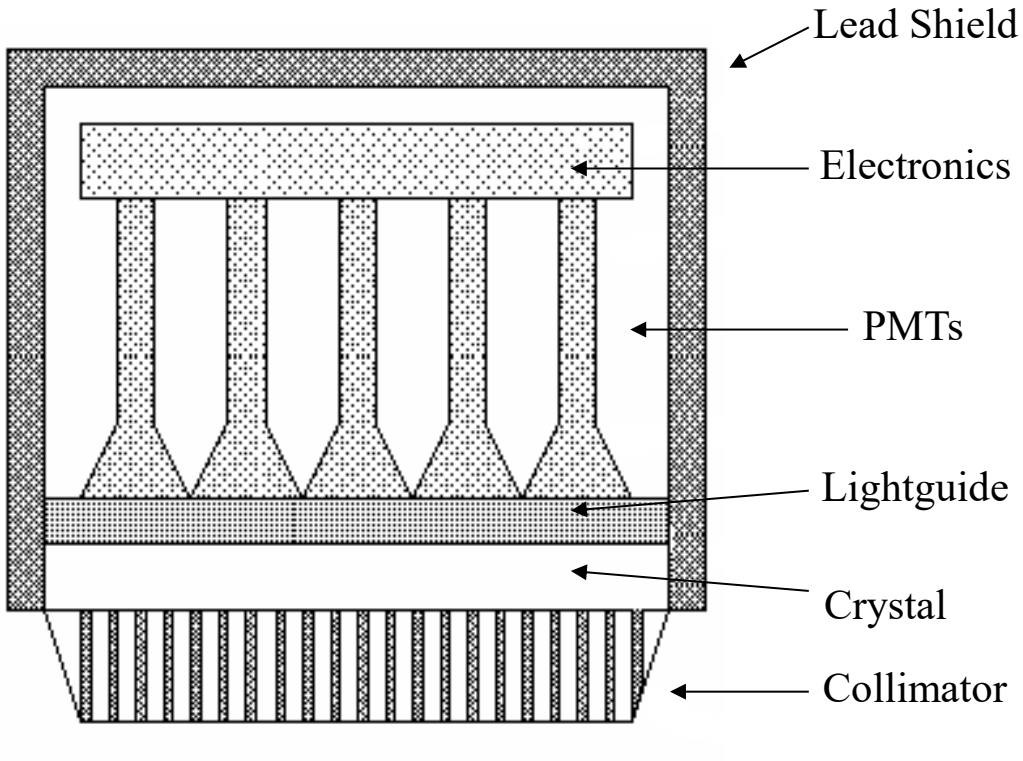
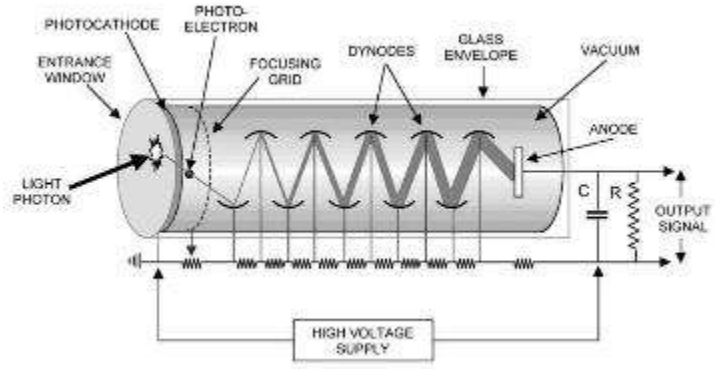
NHS
Hull University Teaching Hospitals
NHS Trust

FRCR Nuclear Medicine

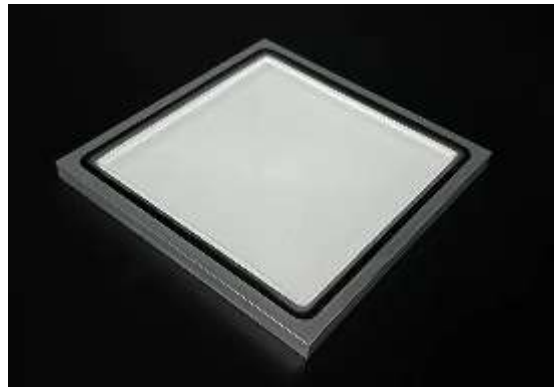
Lecture 2
SPECT and PET Imaging

Quick recap:





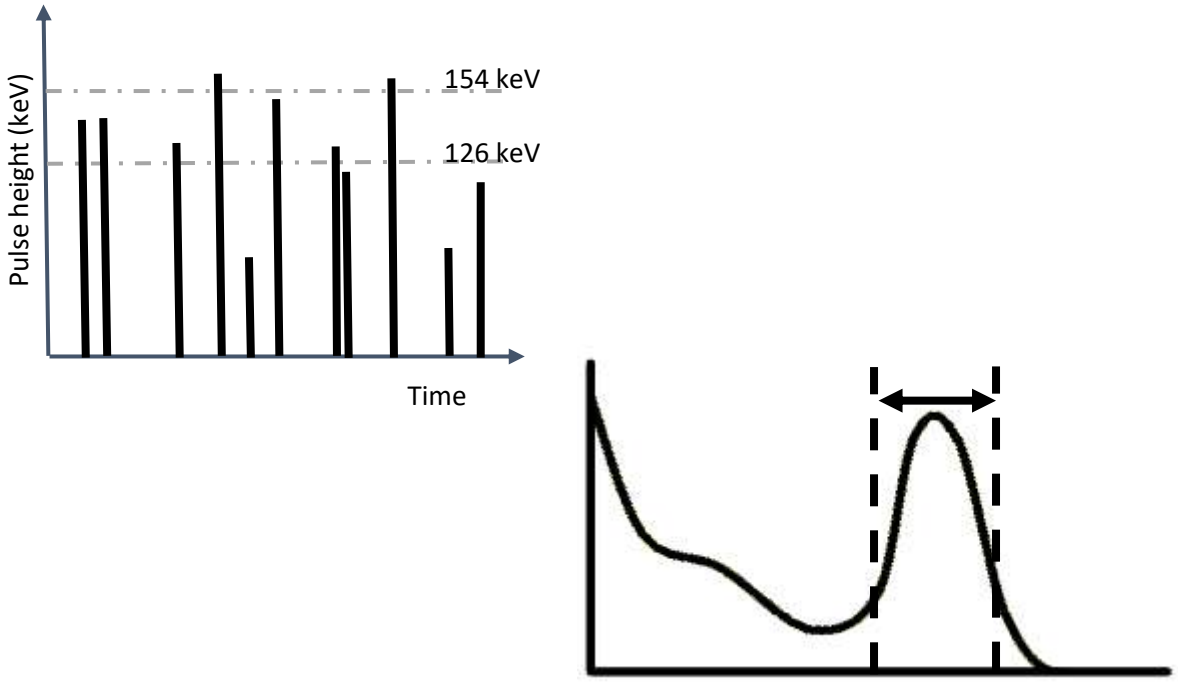
Sodium Iodide scintillation crystal
Light output proportional to energy absorbed



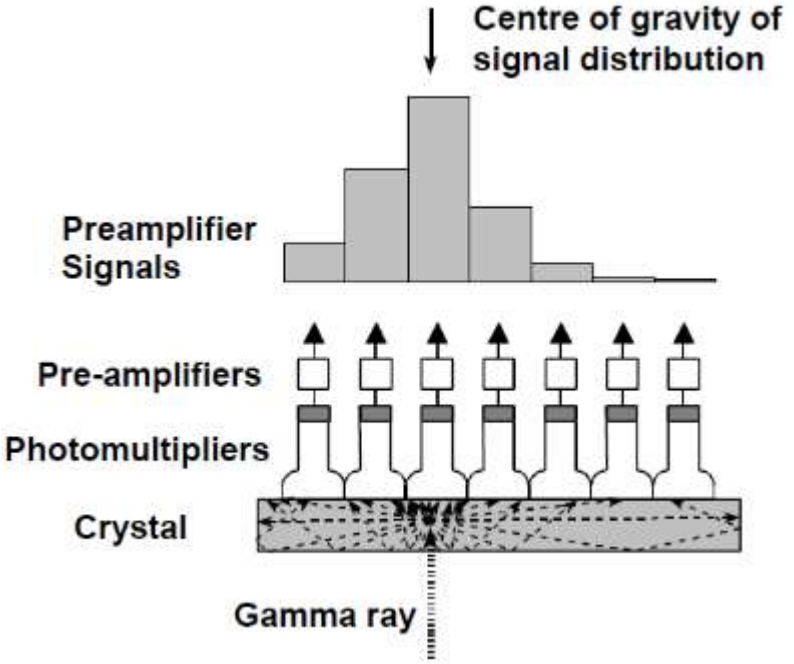


1. Septal Thickness
2. Septal Spacing
3. Septal Length

Quick recap:



Energy Discrimination – Pulse Height Analyser



Localisation – Anger Logic

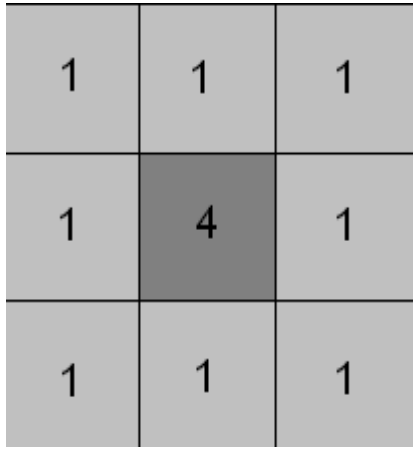
Image Acquisition Techniques

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

Image Acquisition Techniques

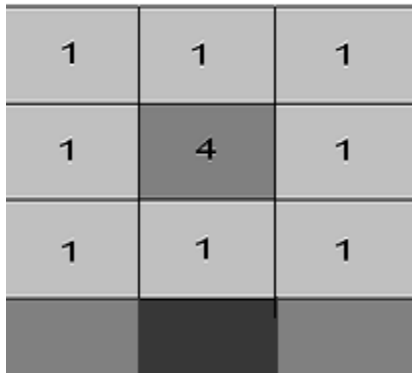
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Pitfalls of Planar Imaging



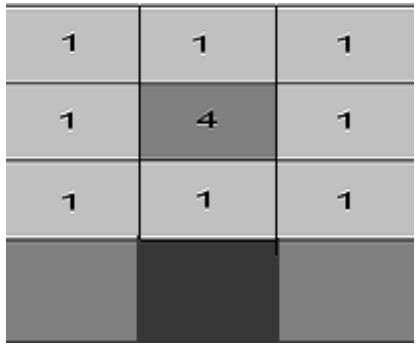
- Planar imaging
  - 2D representation of 3D distribution of activity
  - No depth information
  - Structures at different depths are superimposed
    - Loss of contrast

Pitfalls of Planar Imaging



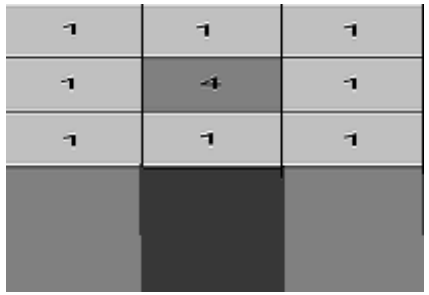
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Pitfalls of Planar Imaging



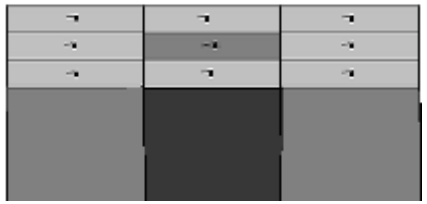
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Pitfalls of Planar Imaging



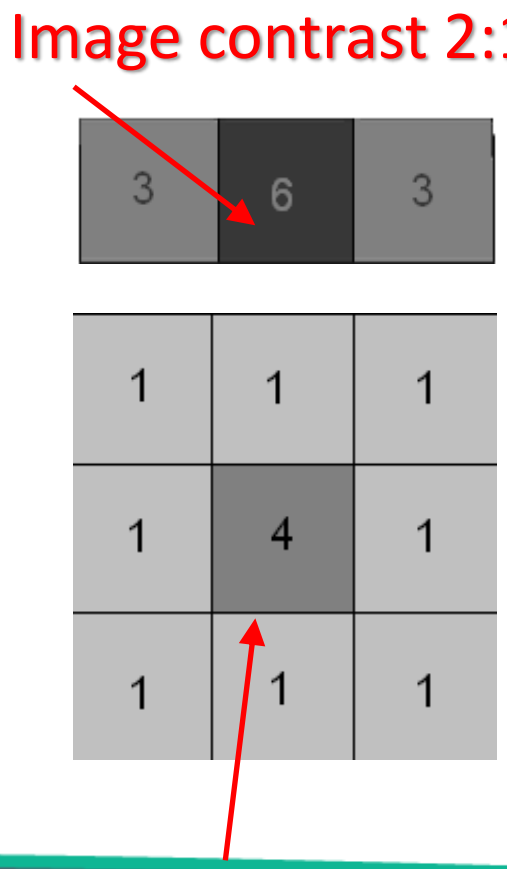
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Pitfalls of Planar Imaging



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Pitfalls of Planar Imaging



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Image Acquisition Techniques

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Image Acquisition Techniques

- Planar Imaging
  - Static
  - Dynamic
  - Multiple Gated (MUGA)
  - Whole Body / Continuous
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Image Acquisition Techniques

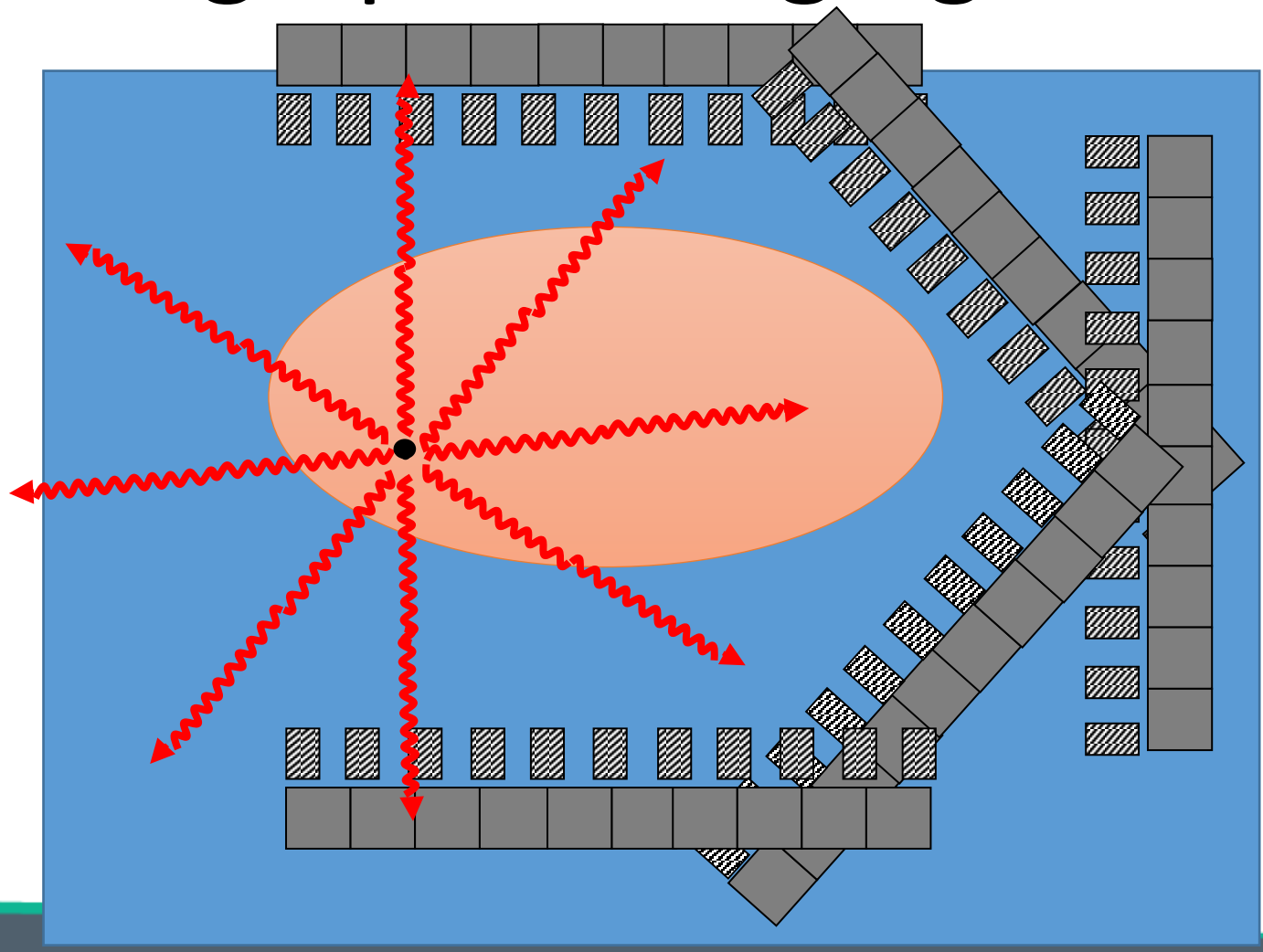
- Planar Imaging
  - Static
  - Dynamic
  - Multiple Gated (MUGA)
  - Whole Body / Continuous
- Tomographic Imaging
  - Single Photon Emission Tomography (SPECT)
  - Positron Emission Tomography (PET)

Tomographic Imaging - SPECT

γ/X-rays → SPECT

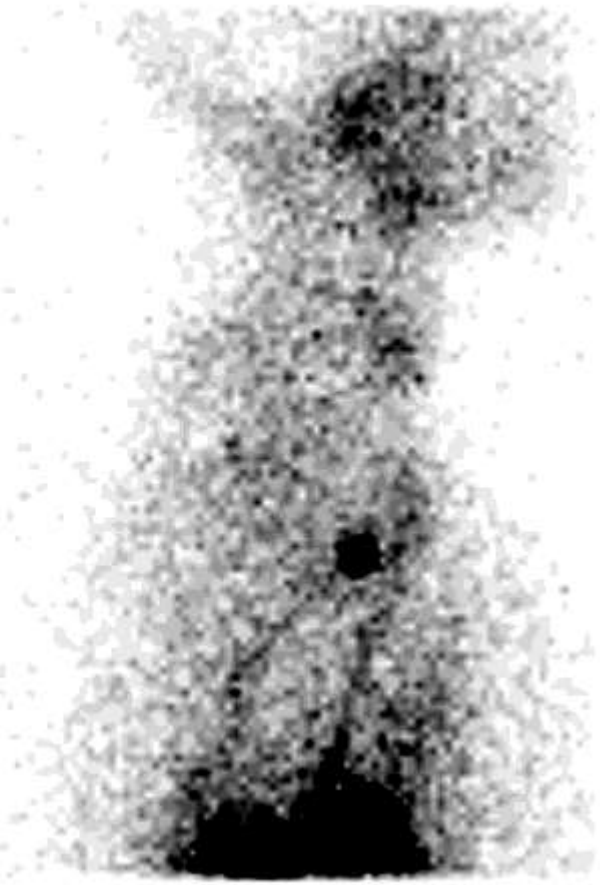
Isotope	Half-life (hr)	Energy (keV)
$^{99}Tc^{m}$	6.0	140
^{111}In	67.3	171 & 245
^{123}I	13.2	159
^{201}Tl	73.0	69-83

Tomographic Imaging - SPECT



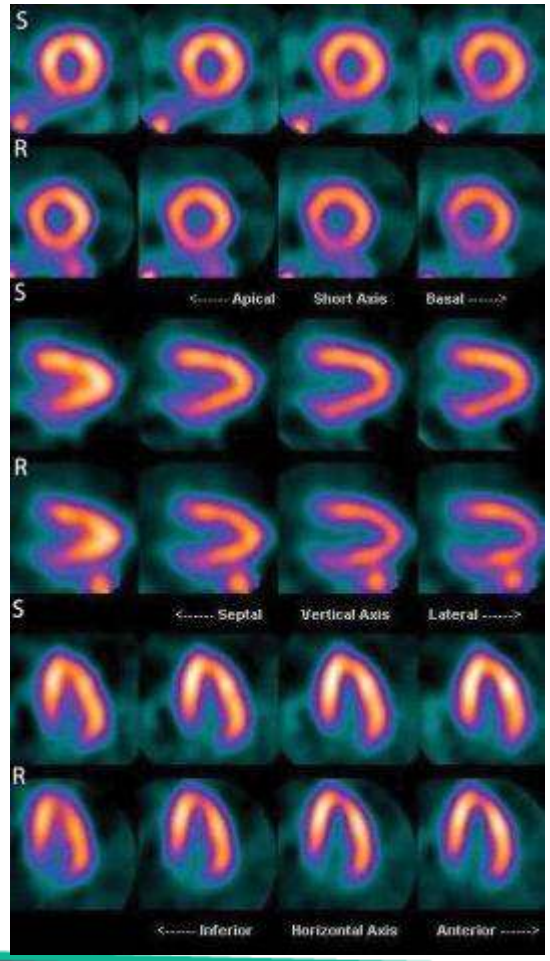
Tomographic Imaging - SPECT

- Multiple planar images (projections)
  - acquired at several angles around the patient
- Projections processed
  - Filtered Backprojection
  - Iterative Reconstruction



