal range: 45 - 55%
- Normal scan
  - bilateral smooth renal outlines
  - equal sized kidneys



Case 2 – Renal Scarring

- More sensitive than ultrasound
- Focal scarring in left kidney
- Atrophic right kidney



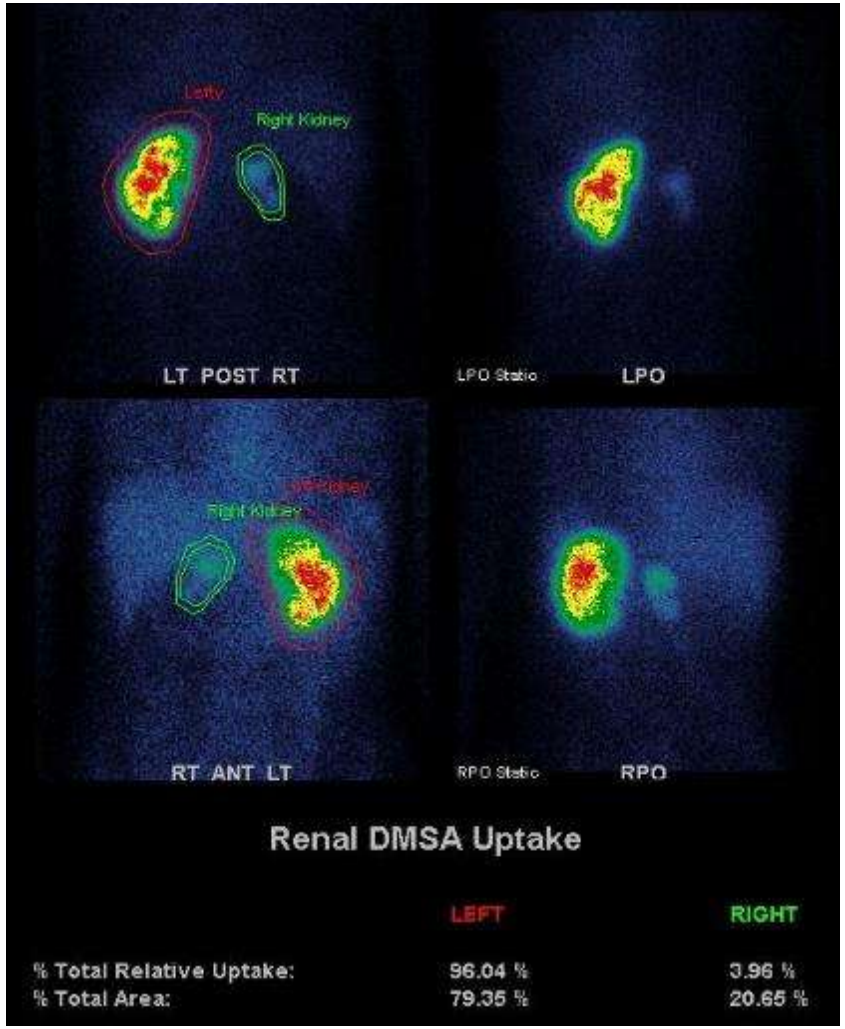


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  - Whole Body
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Dynamic Imaging

- Series of sequential static images
  - e.g. 90 frames each of 20sec
- Images
  - changing distribution of activity within the patient
- Examples include:
  - gastric emptying studies
  - lymphoscintigraphy
  - diuretic renography

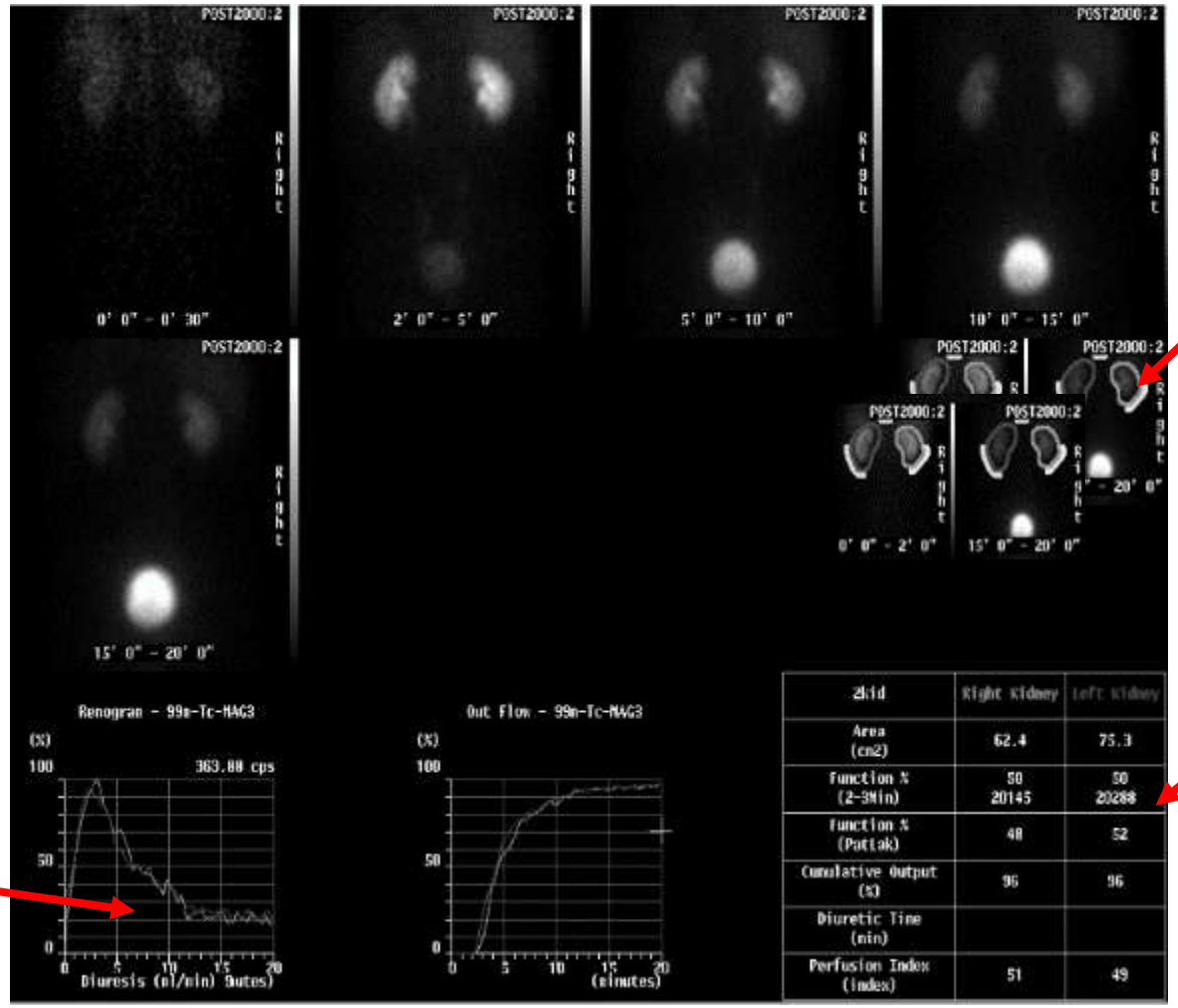


Diuretic Renography

- Radiopharmaceutical
  - ^{99m}Tc-MAG3
- Imaged immediately
- Effective dose
  - 0.7 mSv
- Investigates
  - suspected obstruction
  - dilated system
  - pre-transplant donor assessment



Case 1: Normal Study



Regions of Interest (ROI)