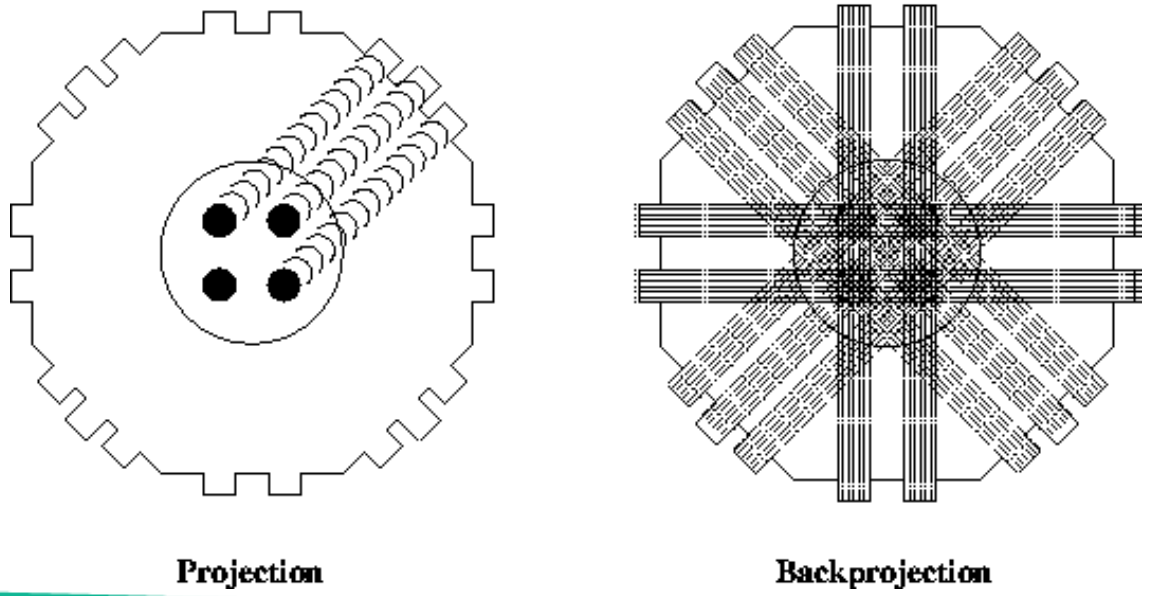
Tomographic Imaging - SPECT

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Filtered Backprojection

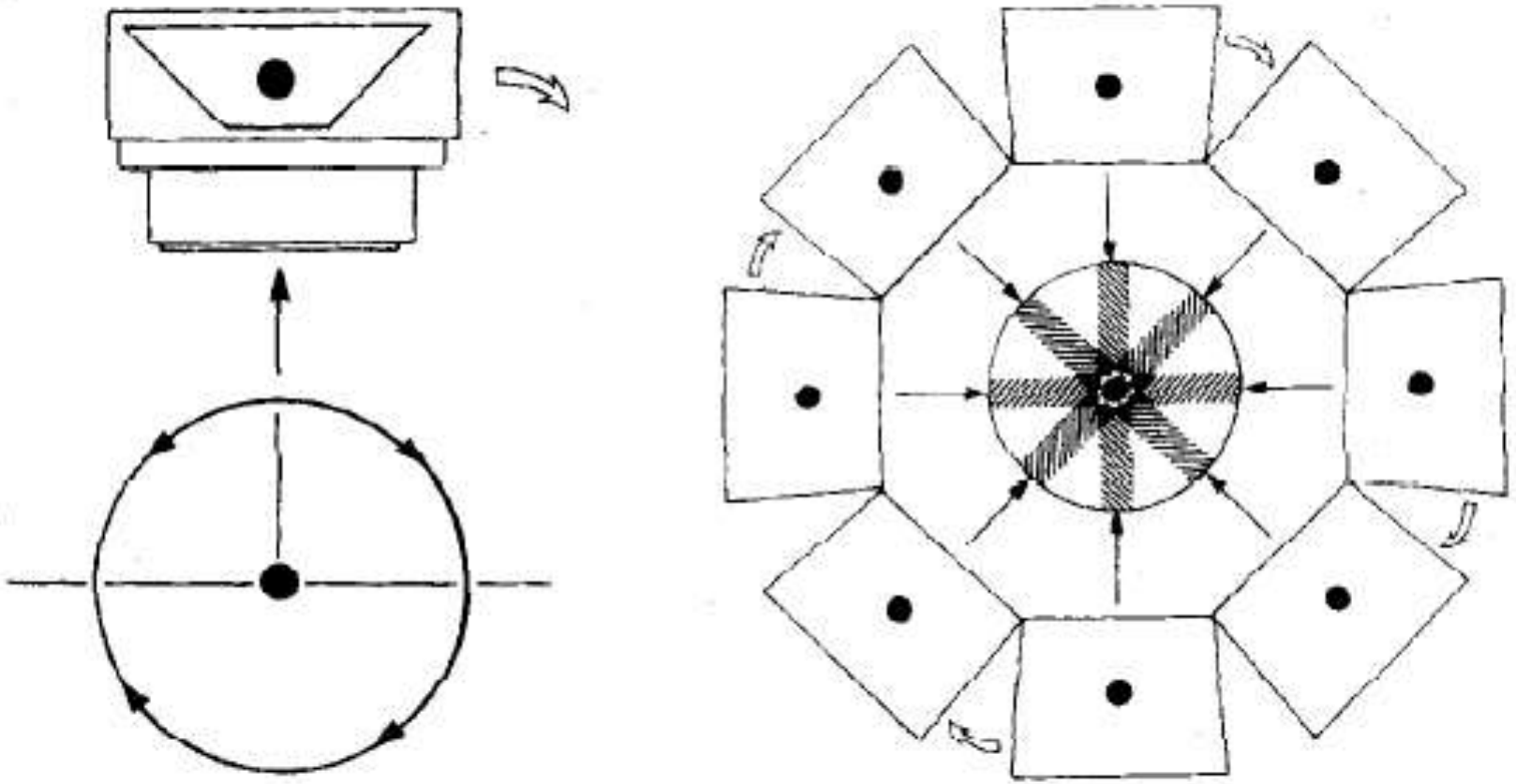
- Simple Backprojection
  - mathematical method to reconstruct a tomographic image



Projection

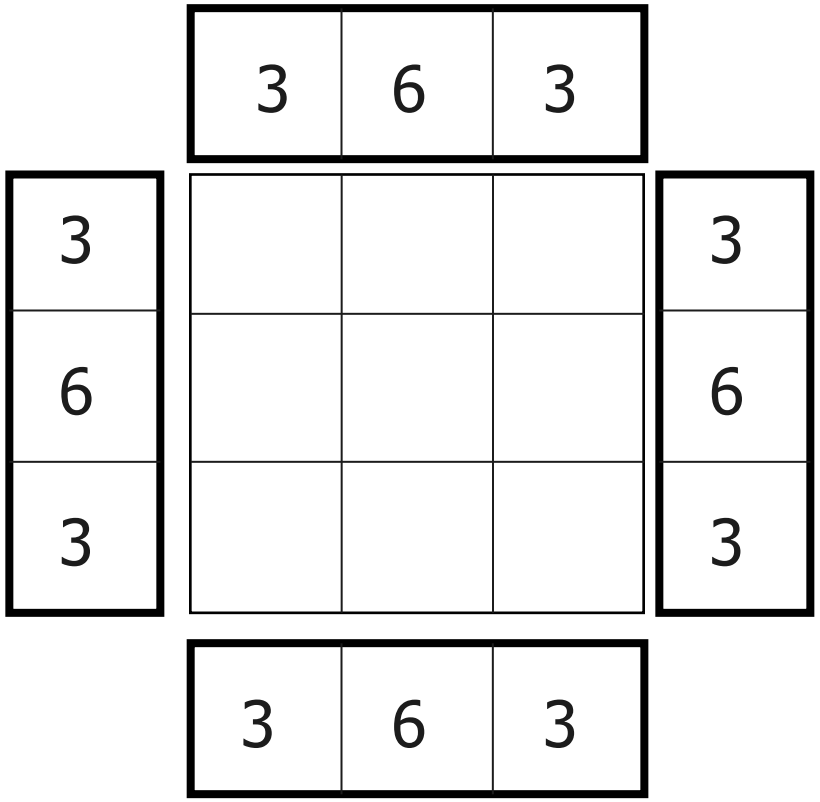
Backprojection

Backprojection



SPECT Imaging – Back Projection

- Simple case of four projections
- Backproject each planar image onto the 3D image matrix



SPECT Imaging – Back Projection

- Simple case of four projections

- Backproject each planar image onto the 3D image matrix

3	6	3
1	2	1
1	2	1
1	2	1

SPECT Imaging – Back Projection

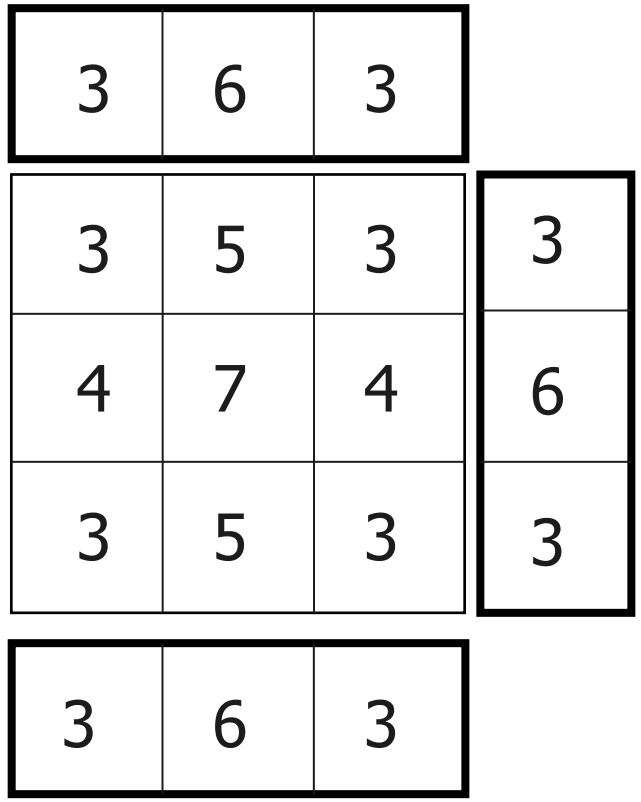
- Simple case of four projections

- Backproject each planar image onto the 3D image matrix

3	6	3	
2	3	2	3
3	5	3	6
2	3	2	3

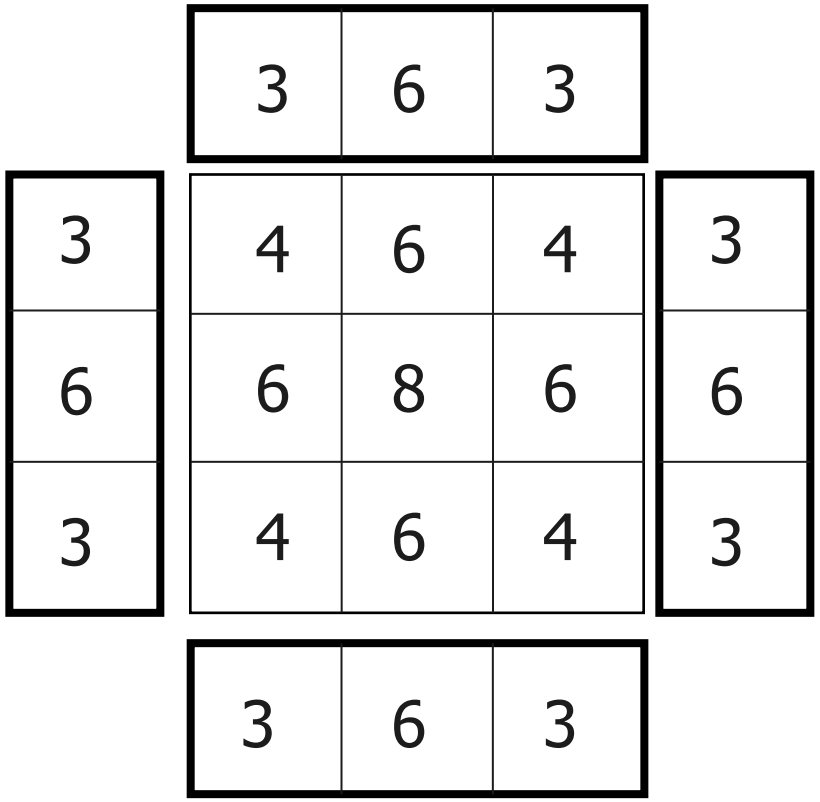
SPECT Imaging – Back Projection

- Simple case of four projections
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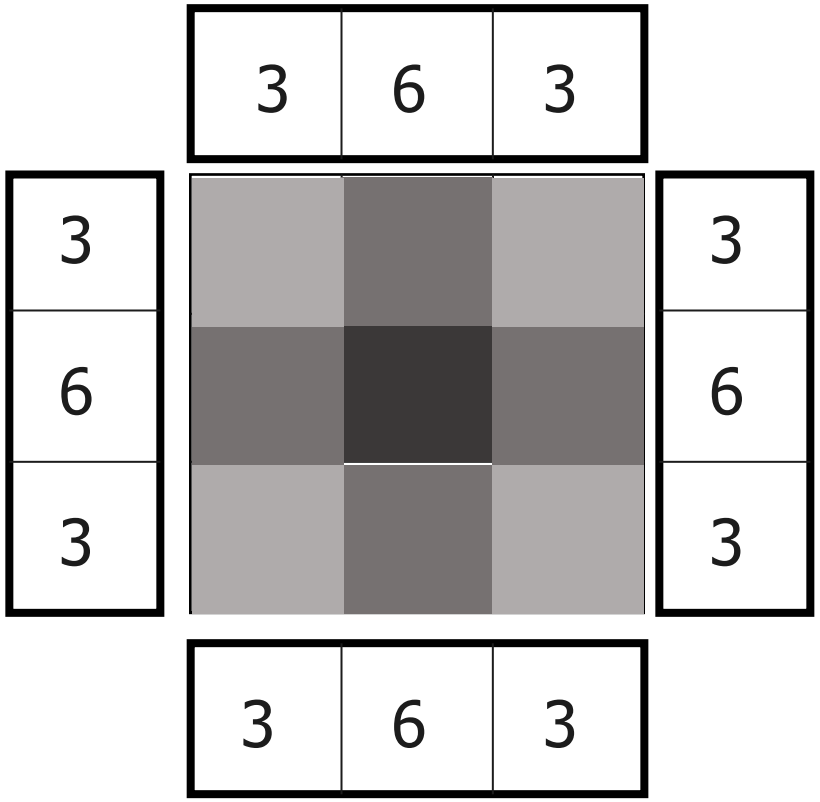
SPECT Imaging – Back Projection

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SPECT Imaging – Back Projection

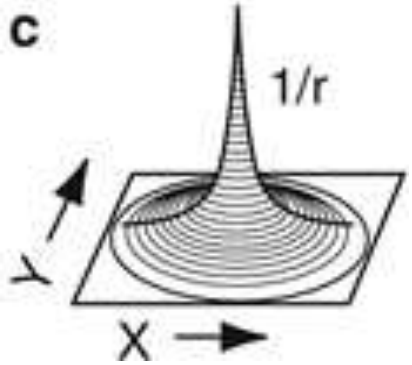
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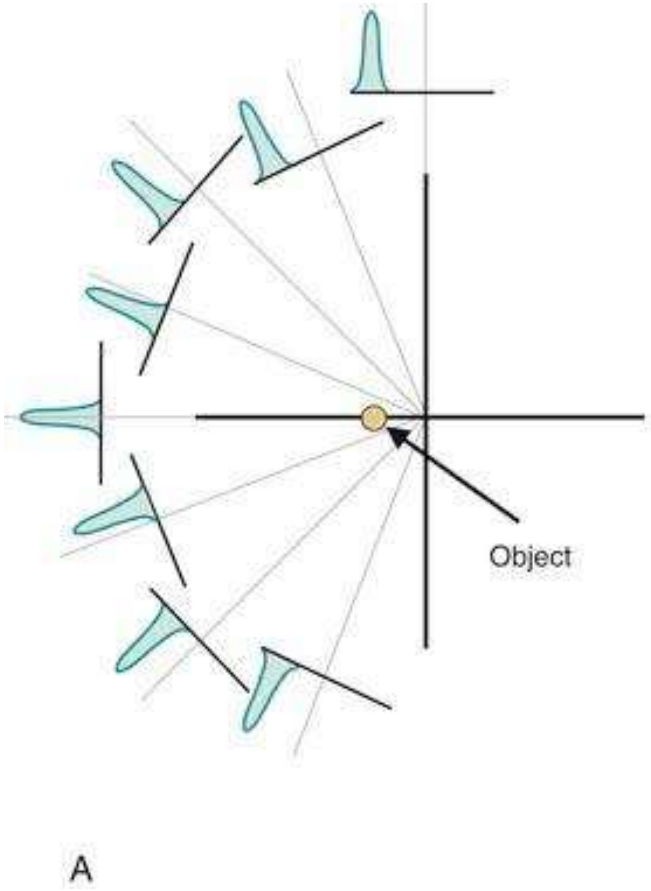


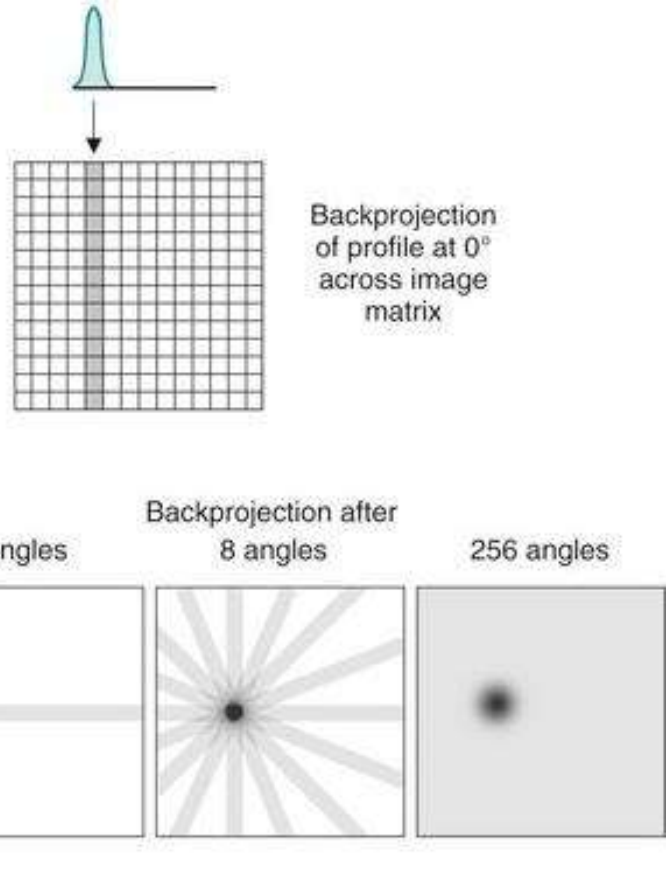
SPECT Imaging – Back Projection

- More projections (or views) means better image reconstruction

- Even with infinite number of views there is still blurring:



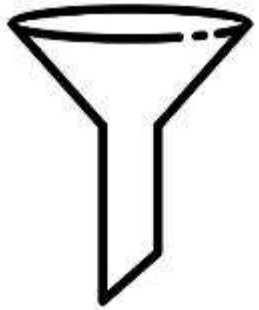




SPECT Imaging – Filtered Back Projection

- Where does the filter come into FBP?

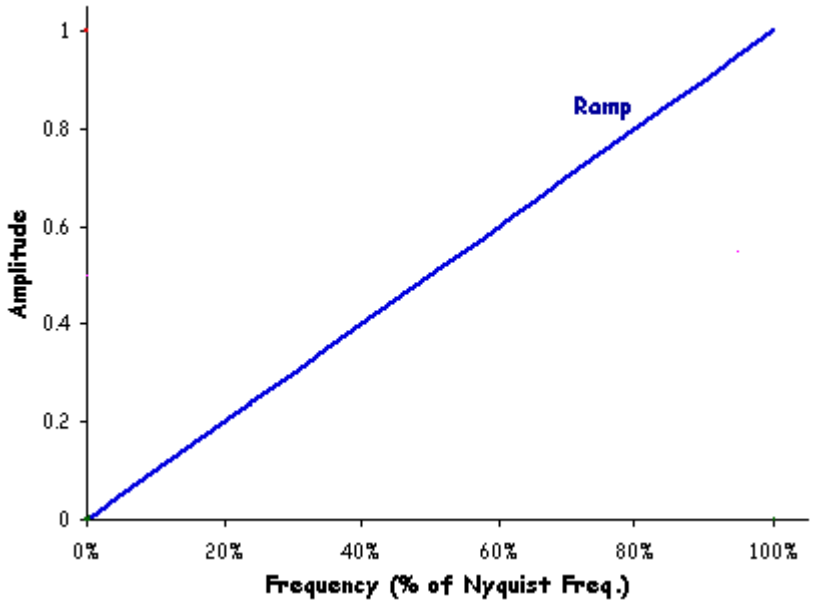
- Filter?
- Mathematical operation applied to pixels in an image

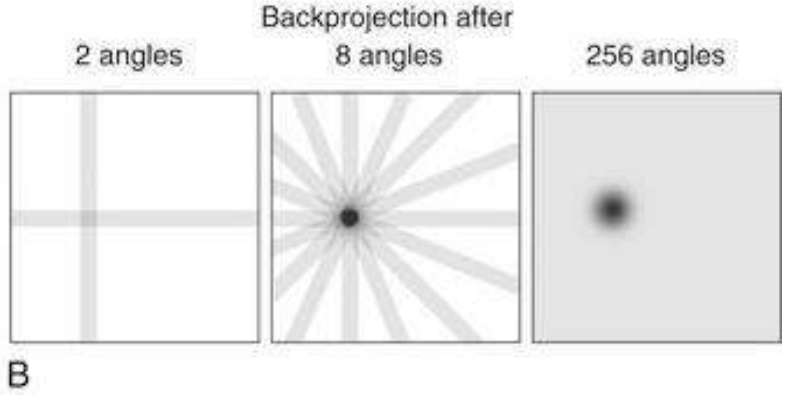


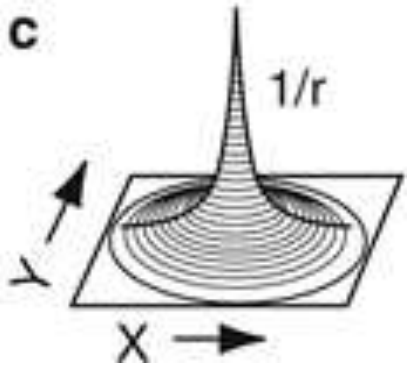
- Choice of filter dependent on what you want to look at in the end image