Curves showing changing renal activity over time

Split Renal Function

Case 2: Obstructed System

Rising time-activity curves on both kidneys

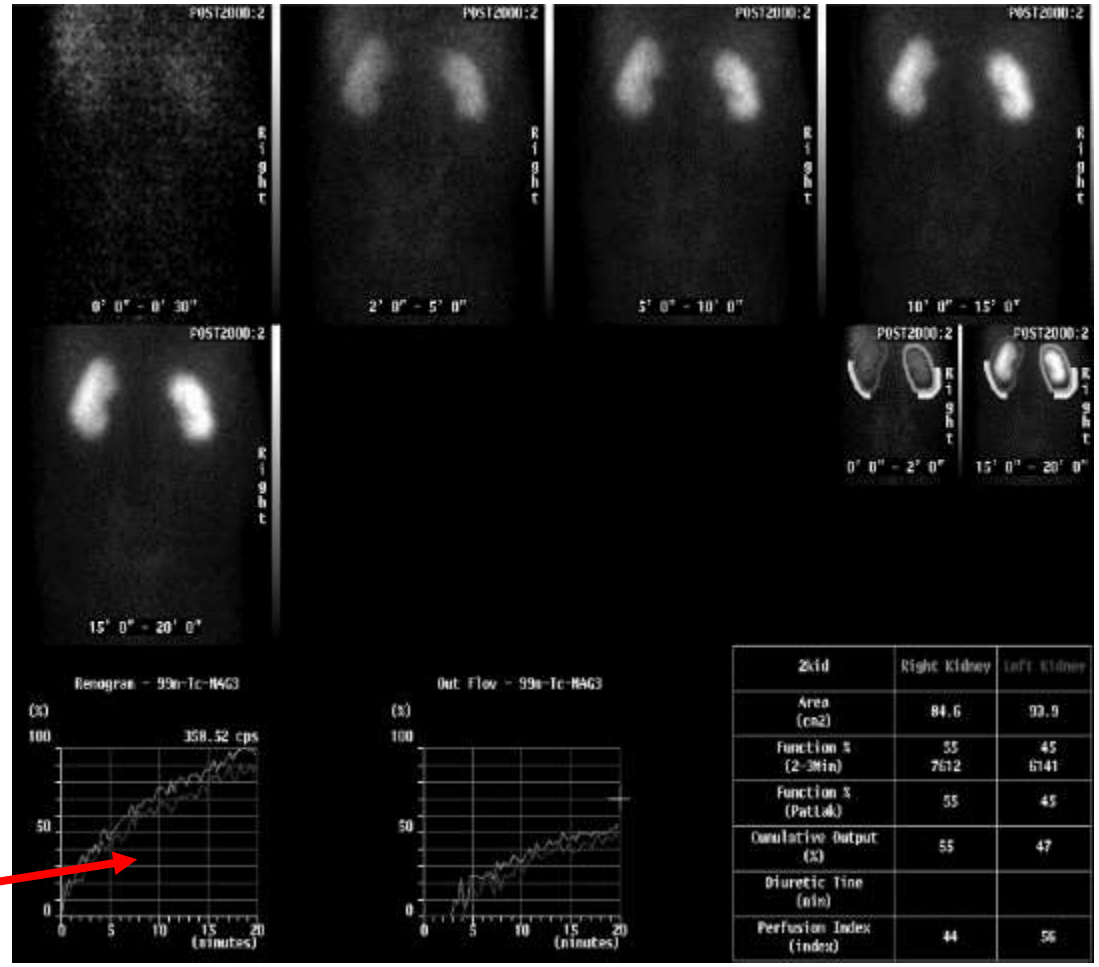


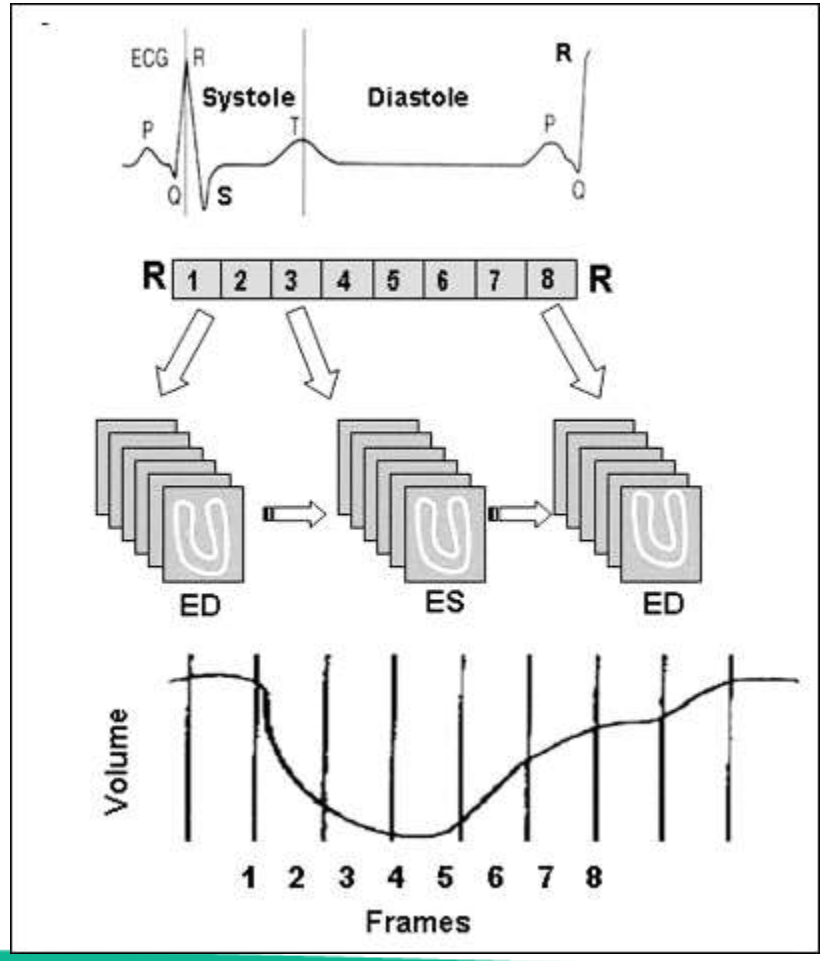
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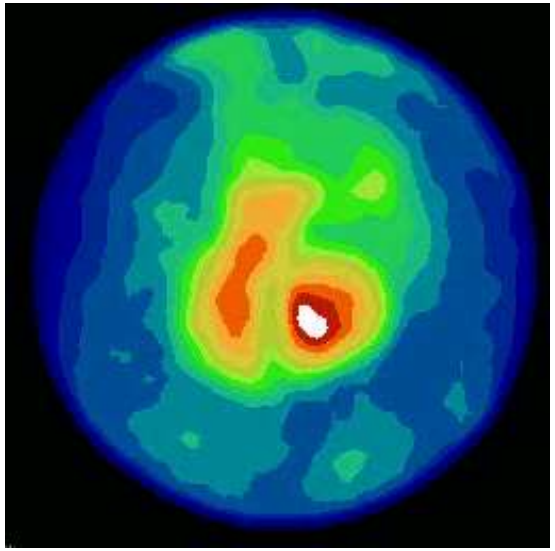
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Multiple Gated Acquisition Imaging (MUGA)





- Multiple images/frames acquired over each cardiac cycle
- ‘Build up’ acquisition over many cycles

Radionuclide Ventriculography (RNVG)

- Radiopharmaceutical
  - Tc-99m labelled red cells
- Imaged immediately
- Effective dose
  - 6 mSv
- Investigates
  - left ventricular function
  - regional wall motion



- Allows precise/repeatable measurement of LVEF
  - left ventricular ejection fraction