- Compromise between reducing noise but not losing the fine detail information

SPECT Imaging – Filtered Back Projection



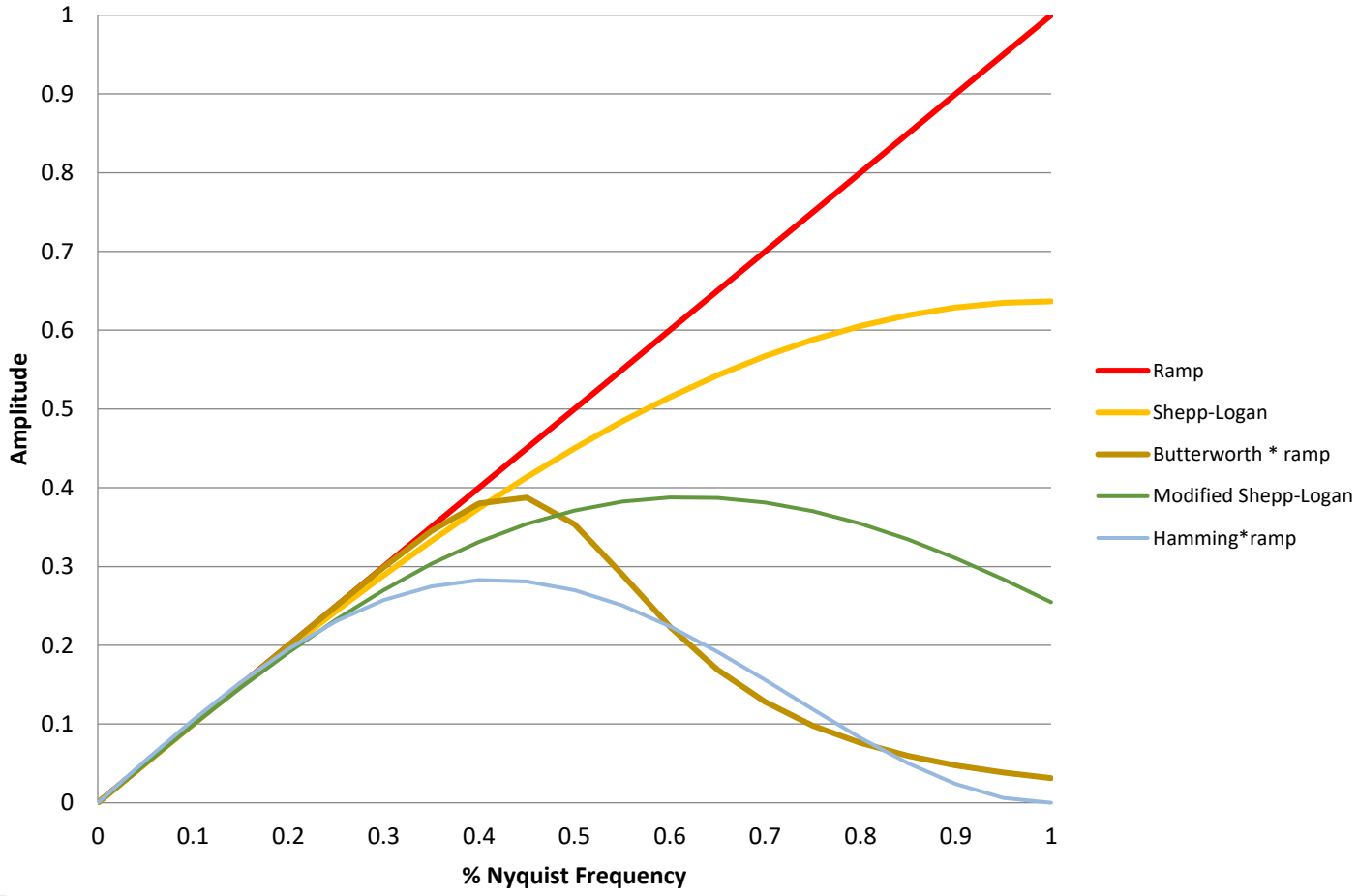




Ramp filter used to reduce blurring in FBP

SPECT Imaging – Filtered Back Projection

- Ramp filter + user selected filter used
- Aim to create image that is easier to ‘read’
- Again depends on what you need to be able to ‘read’ in the image



SPECT Imaging – Filtered Back Projection

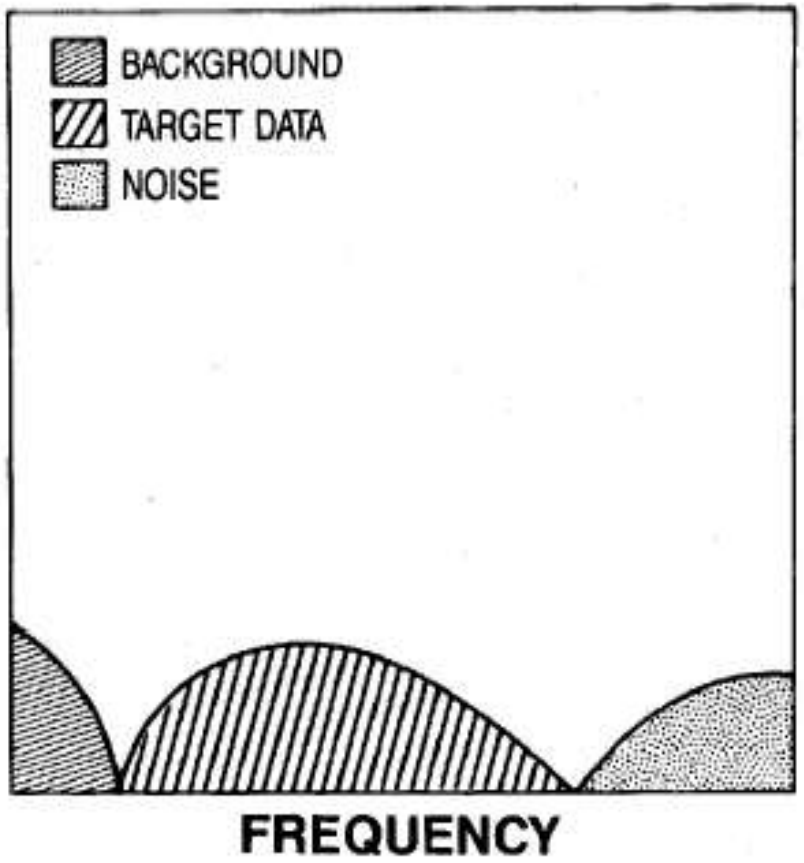
- Filters are applied to the data in the frequency domain
  - Frequency based on difference between pixel counts

- Low frequency = small difference between pixel to pixel counts
  - Indicates blurring in image

- High frequency = large difference between pixel to pixel counts
  - Indicates **sharp edges** in image
  - Statistical noise is also high frequency

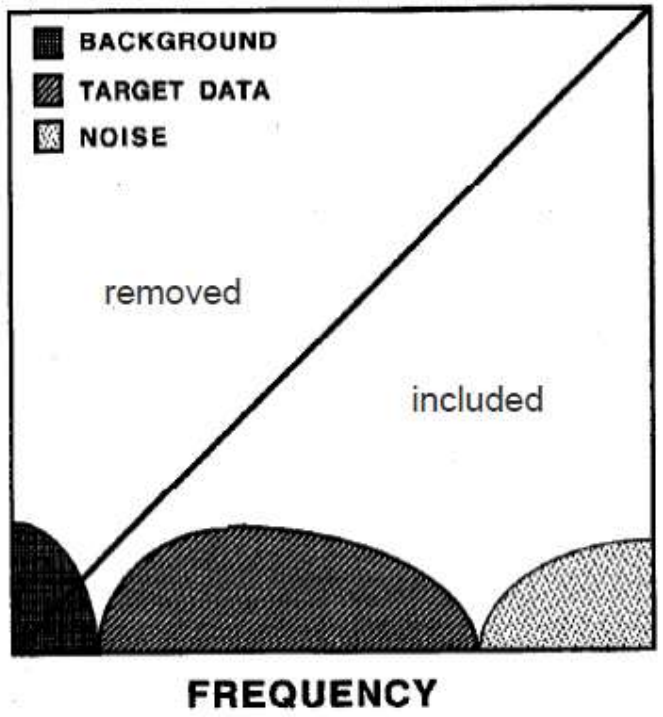
SPECT Imaging – Filtered Back Projection (FBP)

- What do we want to filter out?
- What's in an image?
  - Background – generated from backprojection, ramp filter eliminates most of this
  - Image target data – frequency depends on type of study and what we are looking at
  - Noise – due to statistical fluctuations, proportional to number of counts in image, high frequency

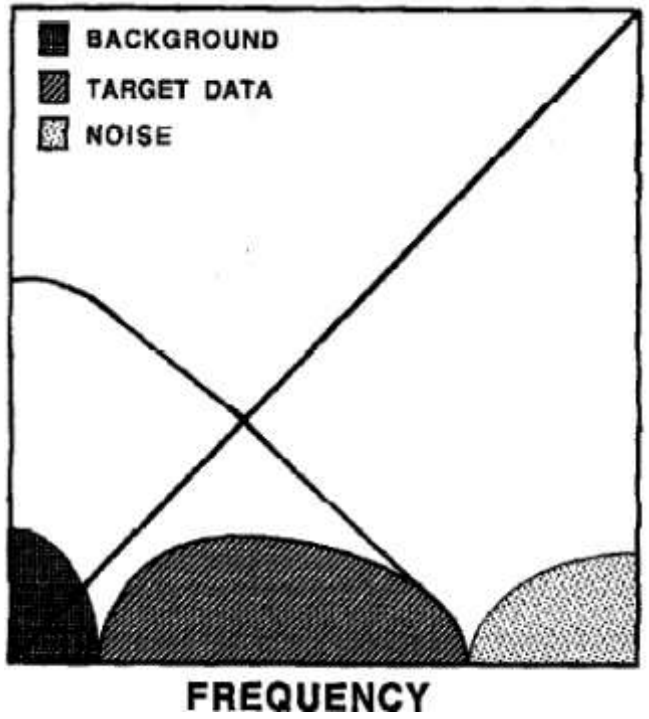


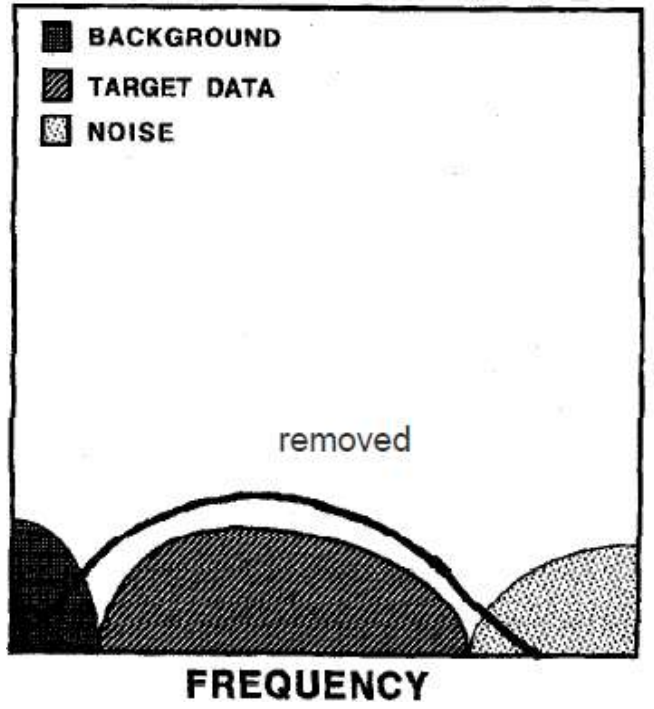
SPECT Imaging – Filtered Back Projection (FBP)

Ramp



User selected





Remember what we remove depends on what we want to see in the image. E.g. do we need sharp edges? Are we willing to accept the noise that comes with this?

Pitfalls of Filtered Back Projection

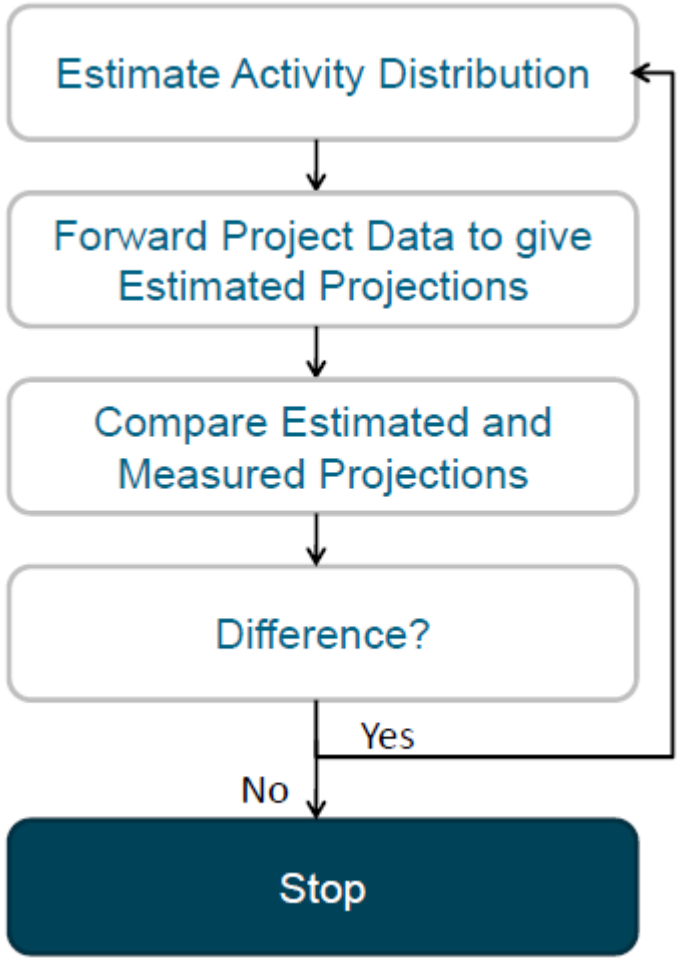
- Filtered Back projection is mathematically correct *but*
  - introduces noise and streaking artefacts
  - cannot apply attenuation correction techniques
  - Cannot be used for quantification

Iterative Reconstruction

- It is **NOT** a new technique
  - pre-dates filtered backprojection
- Computationally intensive
  - long reconstruction times
  - requires fast computers for reconstruction

What is Iterative Reconstruction?

- It is a method based on
  - successive “guesses” of the image
- Processing computer forms image
  - by refining expected projections in comparison to those recorded
- This form of iterative reconstruction is known as
  - “Maximum Likelihood Expectation Maximisation” (MLEM)



SPECT Imaging – Iterative Reconstruction

- This form of iterative reconstruction is known as
  - Maximum Likelihood Expectation Maximisation (MLEM)

- OSEM – Ordered Subset Expectation Maximisation
  - Introduced to improve speed of IR techniques
  - Groups projection data into ordered subsets
  - Is an order of magnitude quicker than MLEM
  - Defined by number of iterations and subsets
  - e.g. 2 iterations of 20 subsets (subset size of 6 for 120 projections) is equivalent to 40 iterations of MLEM

SPECT Imaging – Other Reconstructions

- Resolution recovery
  - Resolution worsens with increasing distance from the collimator
  - Change in resolution with depth in the patient also (greater distance from collimator)



Impact on resolution

SPECT Imaging – Resolution Recovery

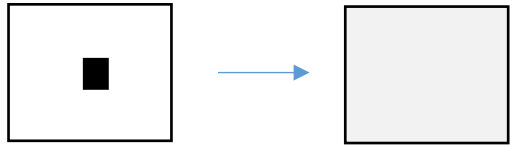
- Resolution recovery
  - Resolution worsens with increasing distance from the collimator
  - Change in resolution with depth in the patient also (greater distance from collimator)
  - Loss in resolution modelled and included in iterative reconstruction
  - Different between manufacturers – can be very hard to determine what is actually being done

  - Better modelling = better images
  - Better images = less activity needed to inject or shorter acquisitions

SPECT Imaging – Pixel Size

- Before acquisition the matrix size can be chosen
- This decides how the image is split into pixels
- E.g. 256 x 256, 128 x 128, 64 x 64

Risk of partial volume effect:
A small area of uptake within a large pixel is averaged out and therefore not seen



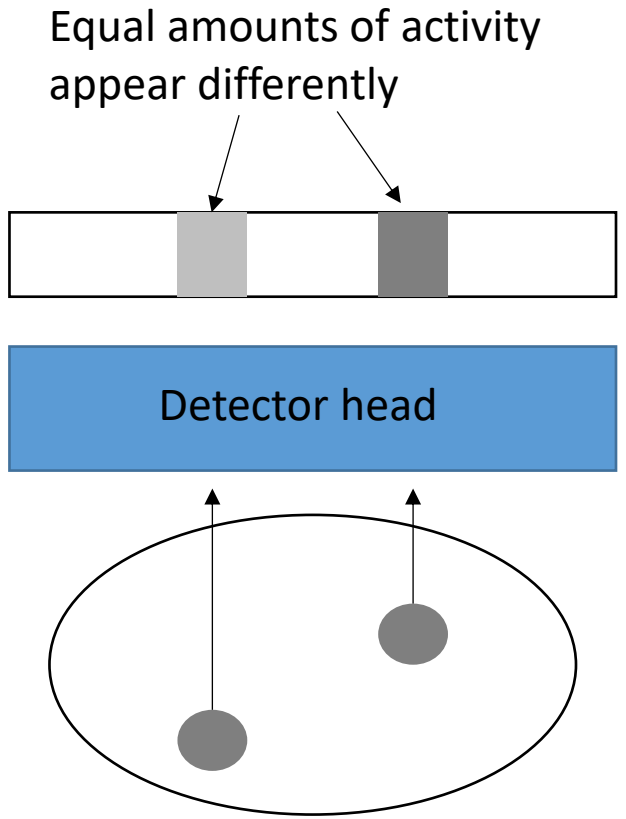
- Bigger pixels = more counts in pixels (less noisy)
- Smaller pixels = better resolution

Balance – dependant on what we want out of the images – what resolution do we require?

- E.g.
  - Gastric emptying – 128 x 128 -> need to outline stomach and look at comparing counts
  - Bone scan 256 x 256 -> need resolution to determine location of potential bone lesions

SPECT Imaging – Attenuation Correction

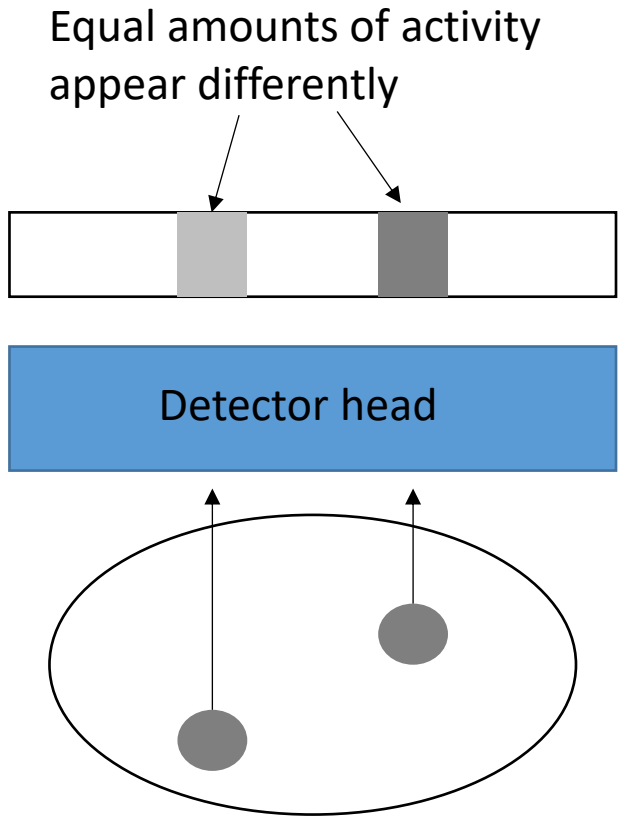
- Why do we need it?
- Photons coming from the patient will be attenuated by the patient's body
- Photons coming from deeper in the patient will be attenuated more than photons coming from near the surface - Areas deeper within the patient will appear less "hot"
- Photons travelling through more dense areas of the patient will also be attenuated more e.g travelling through bone will be more attenuated than through lung



SPECT Imaging – Attenuation Correction

- Attenuation is due to:
  - Absorption of photon in material
  - Scatter of photon in material

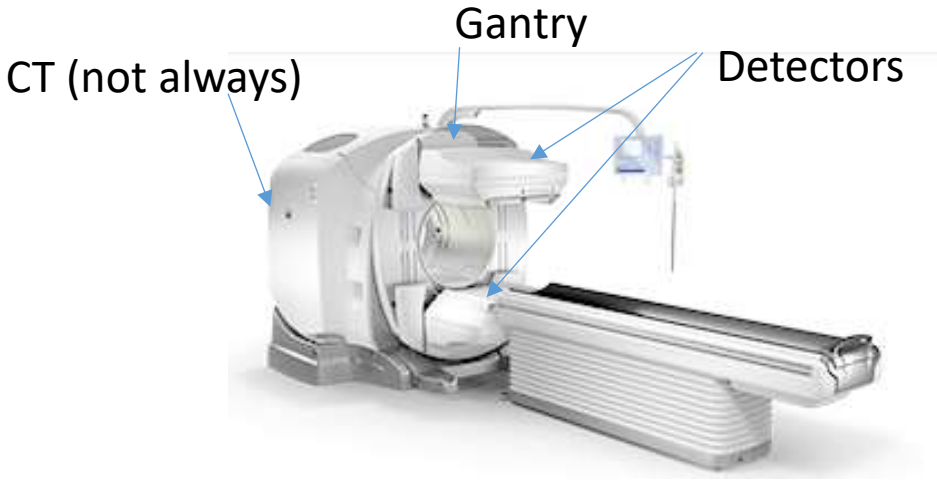
- How much something is attenuated is determined by:
  - Amount of material
  - Density of material e.g. bone will attenuate more than lungs



SPECT Imaging – Attenuation Correction

- Attenuation correction will lead to:
  - Reduced artefacts arising from attenuation (mistakenly ‘cold’ areas)
  - Image appearance will be more representative of activity in the given area
  - Improved quantification
  - Improved image quality
  - May improve diagnostic accuracy
    - Training needed if looking at images without AC or with AC to understand different artefacts

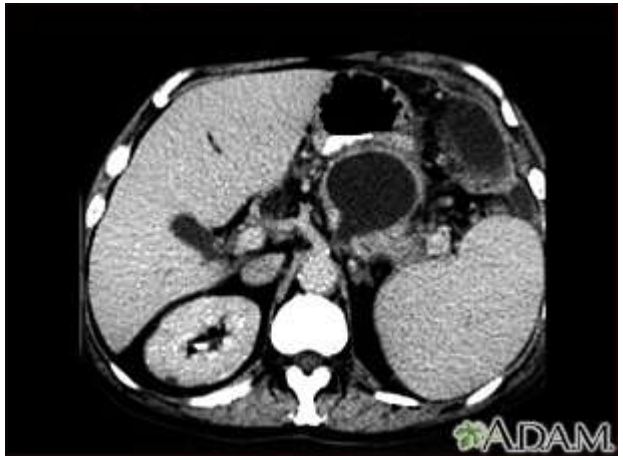
- How do we perform attenuation correction?
  - Use the data from the computed tomography (CT) scan



SPECT Imaging – Attenuation Correction

- Attenuation correction with CT:

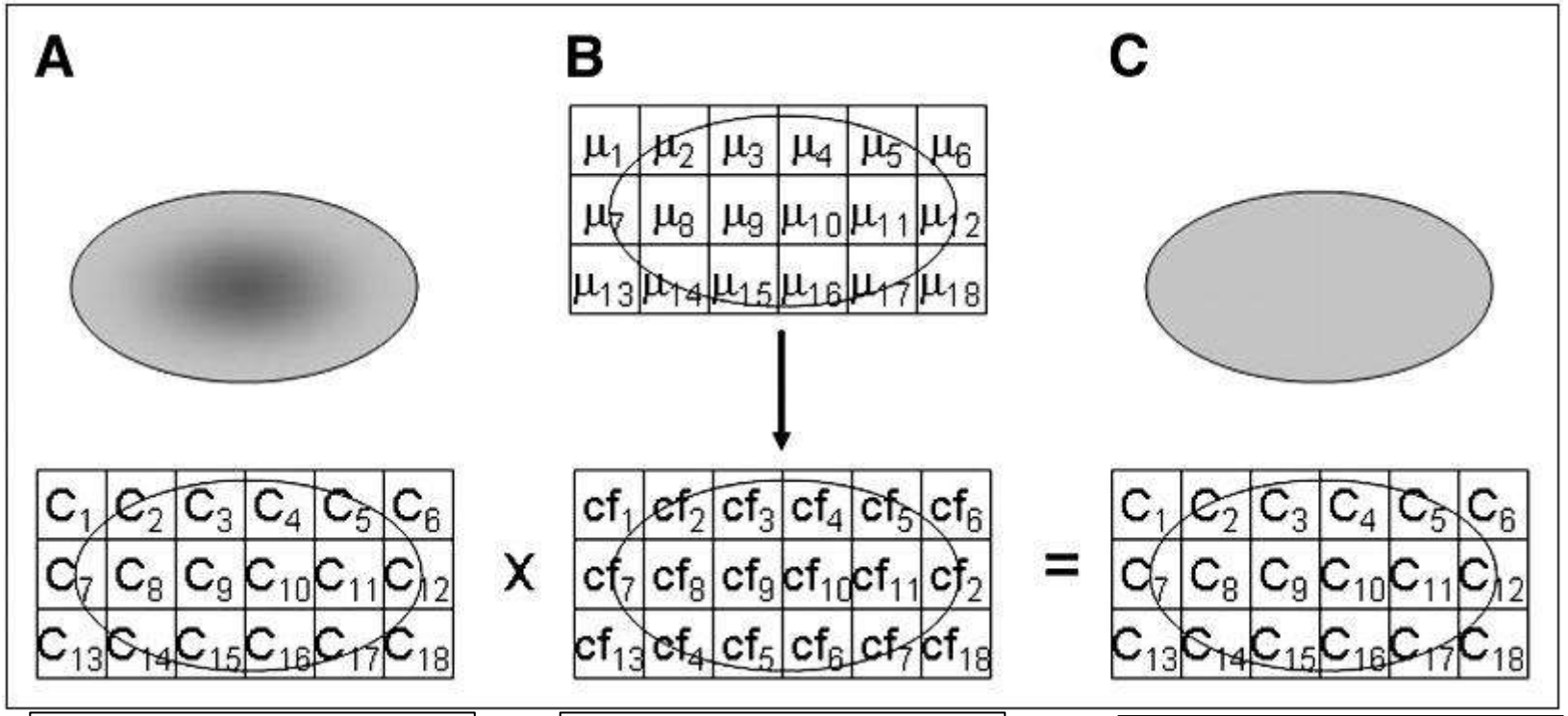
- The CT image is a measure of attenuation at different angles
  - Different materials have different Hounsfield units (or CT number) in the end image
  - Water = 0 HU, Air = 1000 HU, Fat = -30 to -70 HU range
  - Means we can make a map of the different linear attenuation coefficients from the different materials in the image
  - From this we can make an attenuation map – a map of corrections to be applied to the SPECT image



$$HU = \left(\frac{\mu_{material} - \mu_{water}}{\mu_{water}} \right) \times 1000$$

μ = CT linear attenuation coefficient

SPECT Imaging – Attenuation Correction

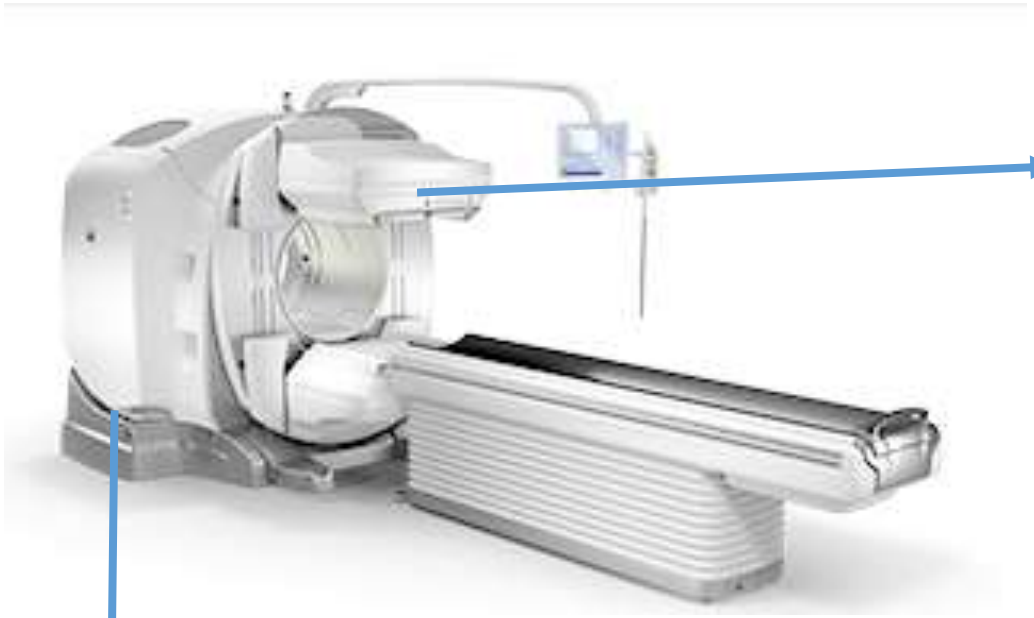


Uncorrected image

Attenuation map of corrections

Corrected image

SPECT Imaging – Attenuation Correction example



SPECT Image

Attenuation Correction

SPECT Image with AC



CT Image



SPECT-CT Fused Image



SPECT Imaging – Attenuation Correction

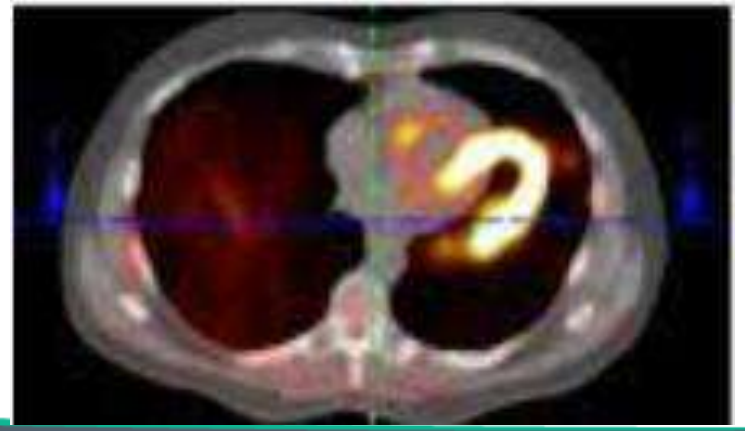
- Potential problems:

- Image registration
  - aligning the SPECT and CT images to one another correctly is vital
  - otherwise the attenuation map will be located incorrectly and corrections applied incorrectly



- Patient movement
  - change alignment of SPECT and CT and impact AC

- CT artefacts propagate through into corrected images

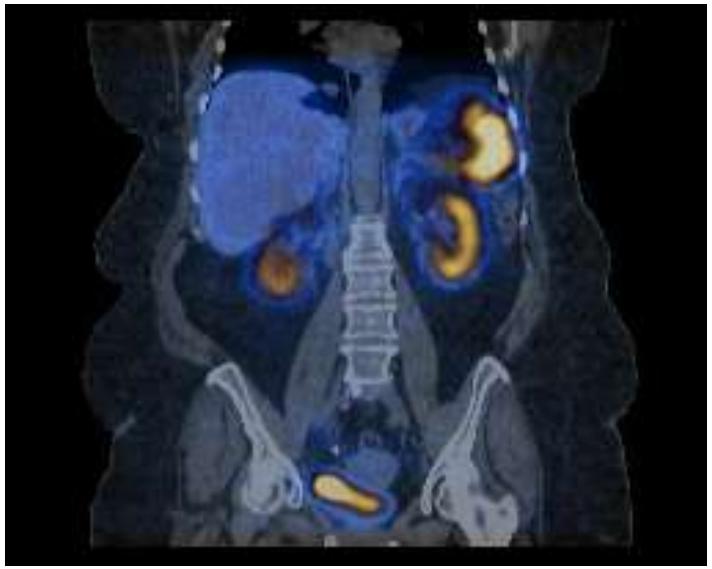


SPECT Imaging – Use of CT

- CT used for attenuation correction
- CT can also be used for localisation purposes
  - CT gives anatomical information that can be used to determine position of lesions etc

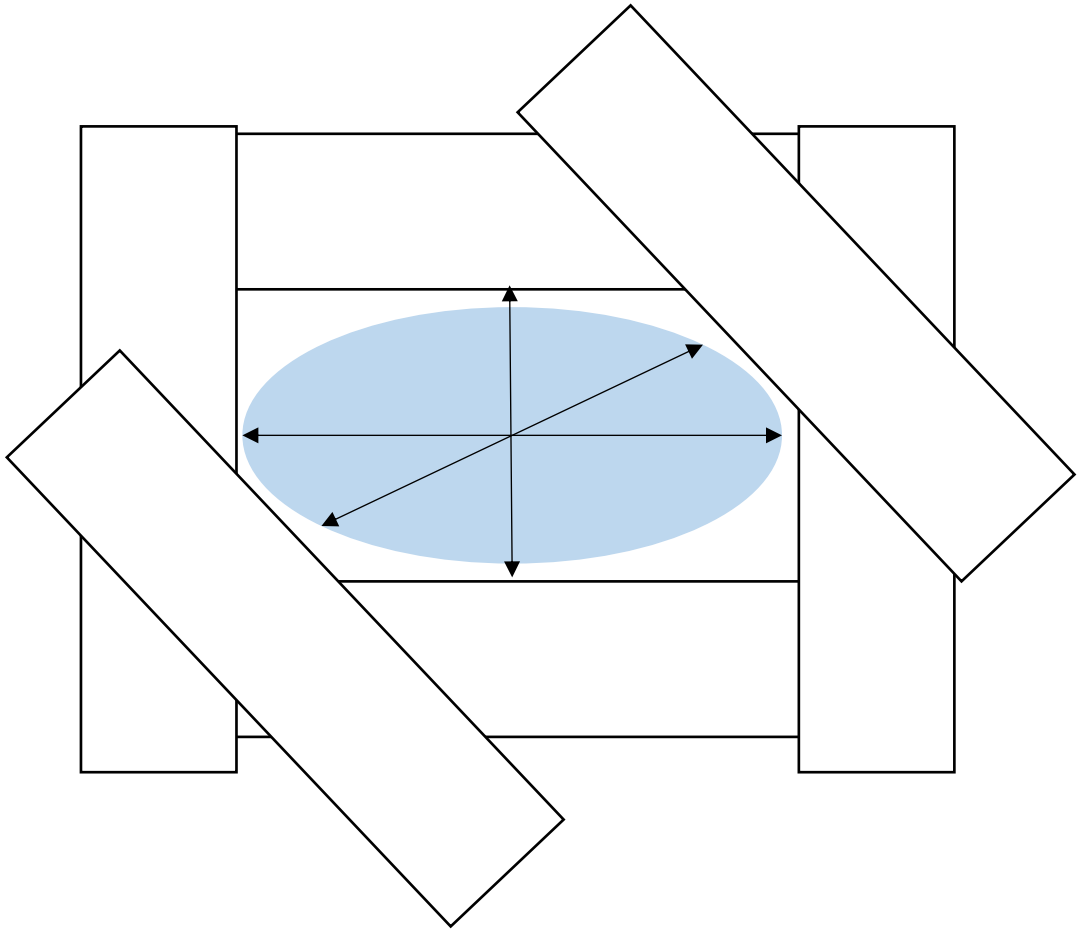
- These are referred to as:
  - AC (attenuation correction)
  - ACL (attenuation correction and localisation)

SPECT-CT Fused Image



- Improved image quality for ACL compared to AC and so these scans often use greater tube current (mA) and result in a higher CT dose to the patient

SPECT Imaging – Clinical Operation



Body contour to move closer to the patient during SPECT acquisition

As we saw previously with WB imaging

NHS
Hull University Teaching Hospitals
NHS Trust

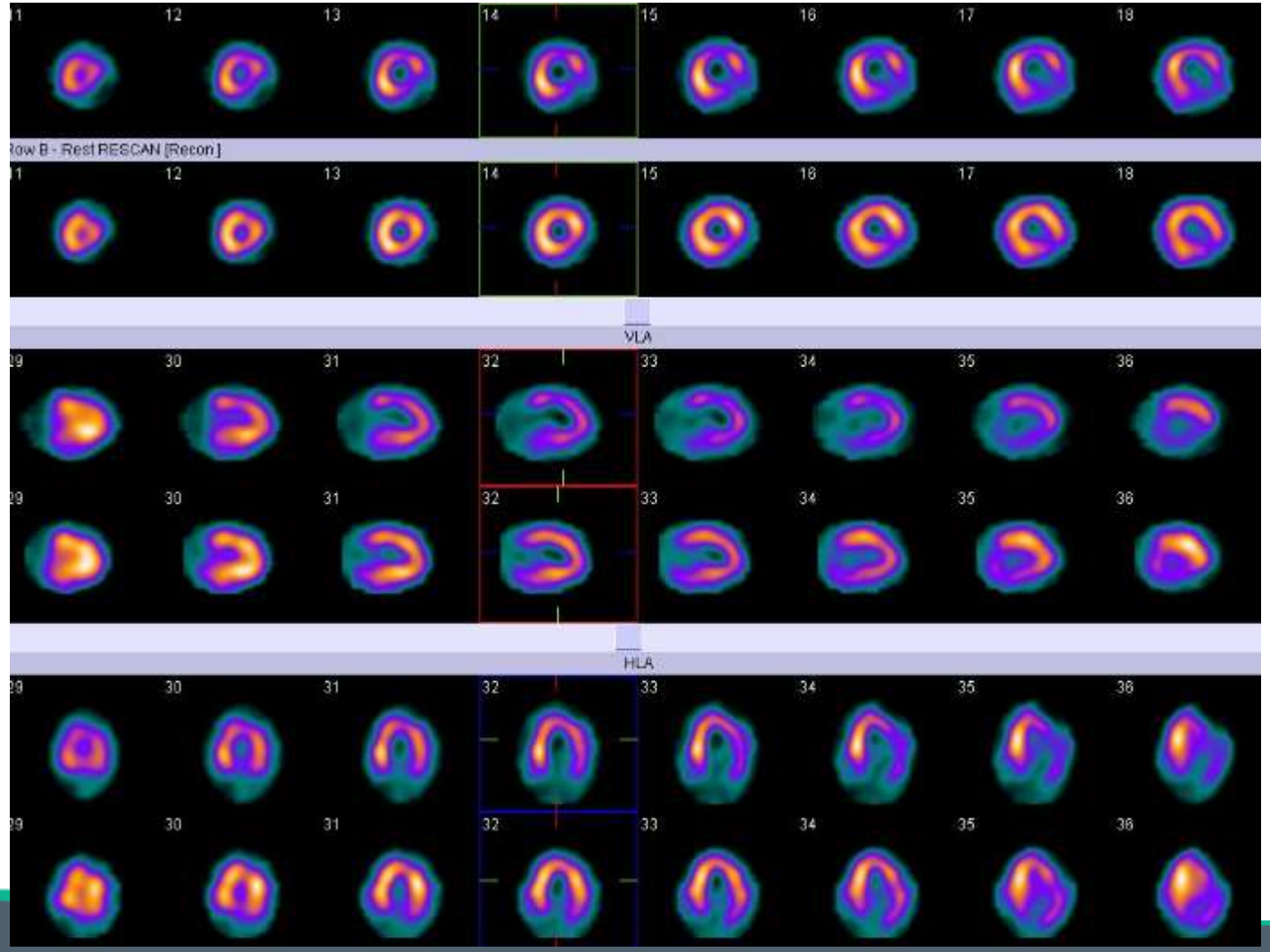
SPECT Applications

Cardiology

Myocardial Perfusion Scintigraphy

- Coronary artery blood flow
  - proportional to uptake of radiopharmaceutical in heart
- Stress and rest studies performed
- Stress
  - exercise
  - pharmacologic stress
- Gated SPECT (unless in Atrial Fibrillation)
- Radiopharmaceuticals
  - $^{99}Tc^{m}$-MIBI or Tetrofosmin
  - ^{201}Tl (thallous chloride)
- Can be used to look at wall motion, thickening and ejection fraction

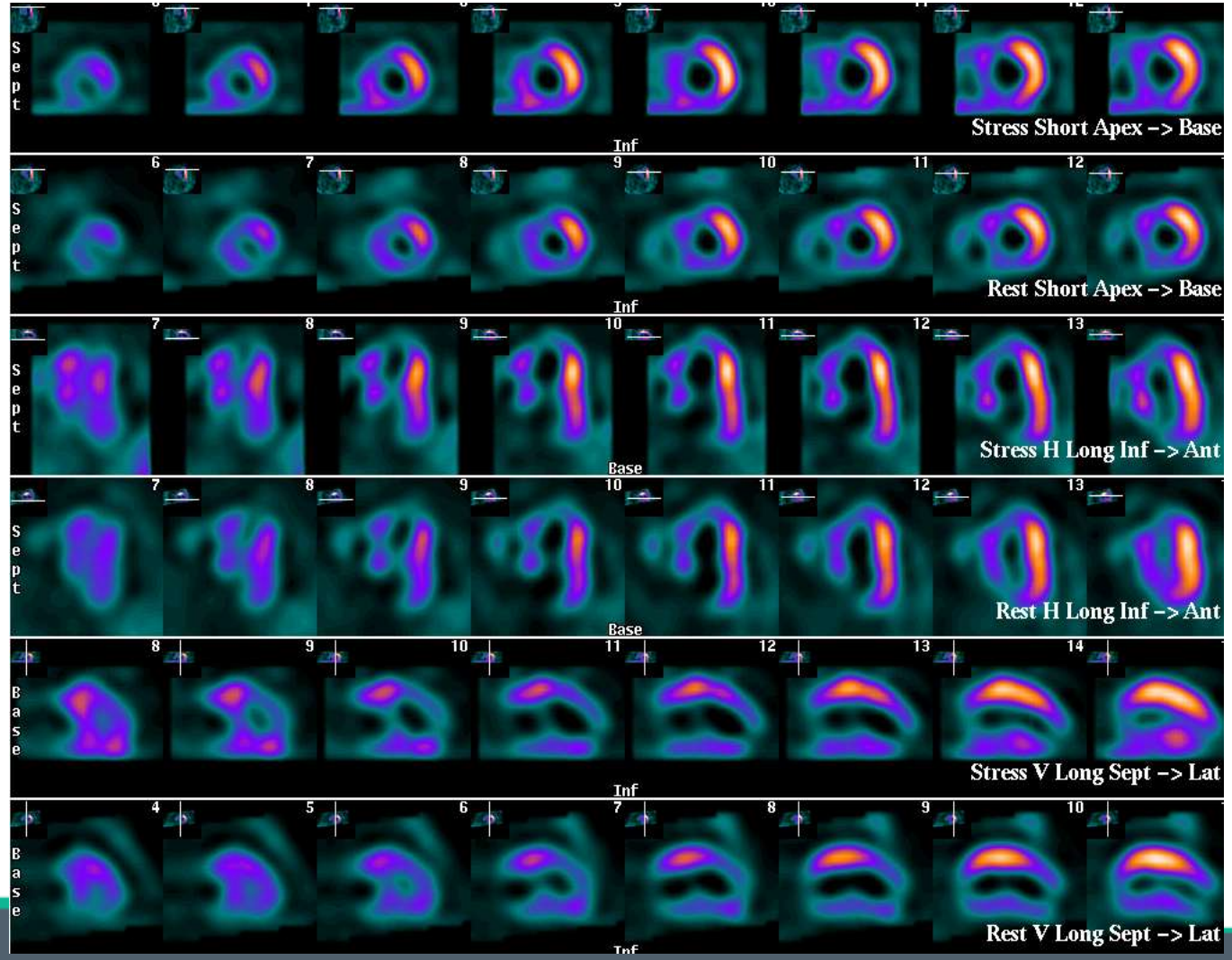
Case 1: Reversible Ischemia



Hull University Teaching Hospitals NHS Trust

Remarkable people.
Extraordinary place.

Case 2: Infarct



Hull University Teaching Hospitals NHS Trust

Remarkable people.
Extraordinary place.