Radionuclide Ventriculography

- LVEF value
- Cardiotoxic drugs

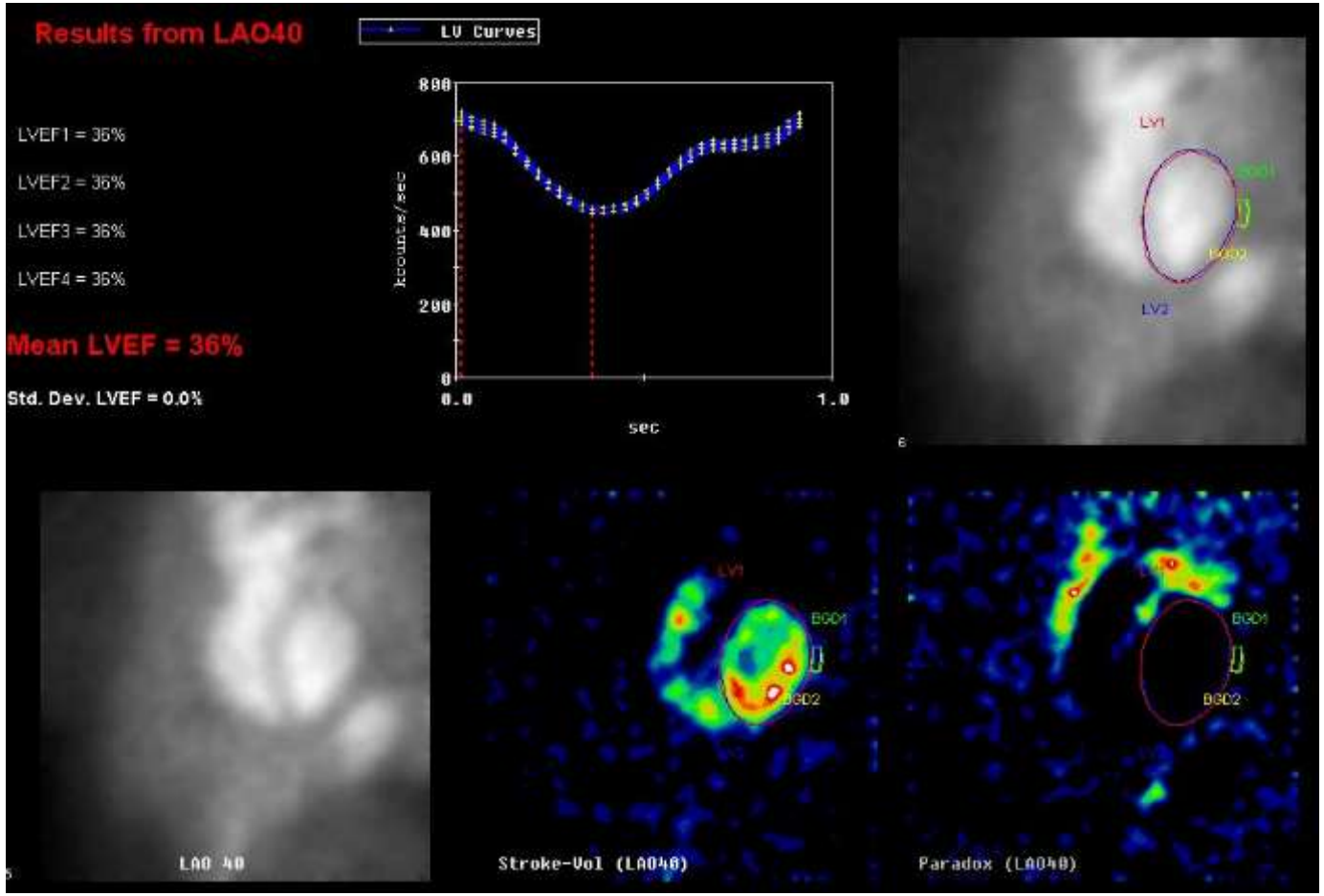


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Whole Body Imaging

- A window (or ramp)
  - opens along the camera face
  - and then slowly scans down the body
- Ramps down as camera
  - reaches the preset end of the body
- Sensors on the camera (PSD's)
  - ensure detectors remain close to the patient