NHS
Hull University Teaching Hospitals
NHS Trust

SPECT Applications

Oncology

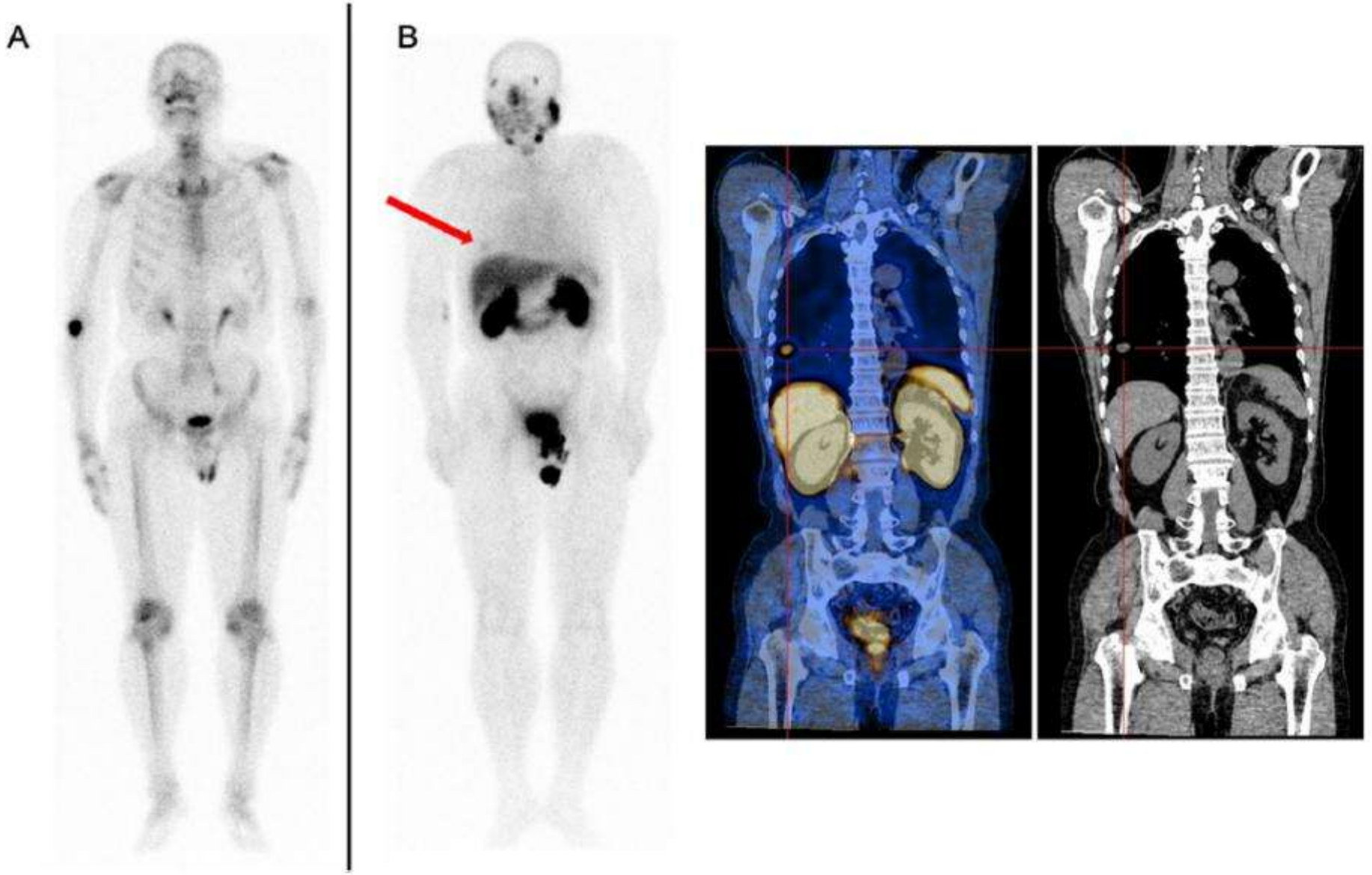


Figure 6. A 66-year-old patient with a BR of PCa. The Gleason score was 7, and the PSA level was 3.14 ng/mL. (**A**): Whole-body planar ^{99m}Tc-MDP. (**B**): Whole-body planar ^{99m}Tc-PSMA and coronal SPECT/CT. ^{99m}Tc-PSMA SPECT/CT helped identify lung metastasis (**B**, red arrow and cross).

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ll University
ıg Hospitals
NHS Trust

Remarkable
Extraordinar

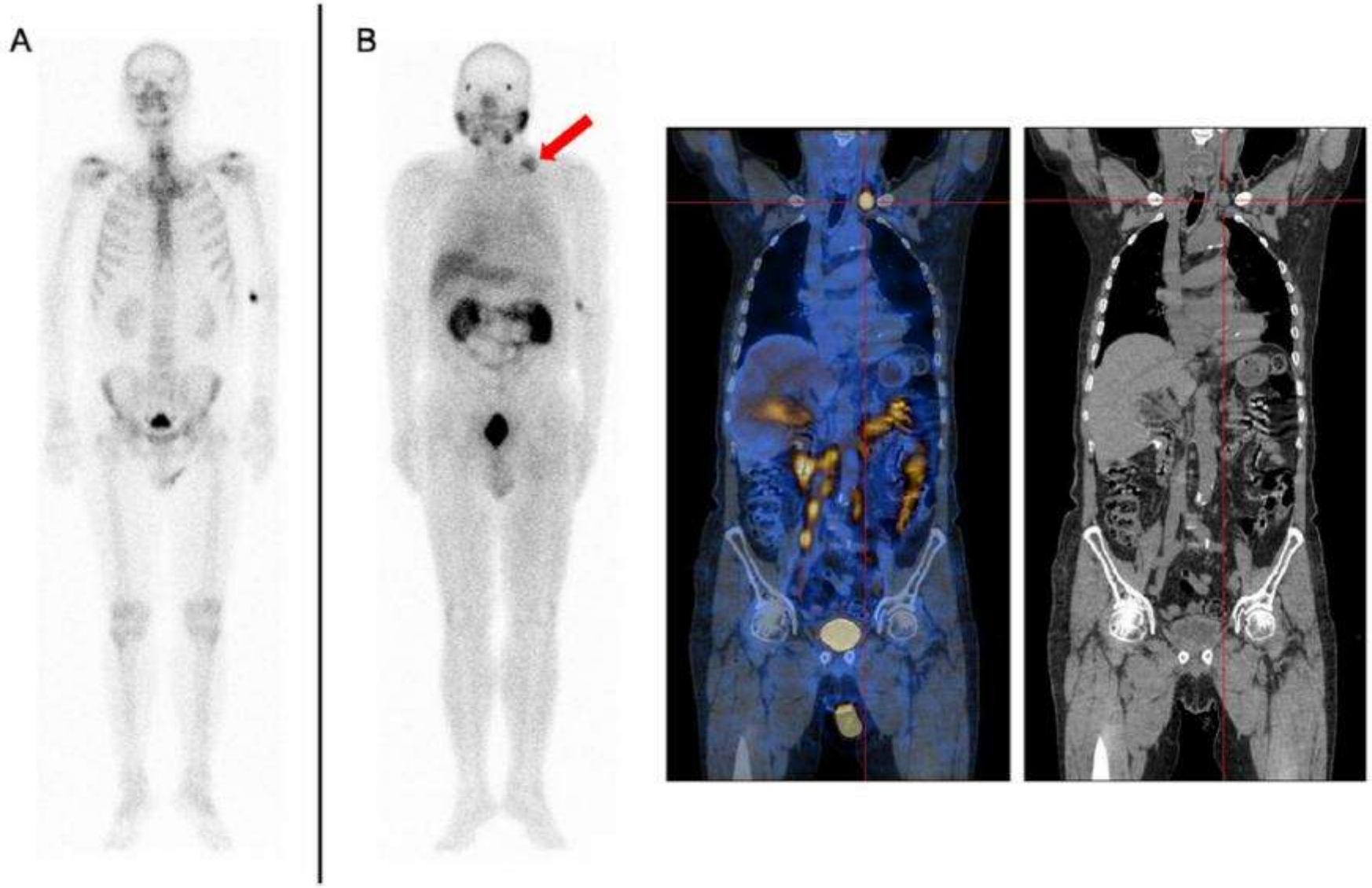


Figure 7. A 67-year-old patient with a restaged PCa. The Gleason score was 10, and the PSA level was 0.11 ng/mL; (A): Whole-body planar ^{99m}Tc-MDP. (B): Whole-body planar ^{99m}Tc-PSMA and coronal SPECT/CT. ^{99m}Tc-PSMA SPECT/CT revealed lymph node metastases in the left supraclavicular fossa (B, red arrow and cross).

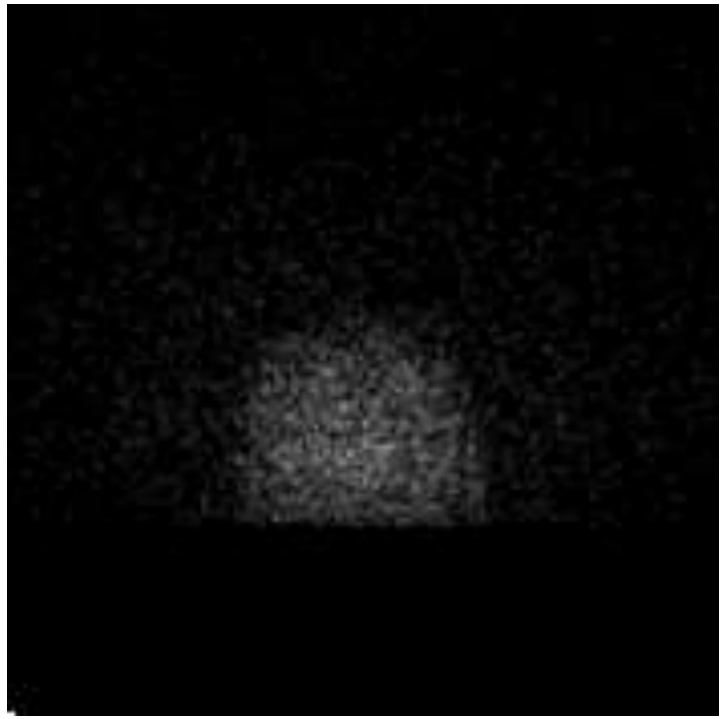
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SPECT Applications

Neurology

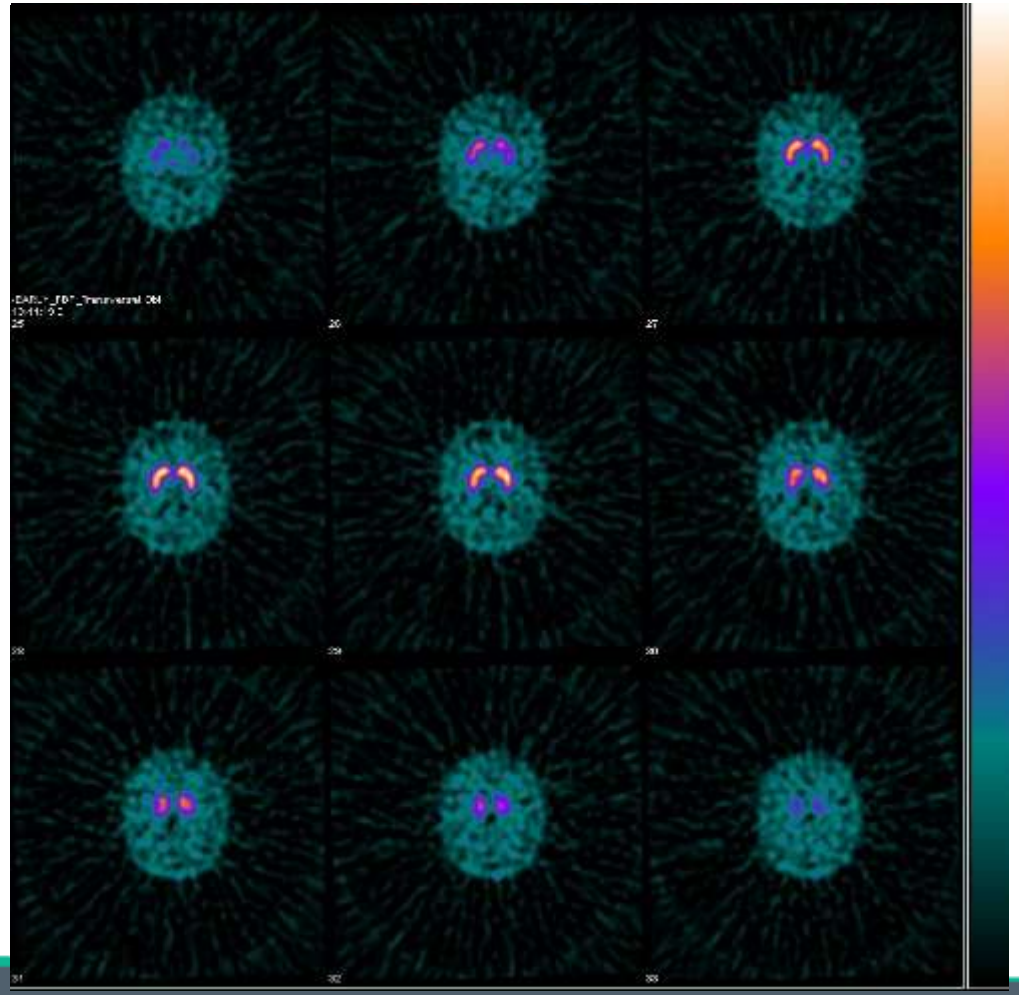
DaTSCAN Brain Imaging

- Radiopharmaceutical
  - ^{123}I-Ioflupane
- Imaged at 3-6 hours
- Effective dose 4.4 mSv
- Differentiates between
  - ET, Drug-induced parkinson's and Parkinsonian syndromes
- Assesses the severity of Parkinsonian syndromes



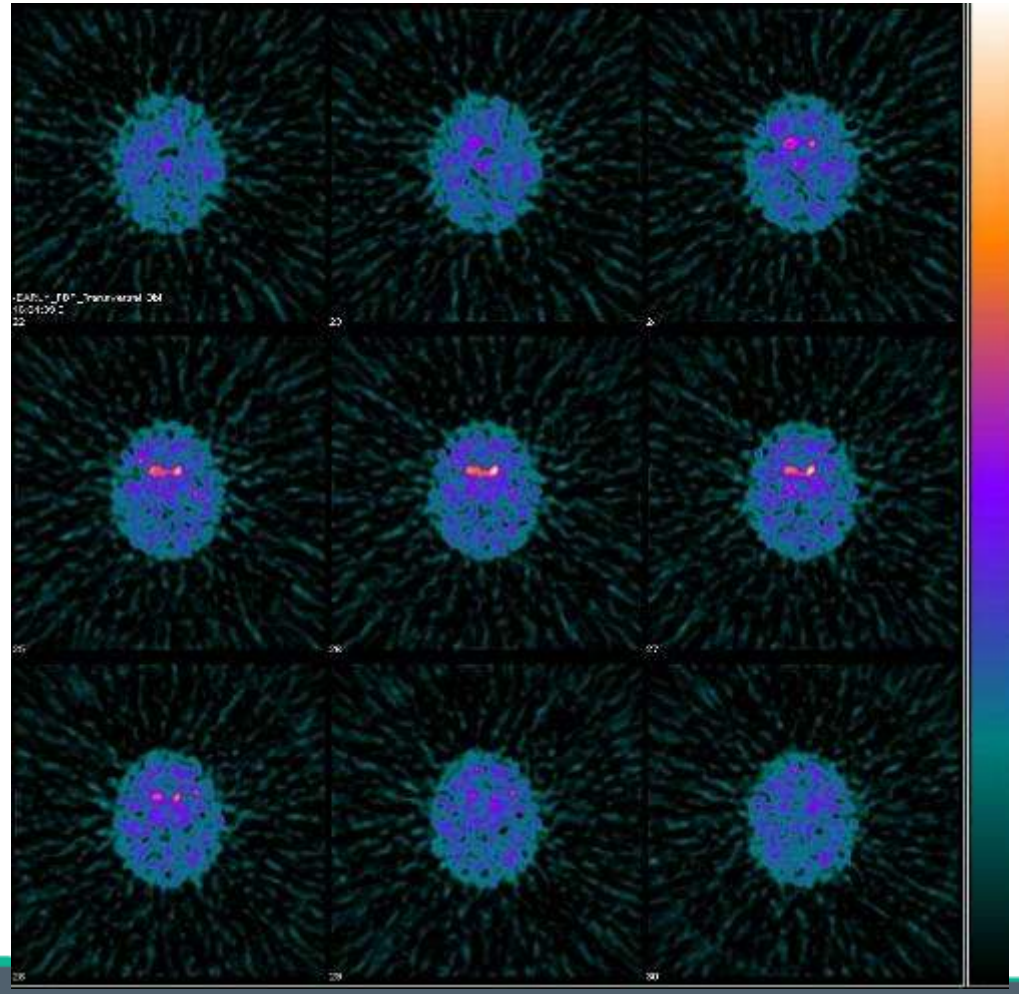
Case 1: Normal Scan

- Ioflupane binds to
  - pre-synaptic dopamine transporters
- Normal appearance is
  - comma shaped putamen
- Abnormal
  - “full stop” shape of one or both putamen



Case 2: Abnormal Scan

- Ioflupane binds to
  - pre-synaptic dopamine transporters
- Normal appearance is
  - comma shaped putamen
- Abnormal
  - “full stop” shape of one or both putamen



Case 3: Abnormal Scan

- Ioflupane binds to
  - pre-synaptic dopamine transporters
- Normal appearance is
  - comma shaped putamen
- Abnormal
  - “full stop” shape of one or both putamen

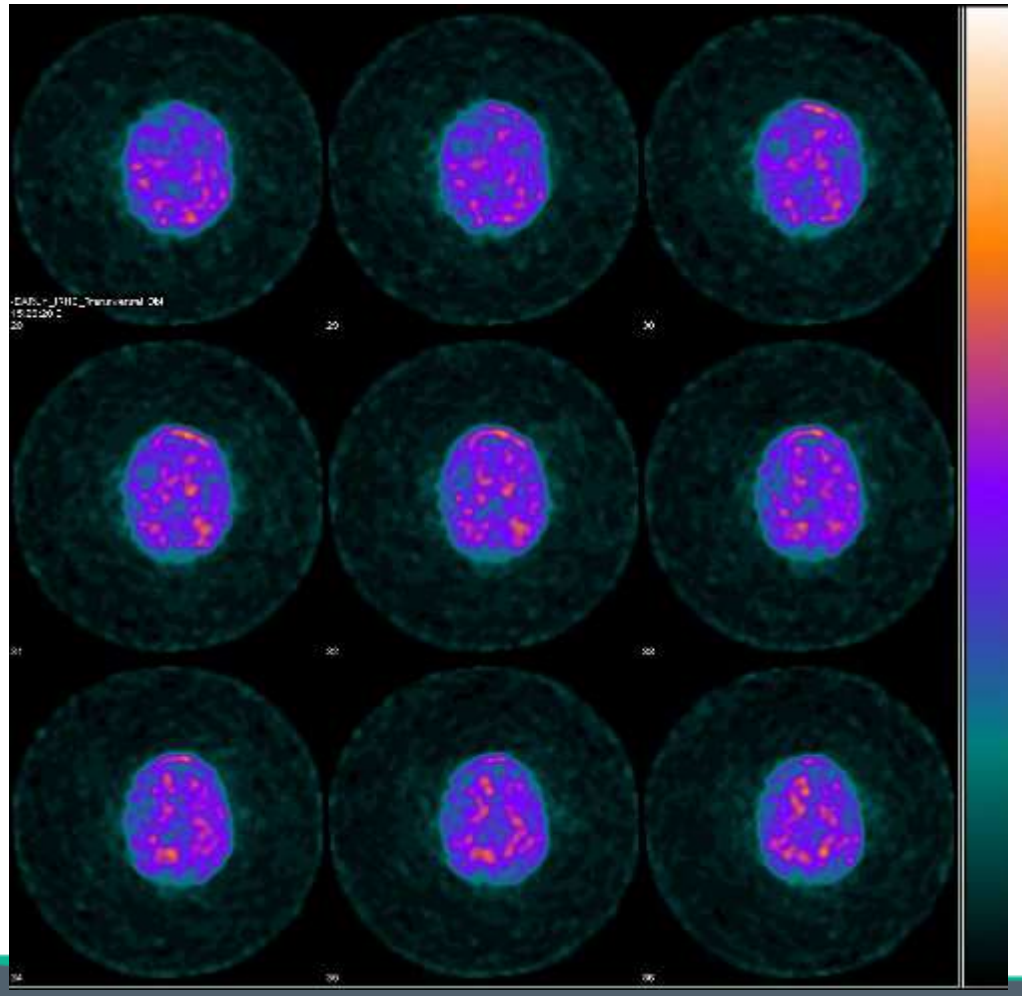


Image Acquisition Techniques

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

Image Acquisition Techniques

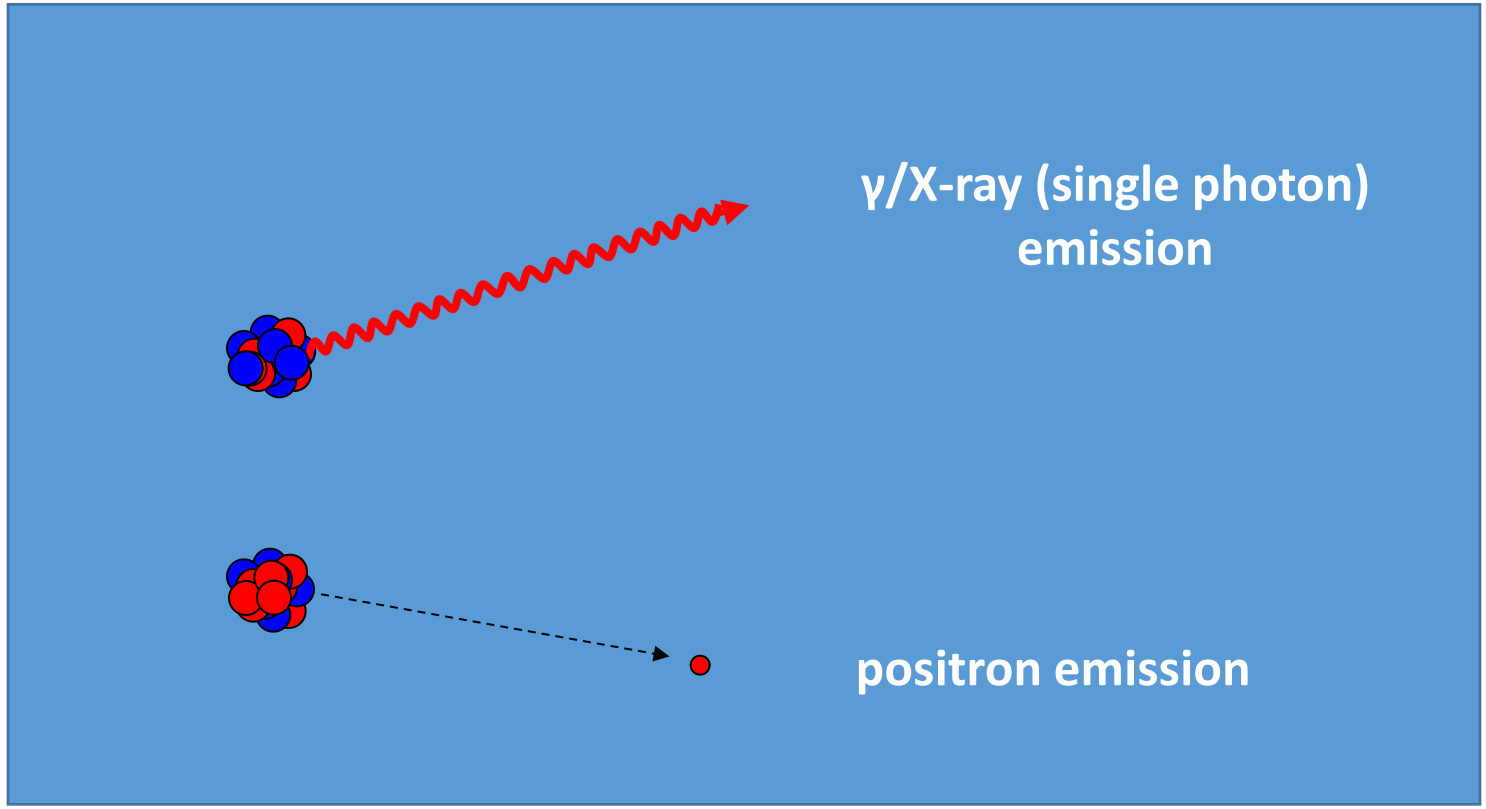
- Planar Imaging
  - Static
  - Dynamic
  - Multiple Gated (MUGA)
  - Whole Body / Continuous
- Tomographic Imaging
  - Single Photon Emission Tomography (SPECT)
  - Positron Emission Tomography (PET)

Image Acquisition Techniques

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

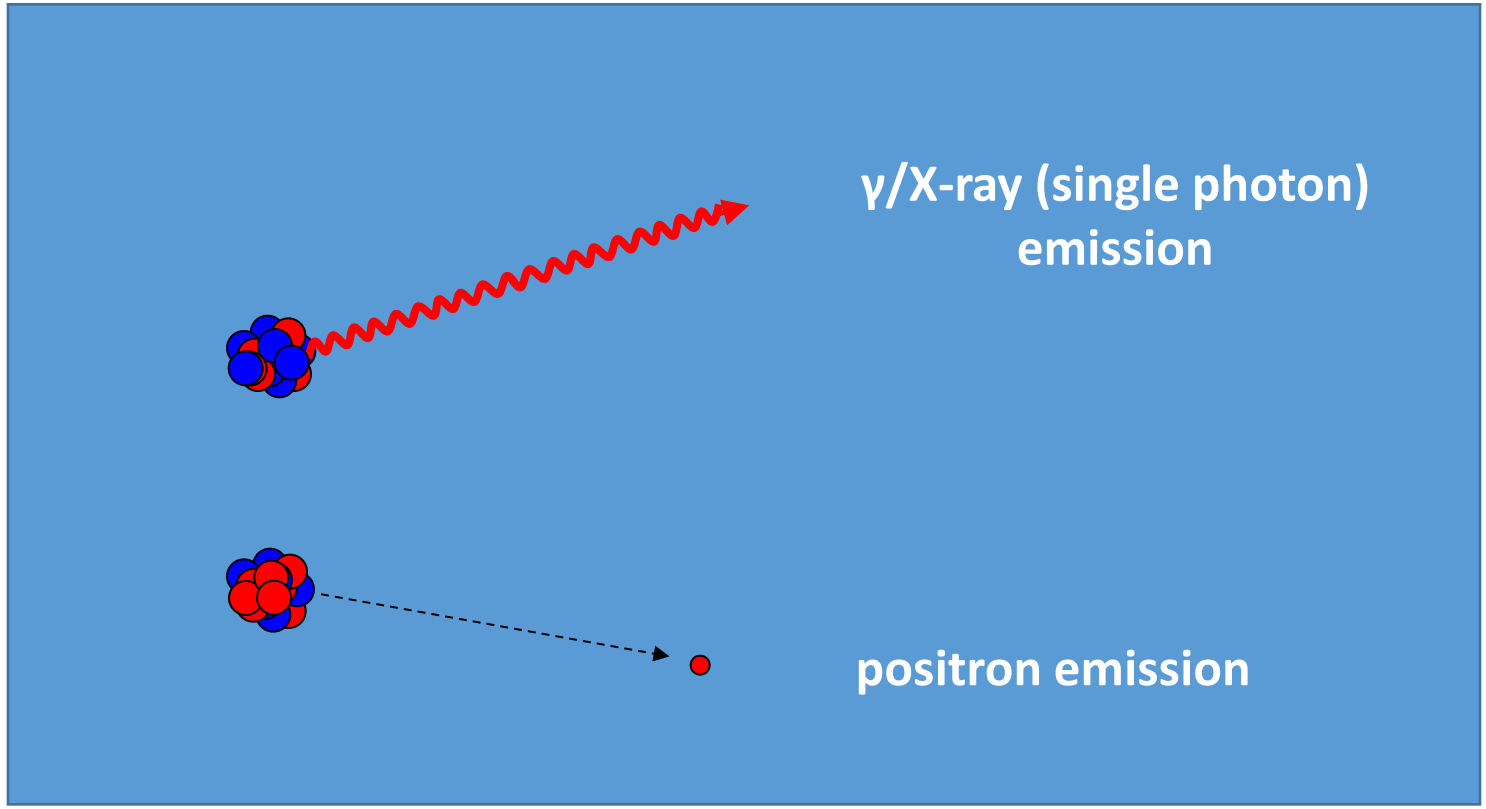
Functional Imaging – PET

Is there another way?

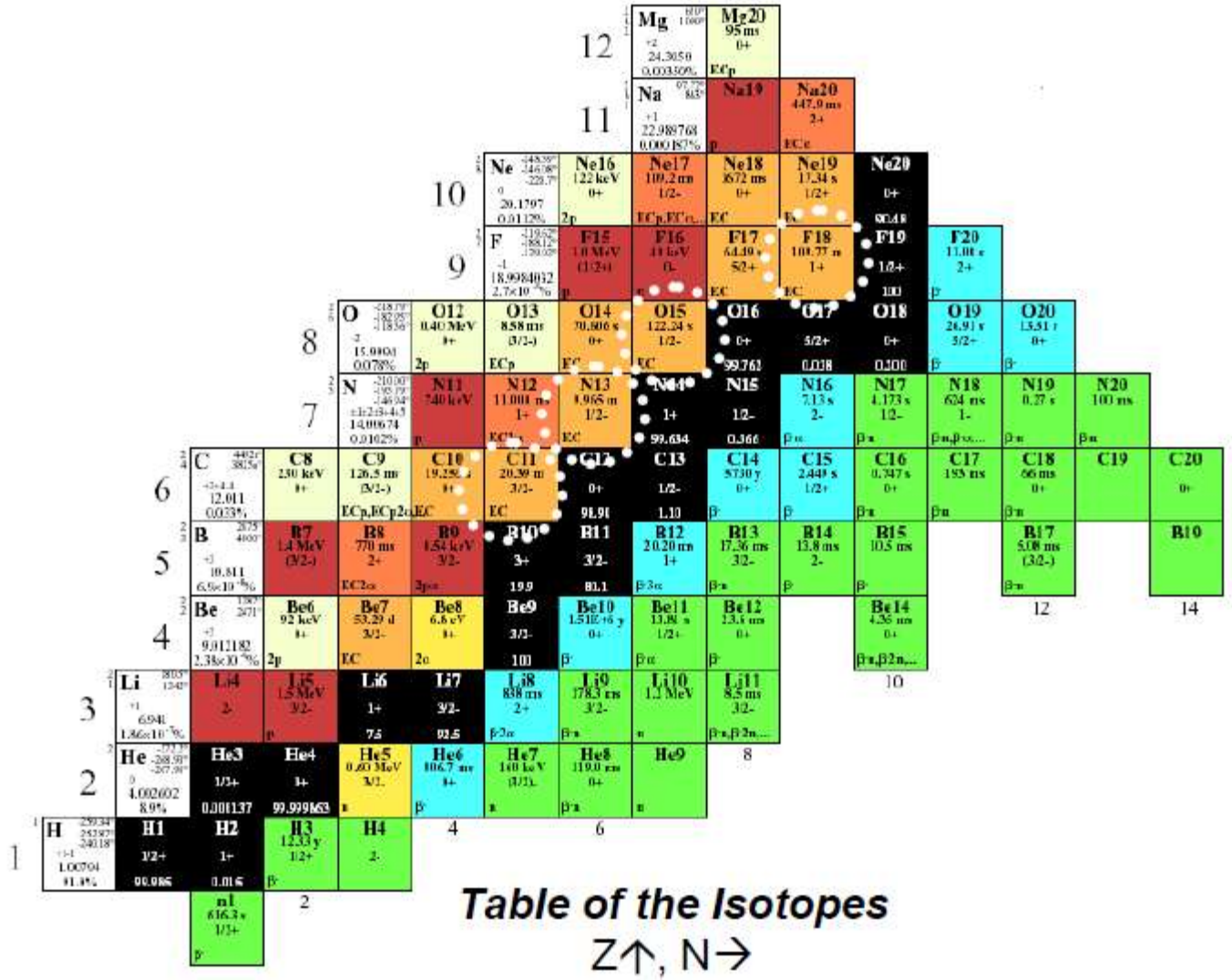


Functional Imaging – PET

Is there a better way?



Radioactive Decay by Positron Emission



Radioisotopes in Functional Imaging

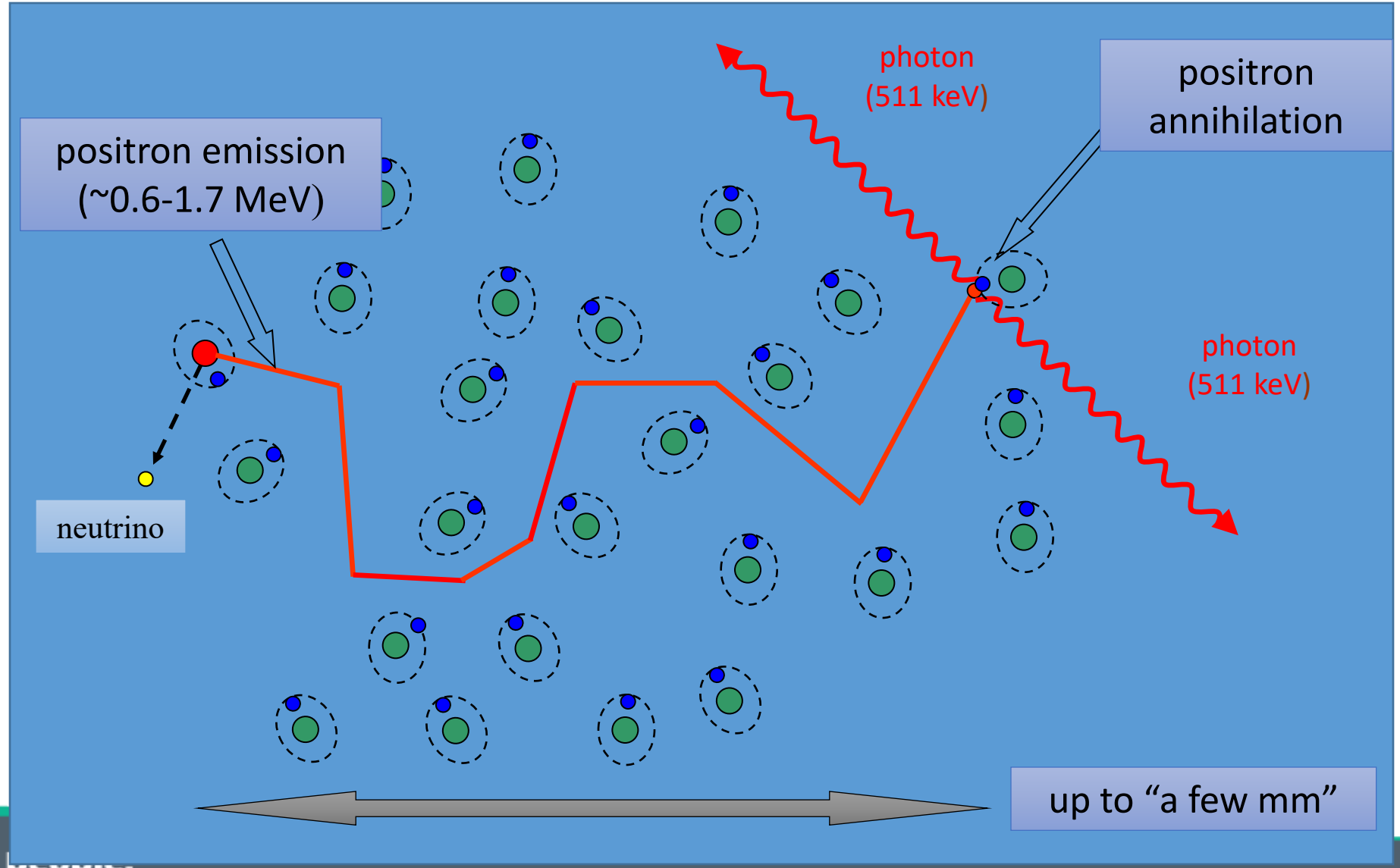
γ/X-rays → SPECT

Isotope	Half-life (hr)	Energy (keV)
$^{99}Tc^{m}$	6.0	140
^{111}In	67.3	171 & 245
^{123}I	13.2	159
^{201}Tl	73.0	69-83

positrons → PET

Isotope	Half-life (min)	Energy (keV)
^{11}C	20.4	511
^{15}O	2.1	511
^{13}N	10.0	511
^{18}F	109.8	511

PET Isotopes



Properties of PET Isotopes

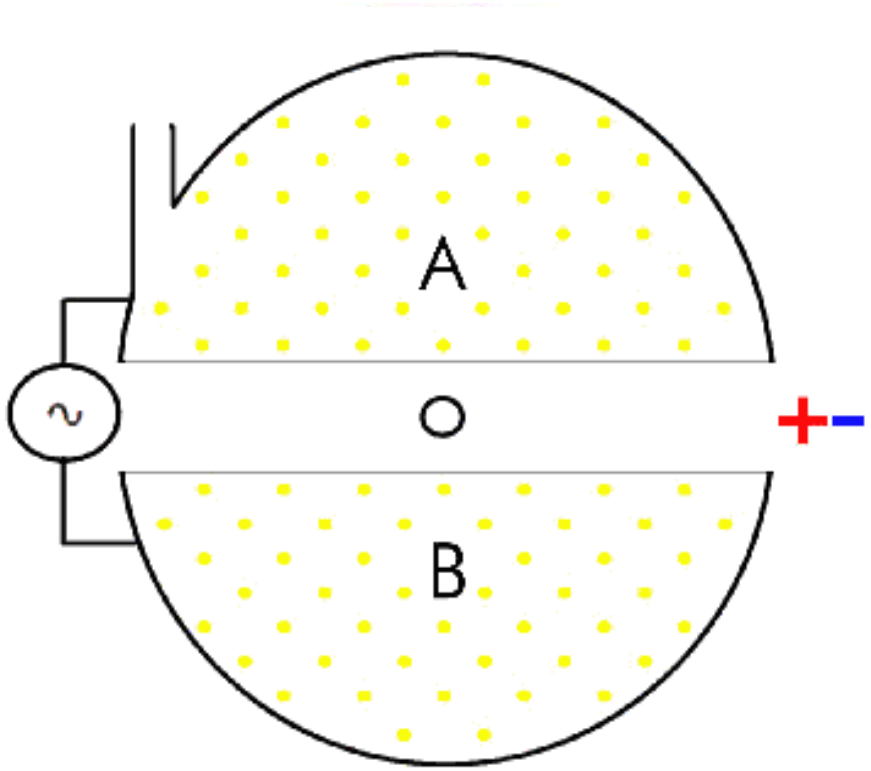
Isotope	Half-life (min)	$E_{max}(\beta^+)$ MeV	Production	Example tracer
^{11}C	20.4	0.96	$^{14}N(p,\alpha)^{11}C$	Methionine
^{13}N	9.96	1.19	$^{16}O(p,\alpha)^{13}N$	Ammonia
^{15}O	2.03	1.72	$^{15}N^*(p,n)^{15}O$ $^{14}N(d,n)^{15}O$	Water
^{18}F	109.7	0.635	$^{18}O^*(p,n)^{18}F$ $^{20}Ne(d,\alpha)^{18}F$	FDG (fluorodeoxyglucose)
^{62}Cu	9.7	2.93	^{62}Zn generator ($t_{1/2}$=9.2 hours)	PTSM (blood flow)
^{82}Rb	1.3	3.35	^{82}Sr generator ($t_{1/2}$=25 days)	Rb^- (blood flow)
^{124}I	4.2 days	2.10	$^{126}Te(p,3n)^{124}I$	Labelled antibodies

Wide range of half-lives, generally shorter than conventional NM

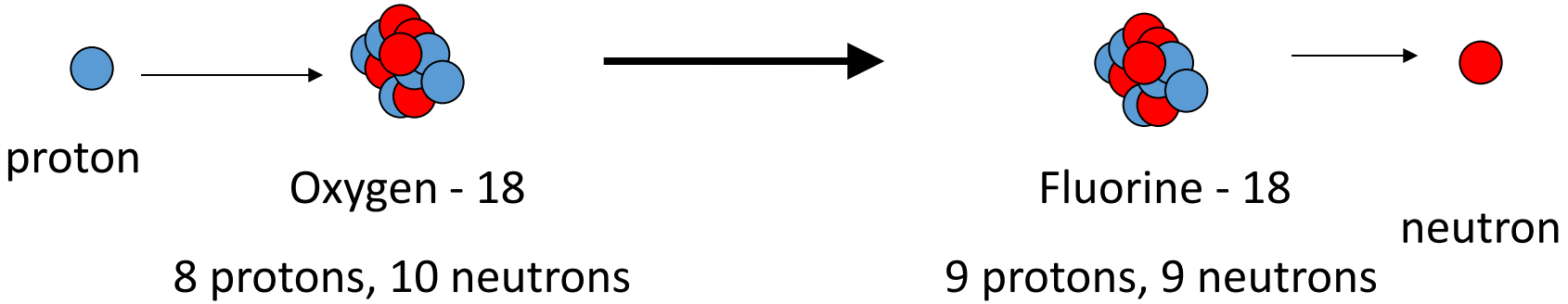
Mainly cyclotron produced but some generators

Physics of the Cyclotron

- A charged particle (p^+)
  - moves in circles in a static magnetic field
- Size of the circle
  - depends on the energy of the particle
- Electric fields are used
  - to accelerate the particle