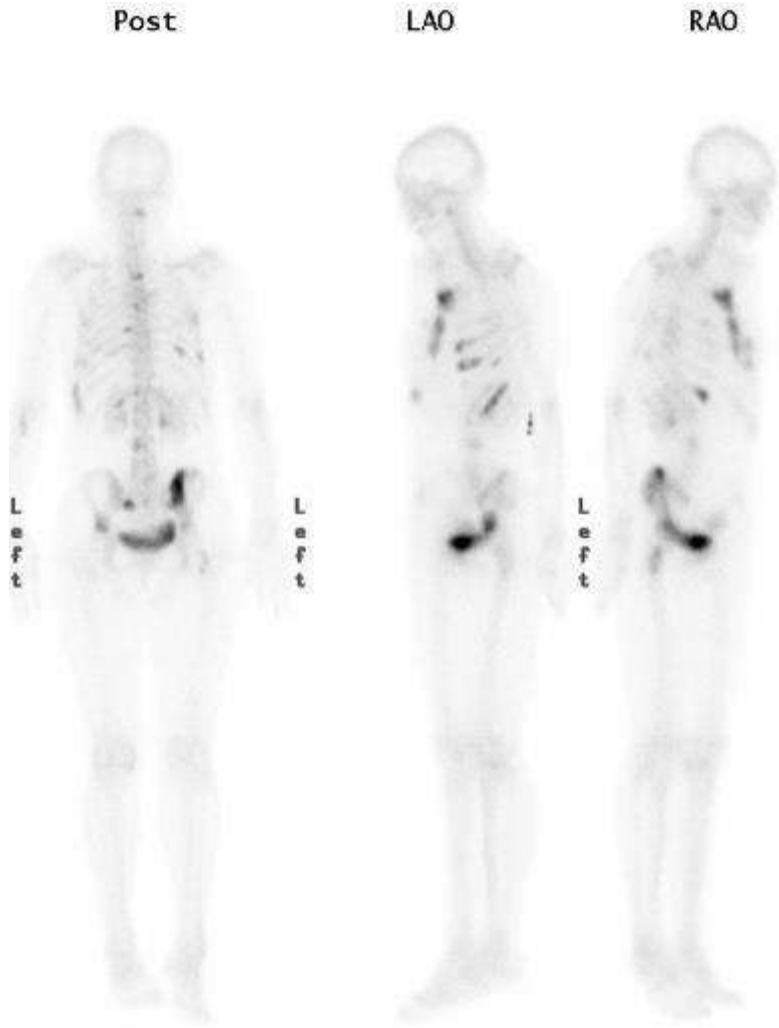
Case 1

- Radiopharmaceutical
  - ^{99m}Tc-HDP
  - Uptake dependent on blood flow and osteoblastic activity
- Imaged at 3-4 hrs
  - High bone to soft tissue ratio
- Effective dose 3 mSv
- Symmetry expected
- Normal physiological uptake in kidneys and bladder



Case 2

- Focal uptake
  - throughout axial skeleton
- Osteo*blastic* metastases
  - breast and prostate
  - high sensitivity
- Osteo*lytic* metastases
  - Renal, breast, lung, myeloma
  - Reduced sensitivity



Case 3

- Superscan
- Non-visualisation of
  - kidneys
  - soft tissue
- Poor visualisation of
  - limb bones
- Diffusely increased
  - Skeletal uptake
- Causes
  - widespread metastases