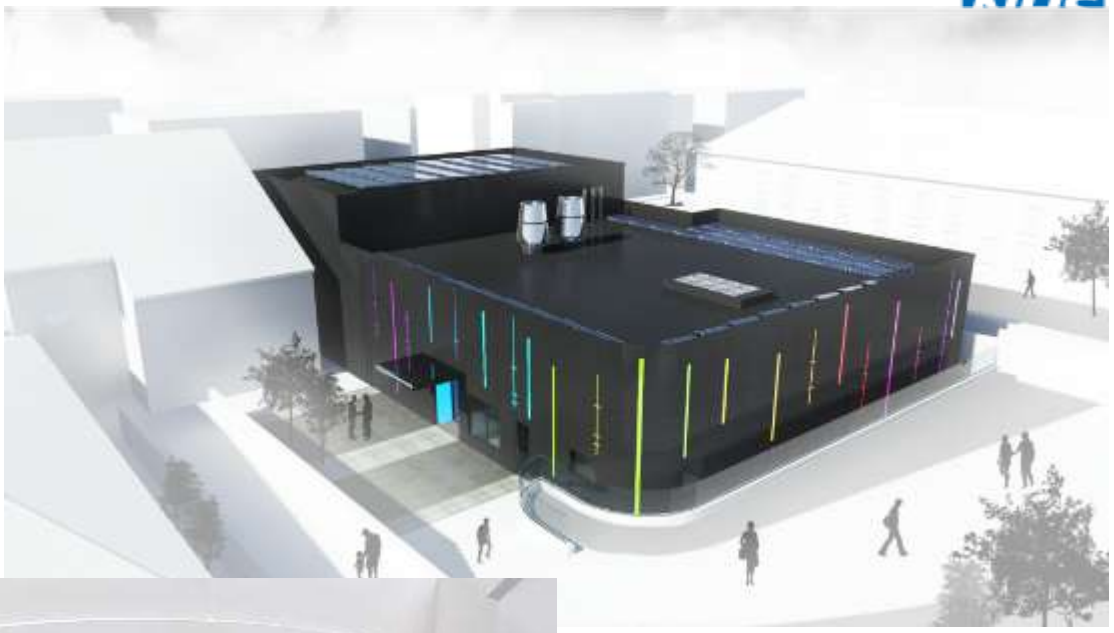


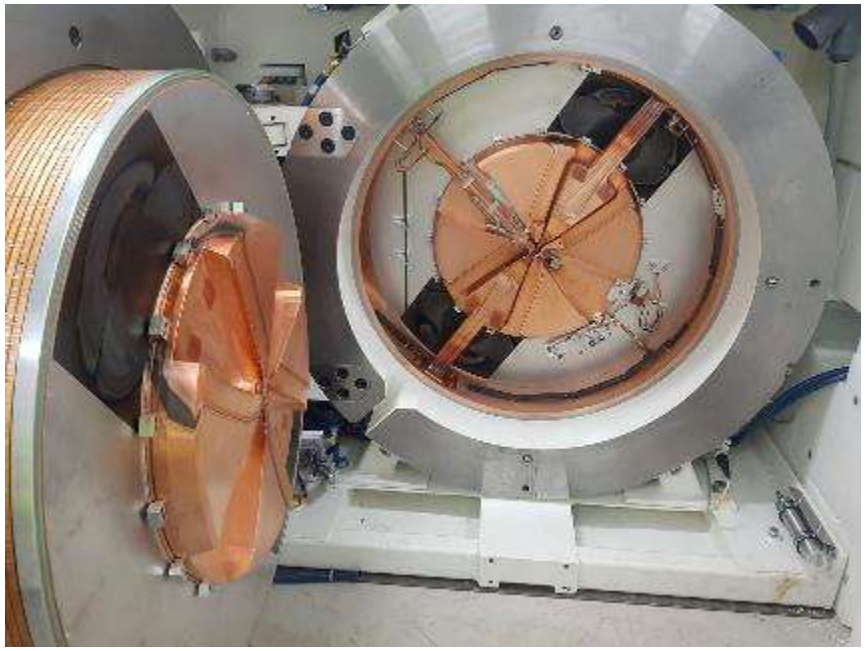
Nuclear Reaction for F-18



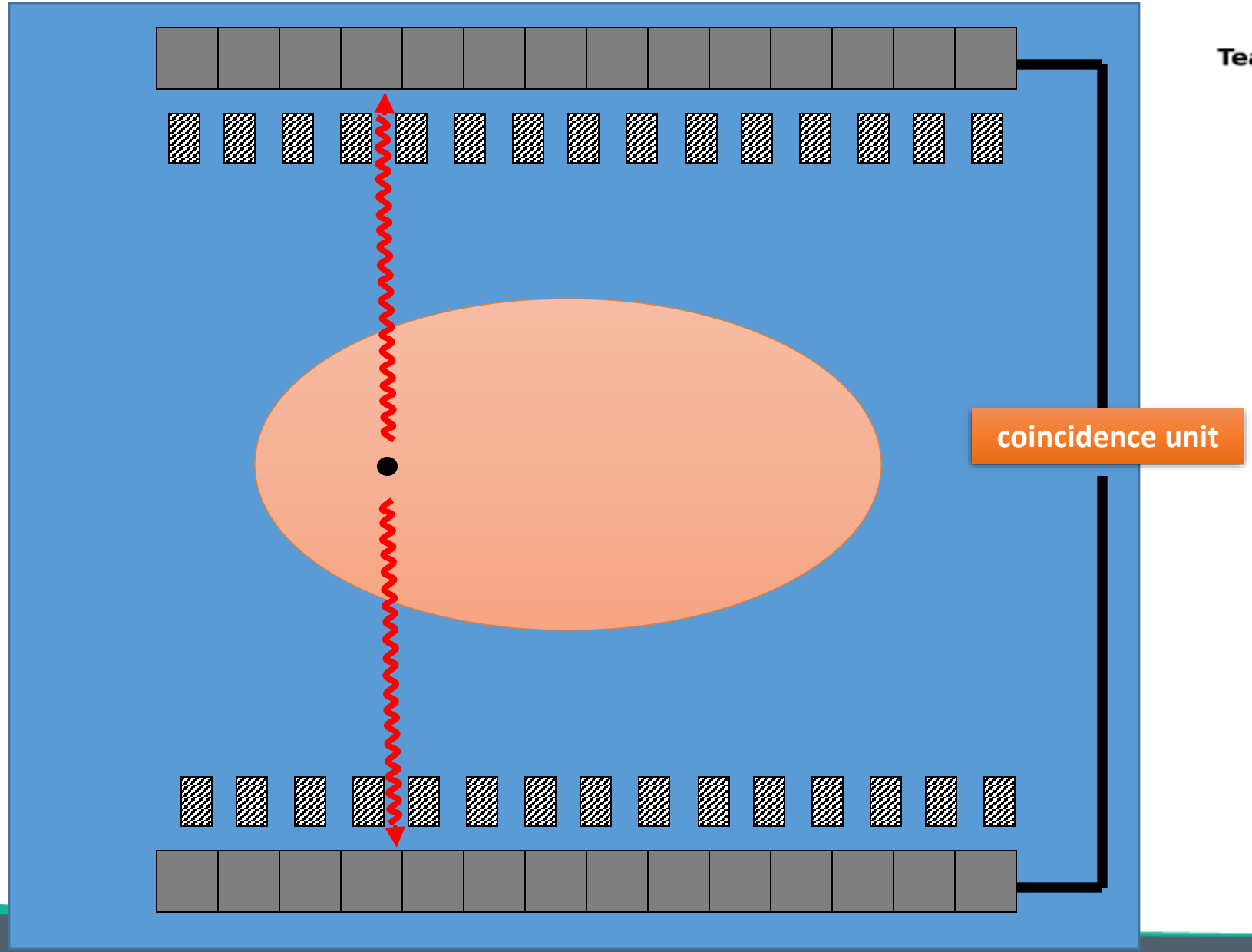
- Proton fired at ^{18}Oxygen
- ^{18}Oxygen absorbs the proton
  - temporary creation of ^{19}Fluorine
  - emission of a neutron
- Creation of ^{18}Fluorine

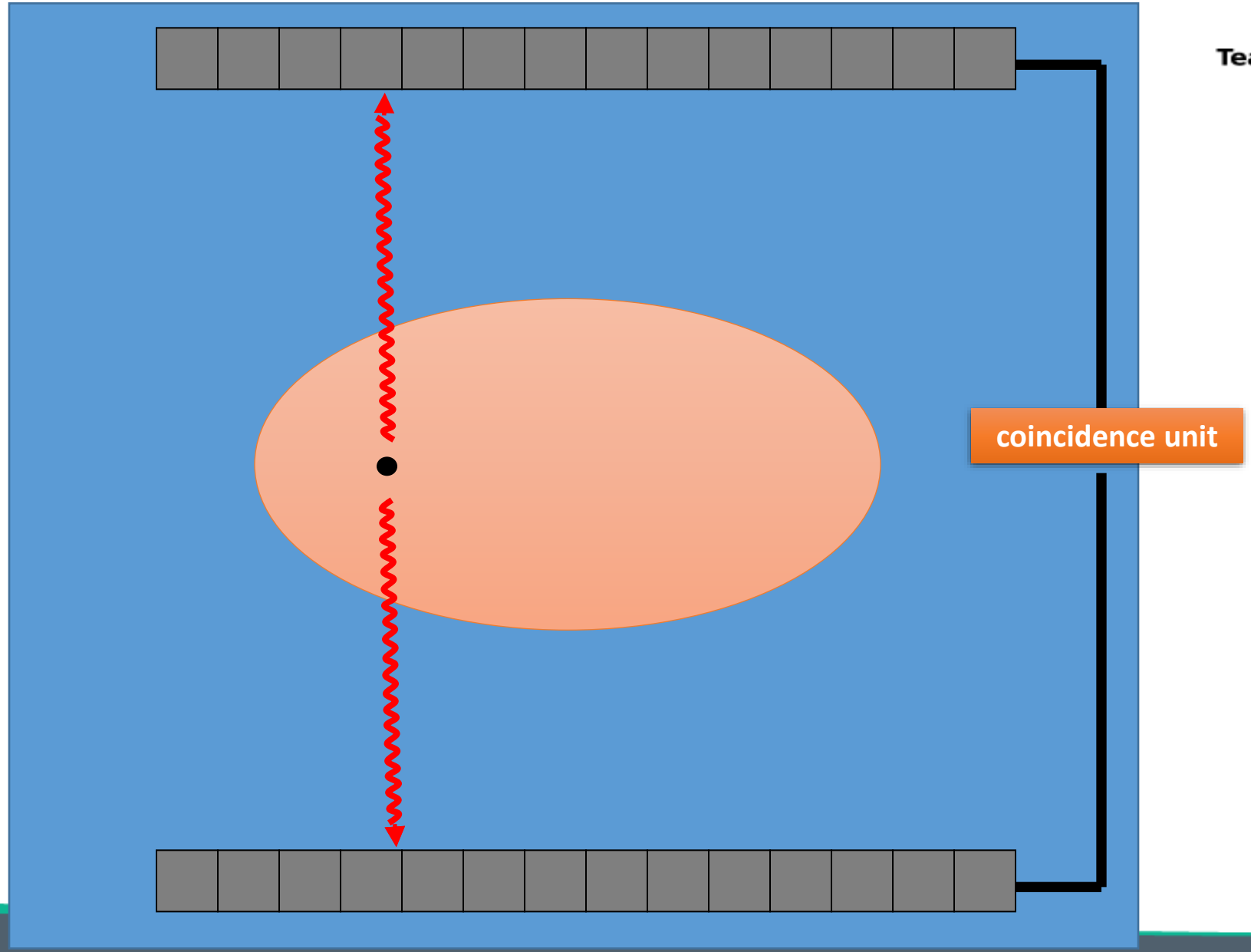
PET Isotopes – Hull MIRC

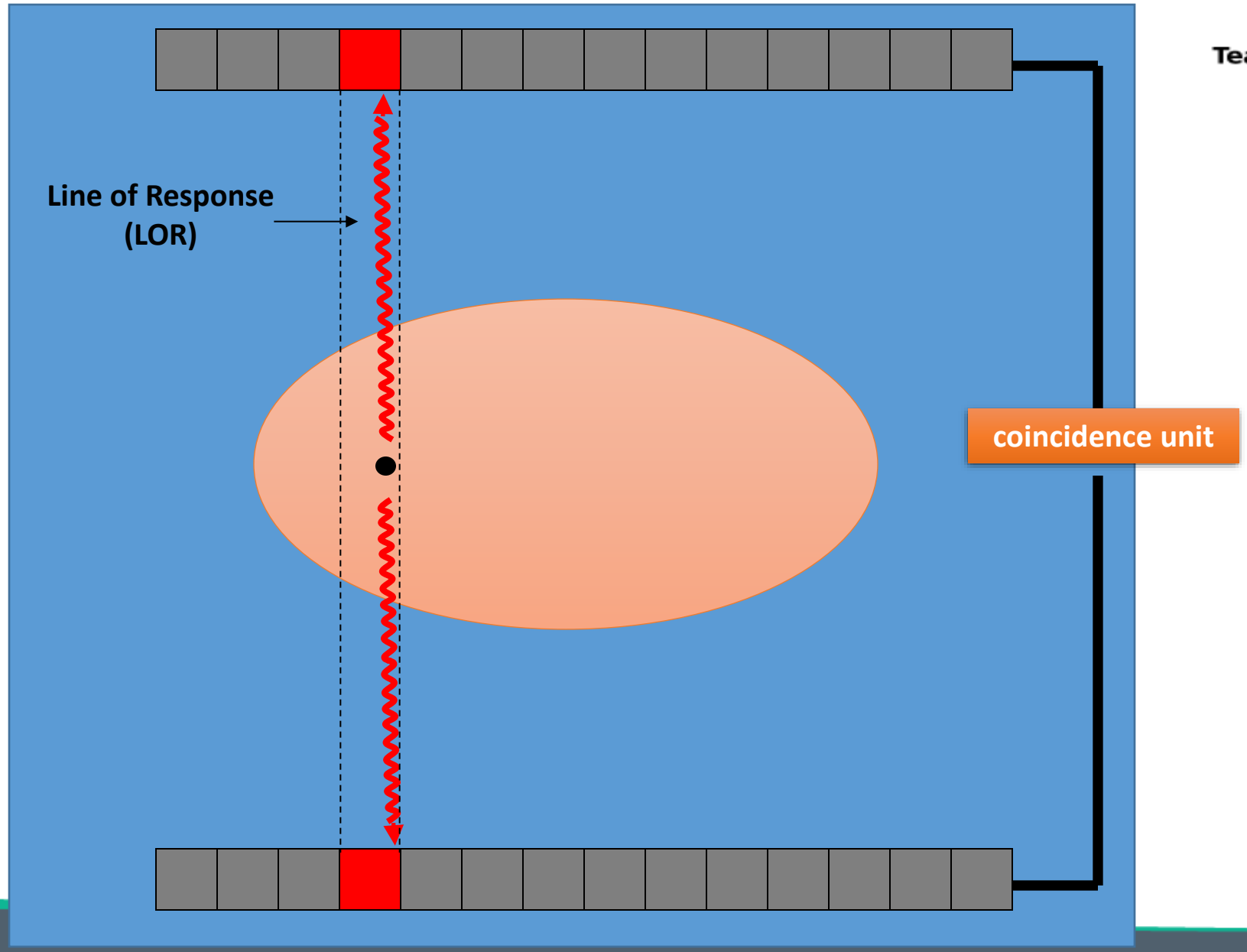






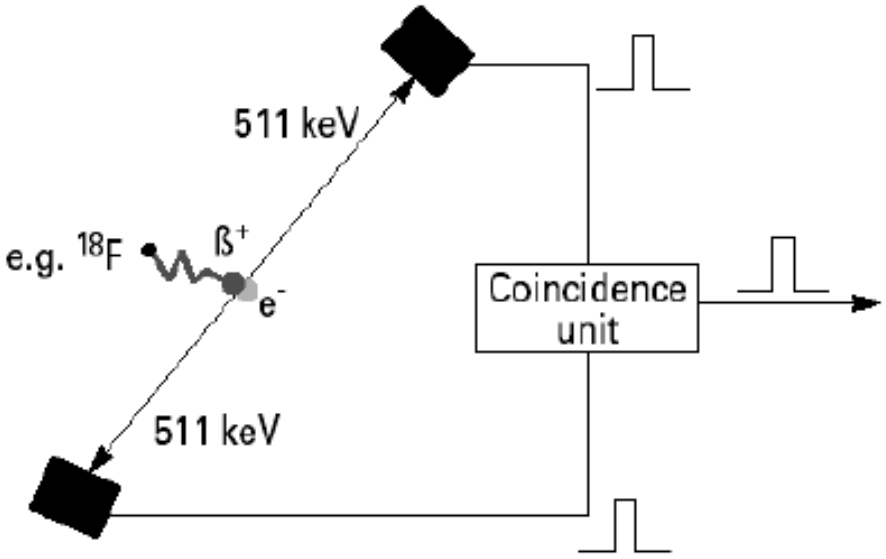

coincidence unit


coincidence unit


Line of Response
(LOR)
coincidence unit

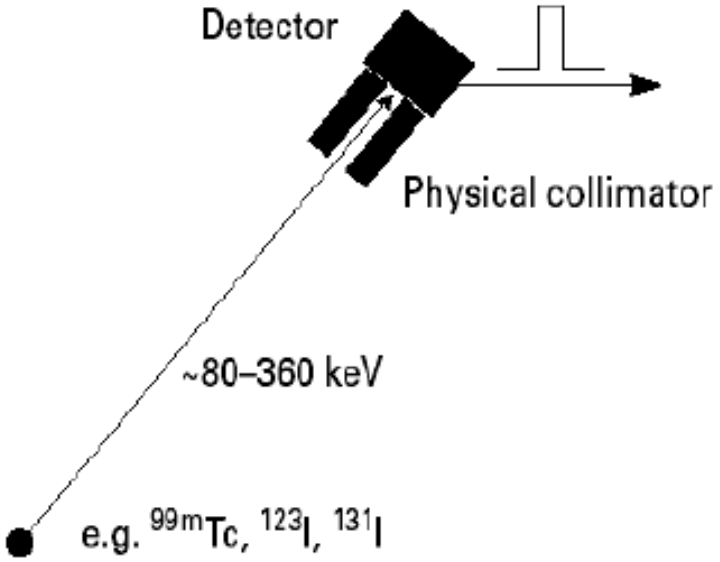
Look – no collimator!

PET

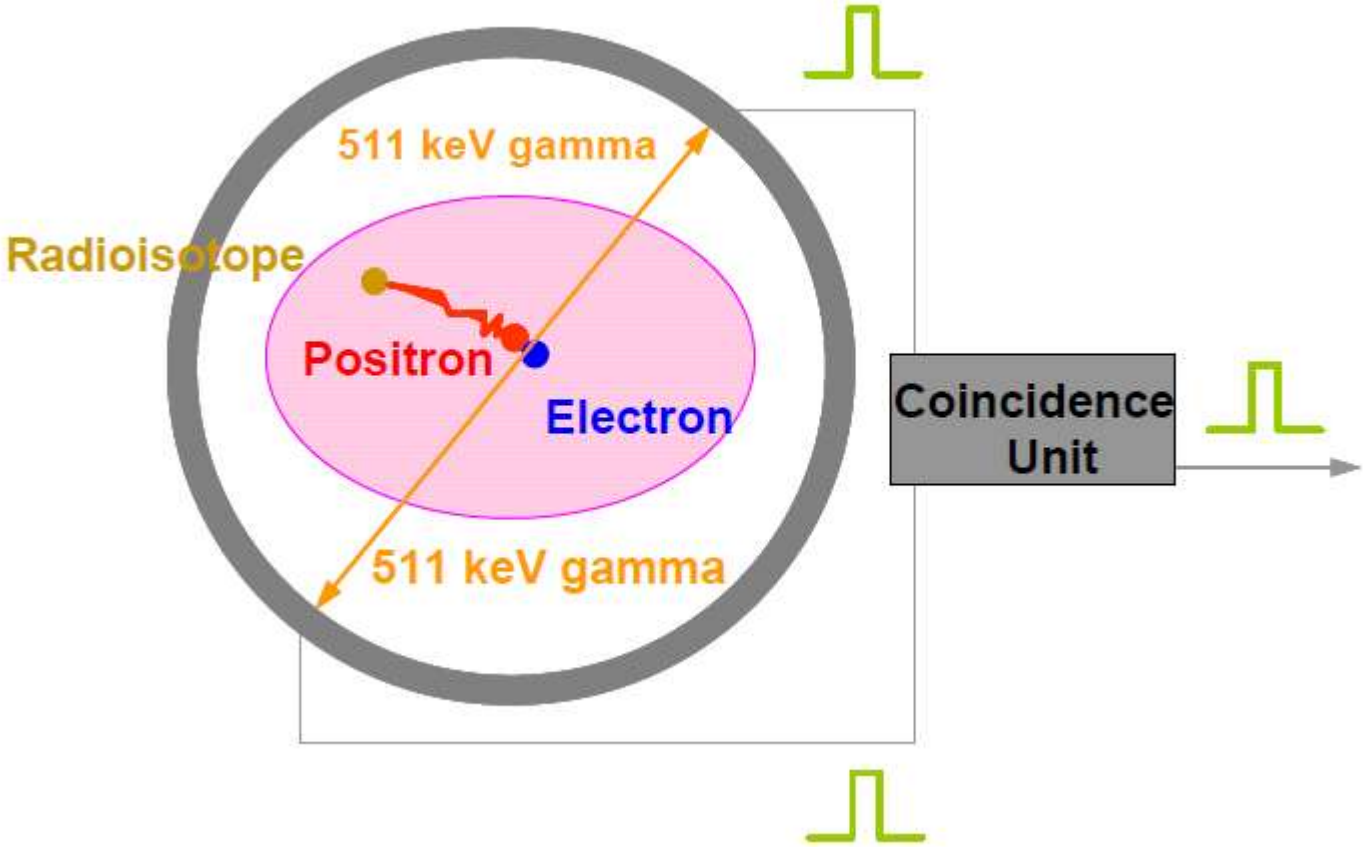


"Electronic collimation"

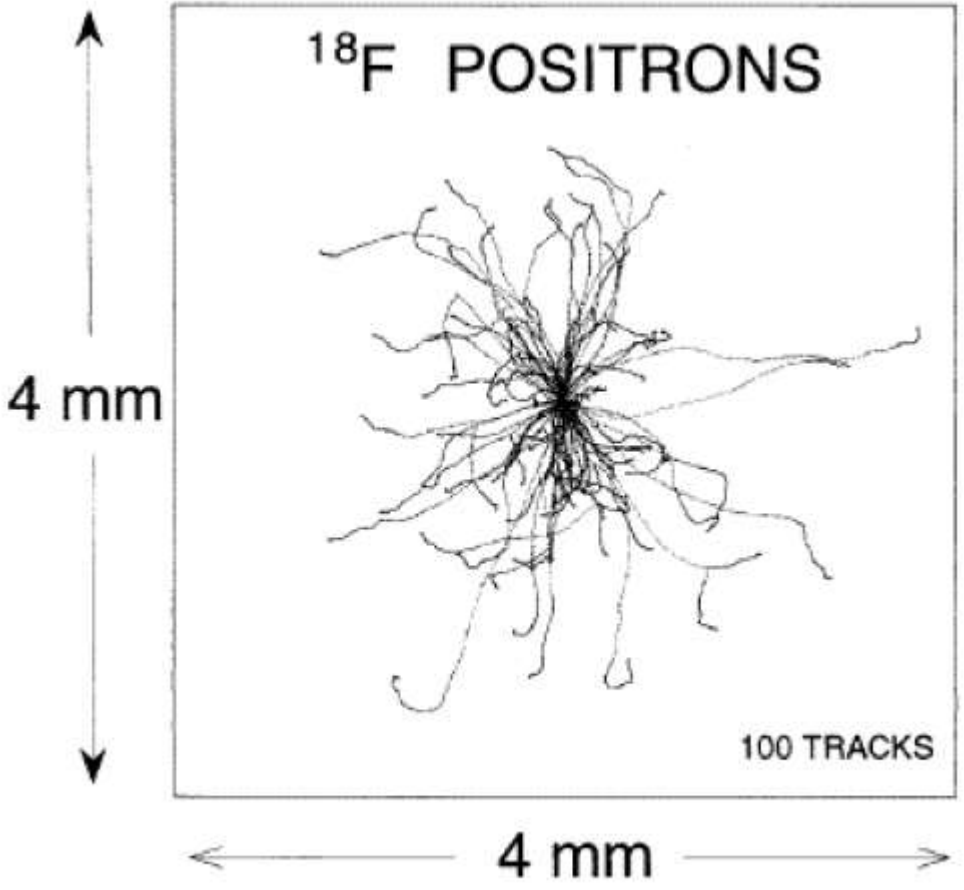
Single-Photon

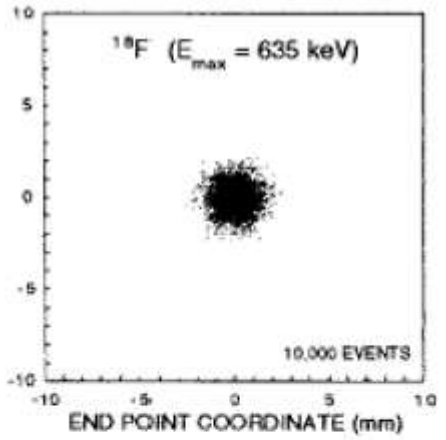


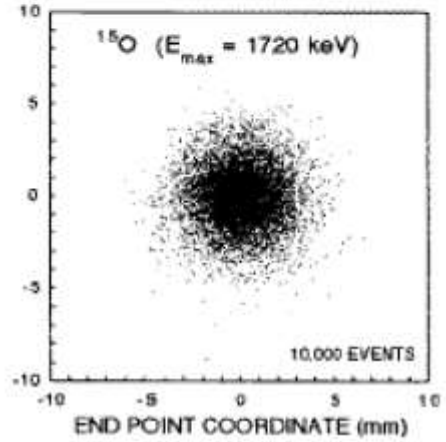
It’s not as simple as that…



Physical Limits on Resolution in PET







Simulated ^{18}F positron tracks from a point source in water.