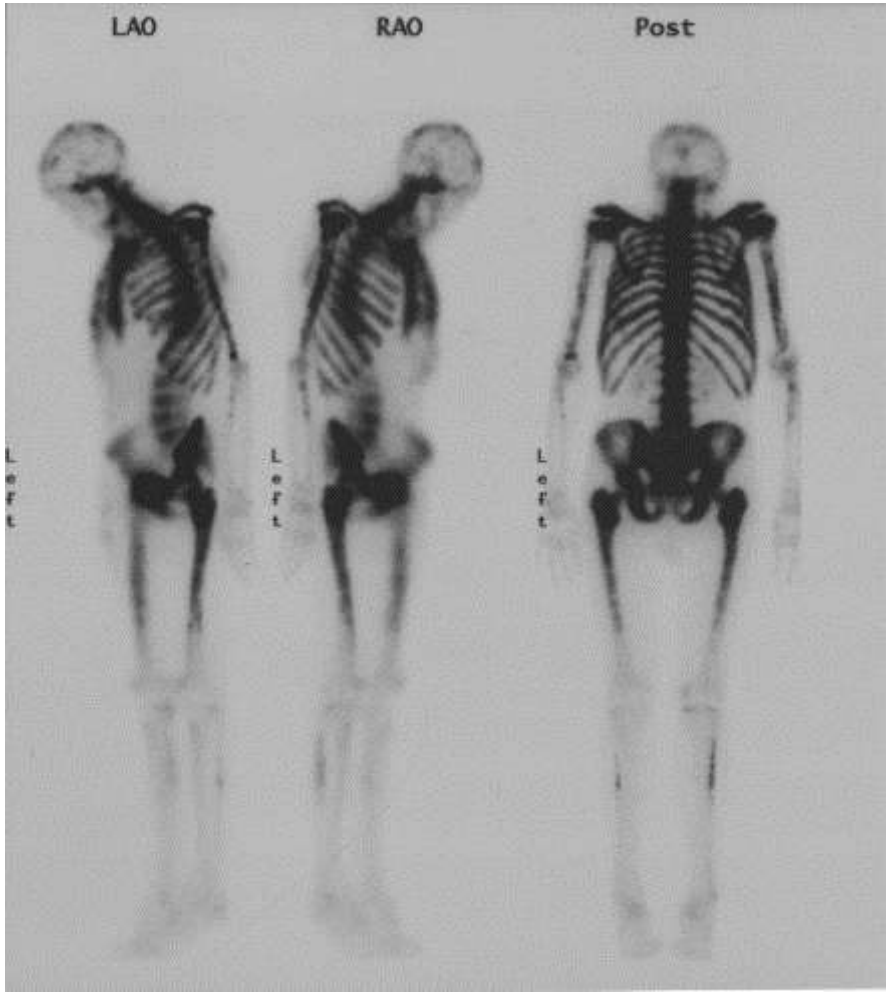


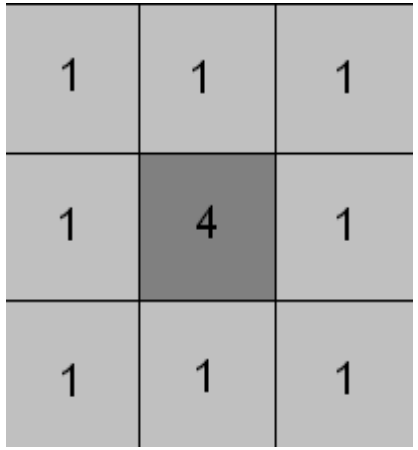
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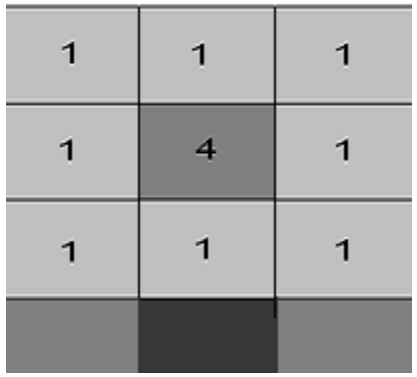
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Pitfalls of Planar Imaging



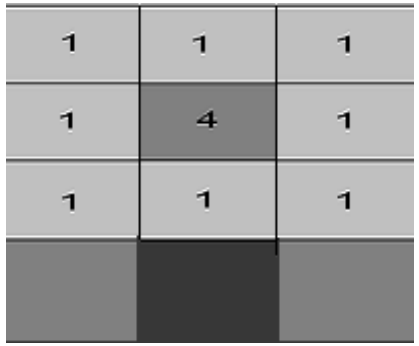
- Planar imaging
  - 2D representation of 3D distribution of activity
  - No depth information
  - Structures at different depths are superimposed
    - Loss of contrast

Pitfalls of Planar Imaging



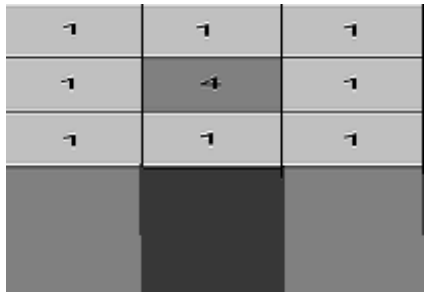
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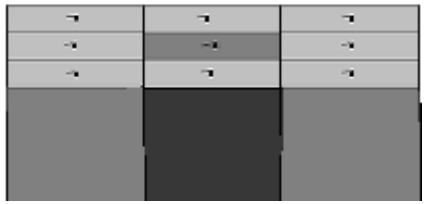
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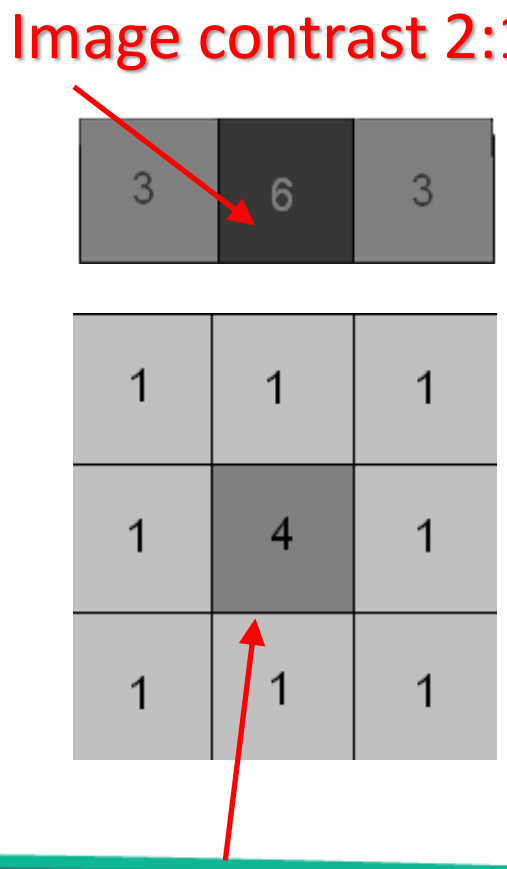
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Today Recap

1. What is Nuclear Medicine?

Administration of radiopharmaceuticals for functional imaging (diagnostic) or therapeutic purposes.

2. What are radiopharmaceuticals? What ideal properties do we require?

Radionuclide (radiation emitter) + Pharmaceutical (physiological uptake), physical half-life, biological half-life

3. What is a gamma camera?
   - Components

Collimator, scintillation crystal, PMTs, electronics

4. How do we form an image using a gamma camera?

Gamma -> scintillation light -> photoelectron, Energy discriminator (Pulse Height Analyser), Location (Anger Logic)

5. What types of imaging can we do using the gamma camera?

Static, Dynamic, Gated…… TBC!

6. Clinical examples of different types of scans using the gamma camera

DMSA, renogram, RNVG, WB Bone

Thank you for listening!