from Levin & Hoffman PMB 1999; 46:781-799

Variation of Resolution with Positron Energy

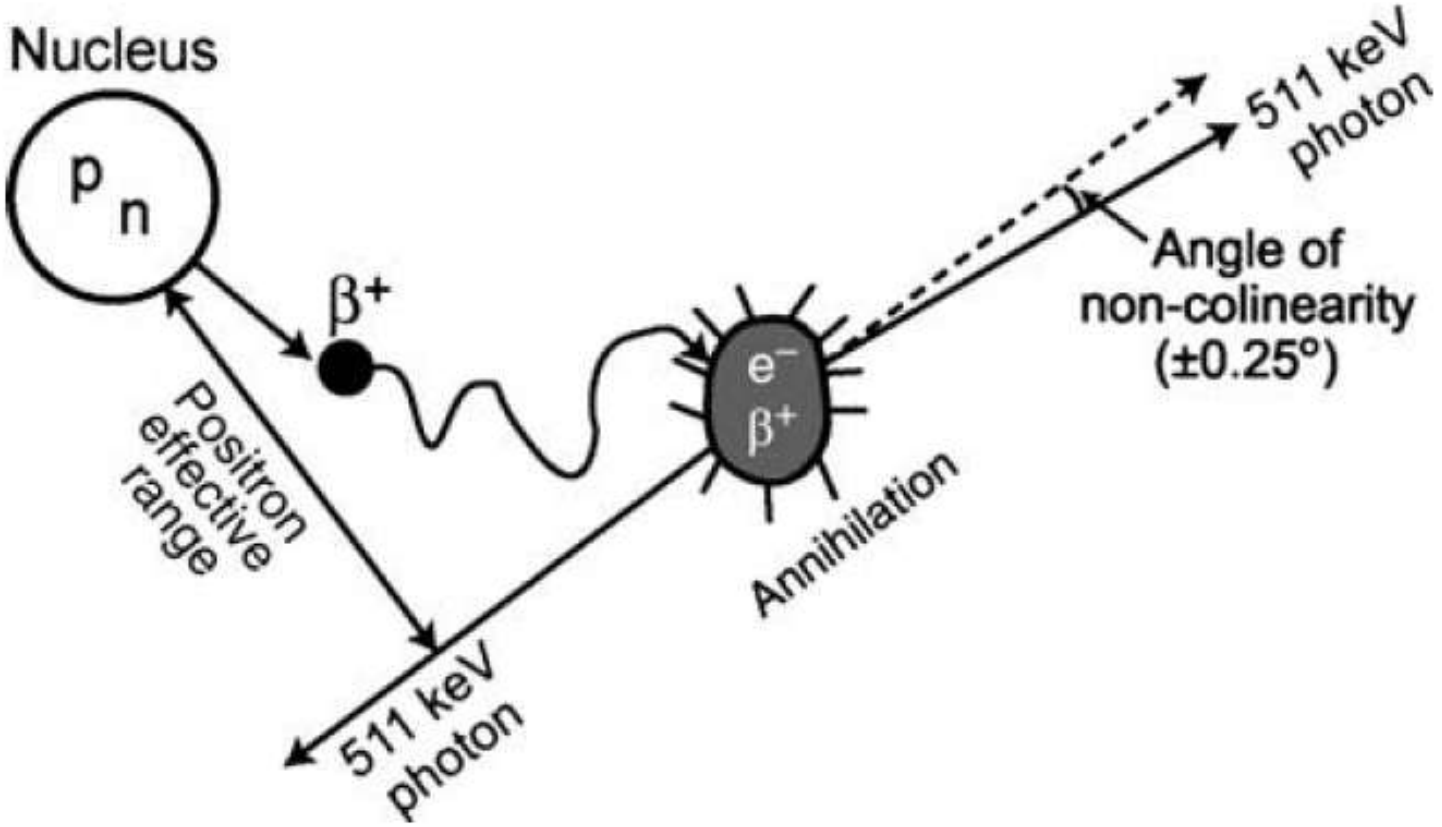
Isotope	Half-life (min)	$E_{max}(\beta^+)$ MeV	Production	Example tracer
^{11}C	20.4	0.96	$^{14}N(p,\alpha)^{11}C$	Methionine
^{13}N	9.96	1.19	$^{16}O(p,\alpha)^{13}N$	Ammonia
^{15}O	2.03	1.72	$^{15}N^*(p,n)^{15}O$ $^{14}N(d,n)^{15}O$	Water
^{18}F	109.7	0.635	$^{18}O^*(p,n)^{18}F$ $^{20}Ne(d,\alpha)^{18}F$	FDG (fluorodeoxyglucose)
^{62}Cu	9.7	2.93	^{62}Zn generator ($t_{1/2}$=9.2 hours)	PTSM (blood flow)
^{82}Rb	1.3	3.35	^{82}Sr generator ($t_{1/2}$=25 days)	Rb^- (blood flow)
^{124}I	4.2 days	2.10	$^{126}Te(p,3n)^{124}I$	Labelled antibodies

(*=enriched target)

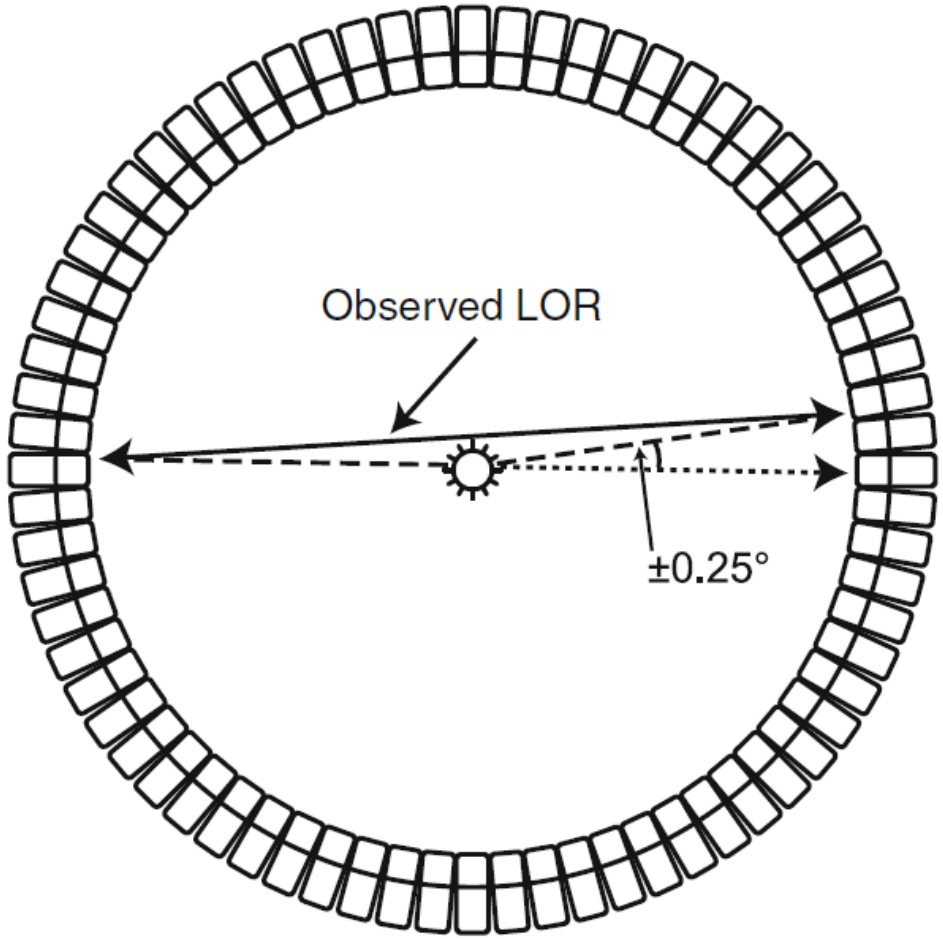
Wide range of positron energies

higher energy → worse spatial resolution

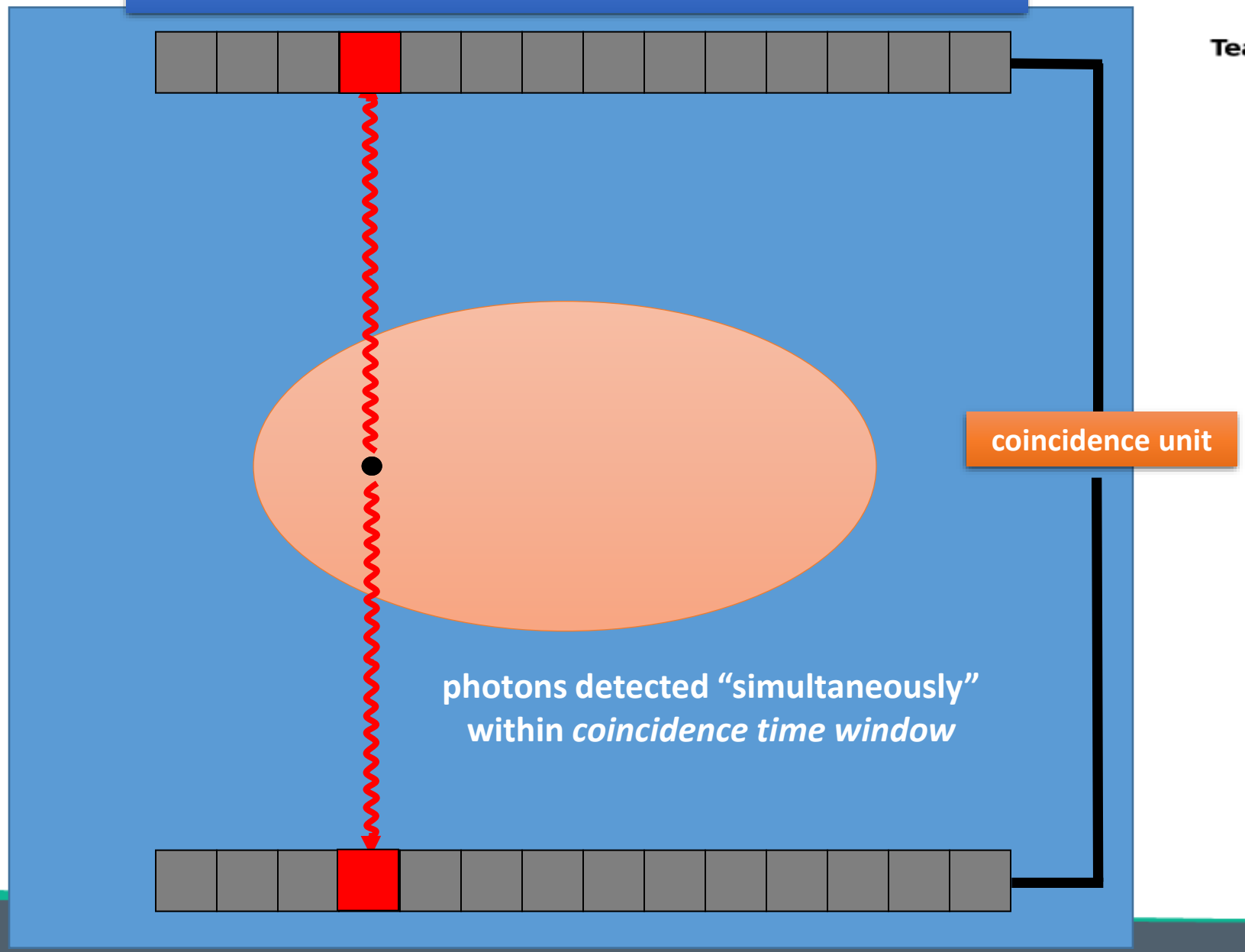
Variation of Resolution with Positron Energy



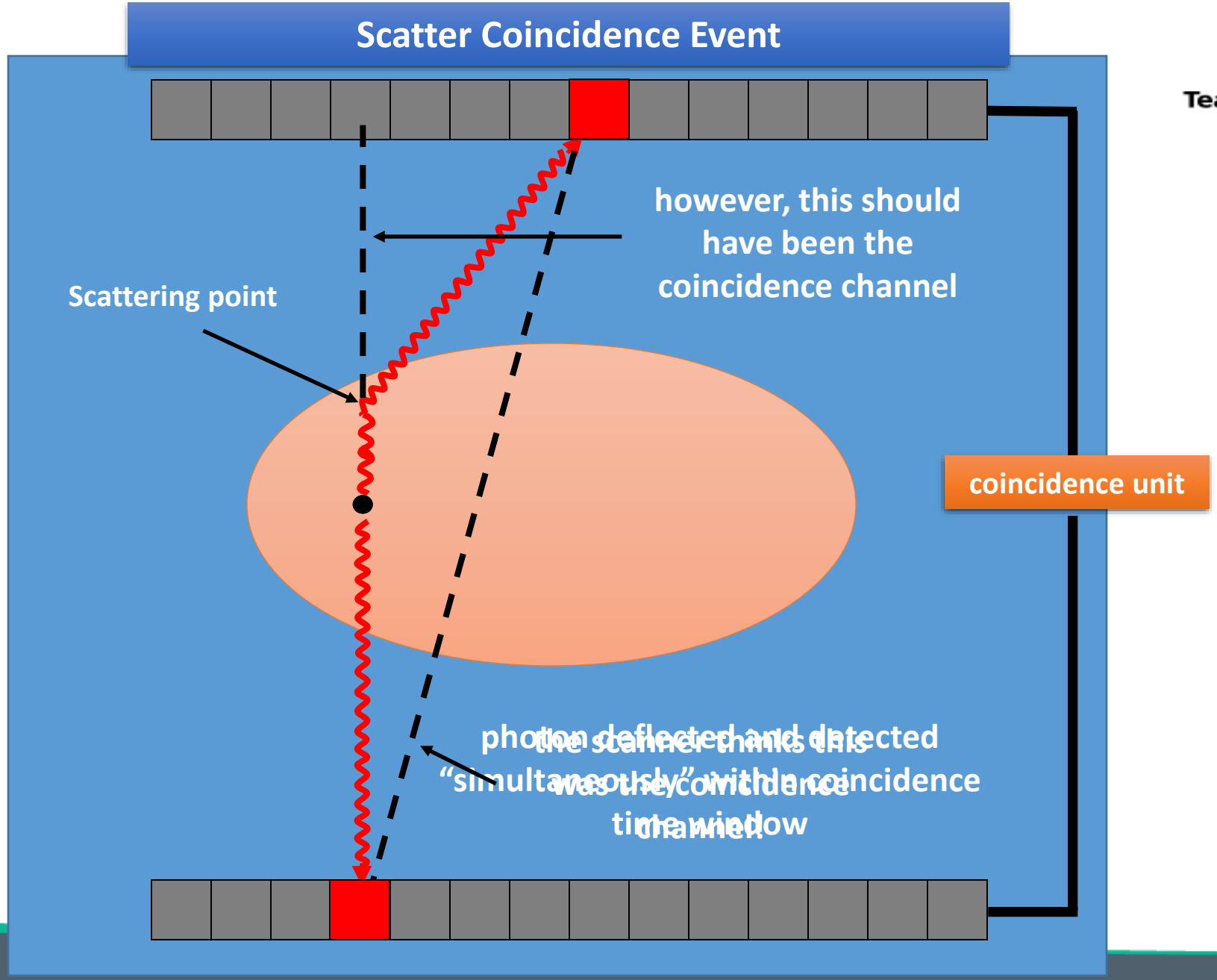
Variation of Resolution with Positron Energy



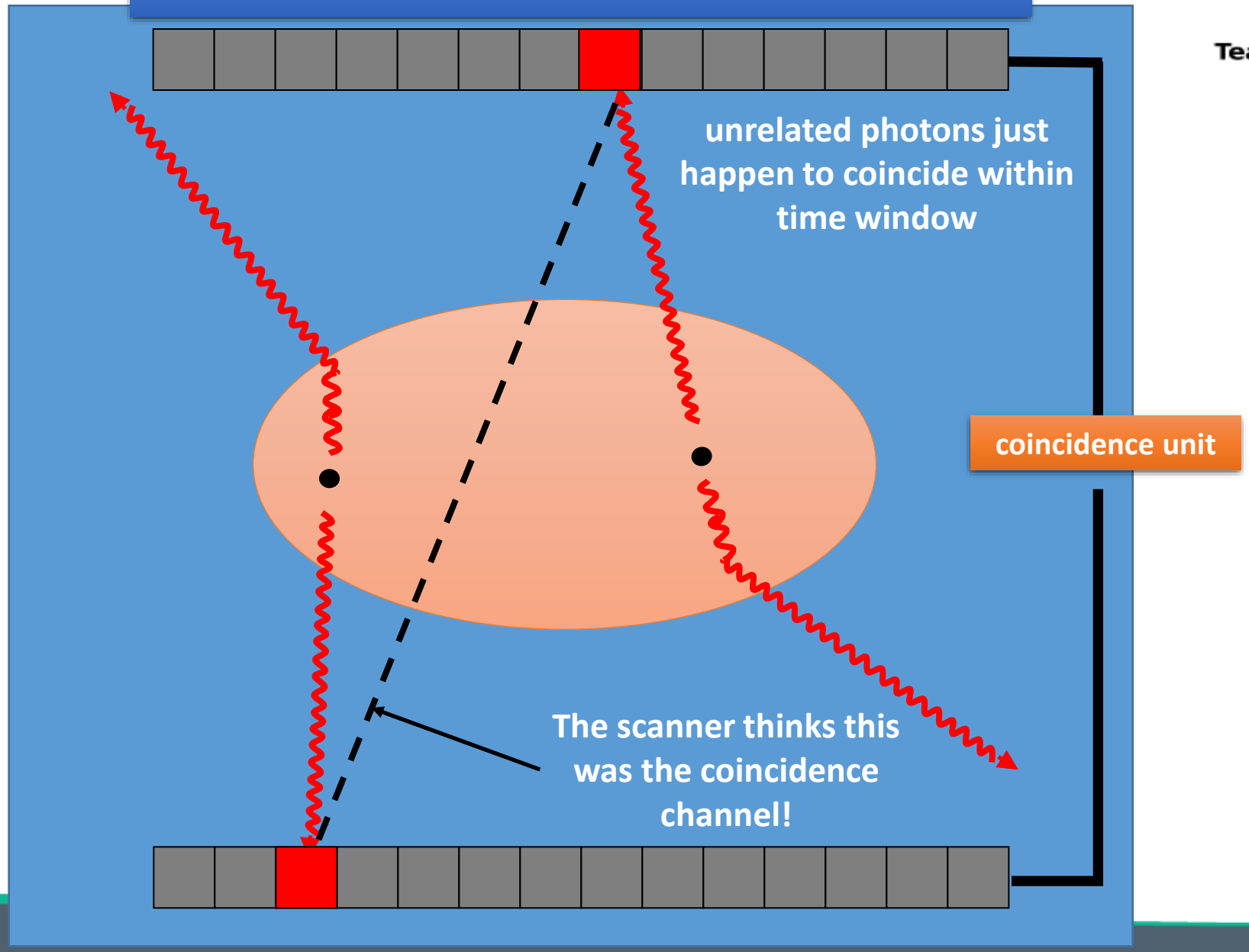
True Coincidence Event



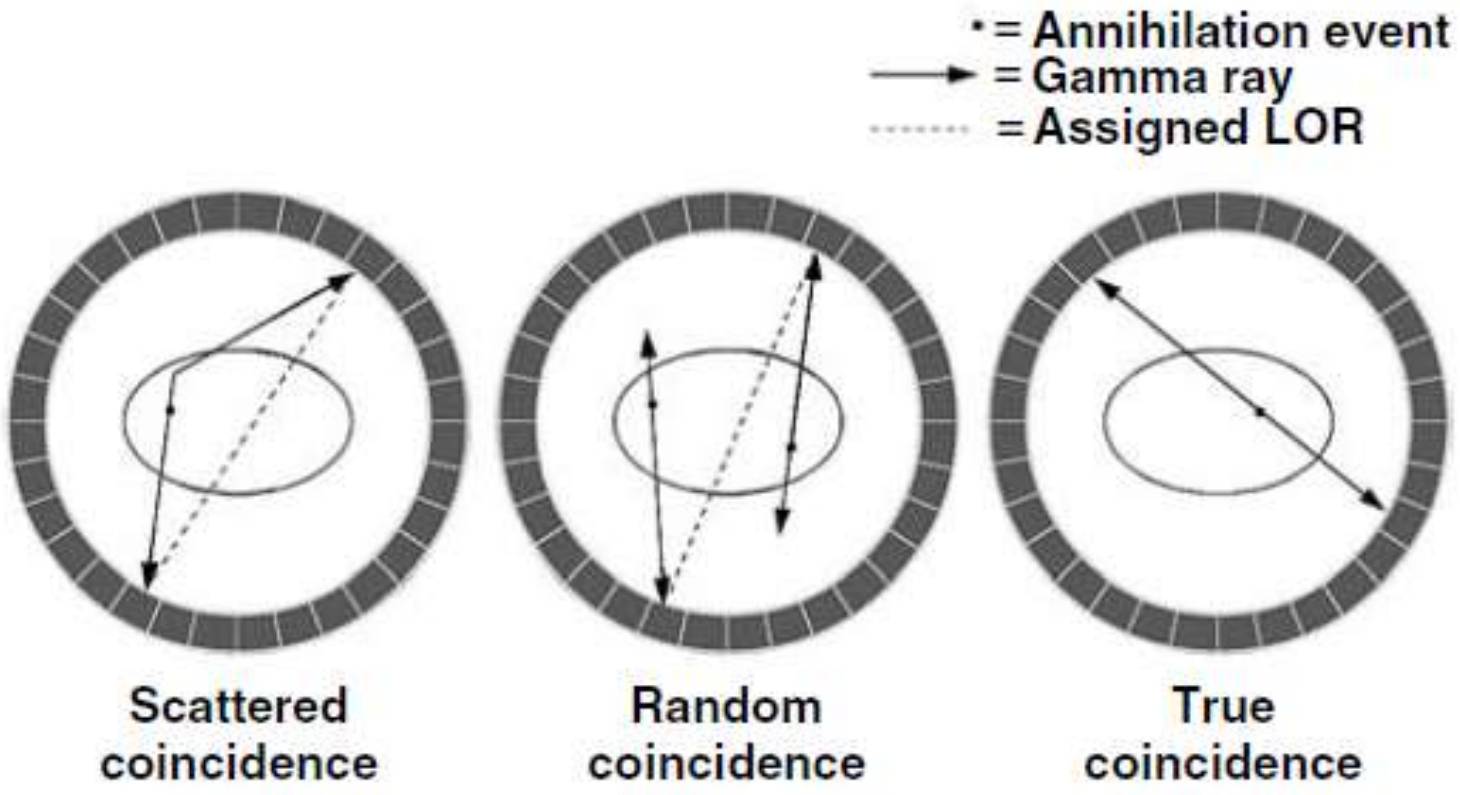
Scatter Coincidence Event



Random Coincidence Event

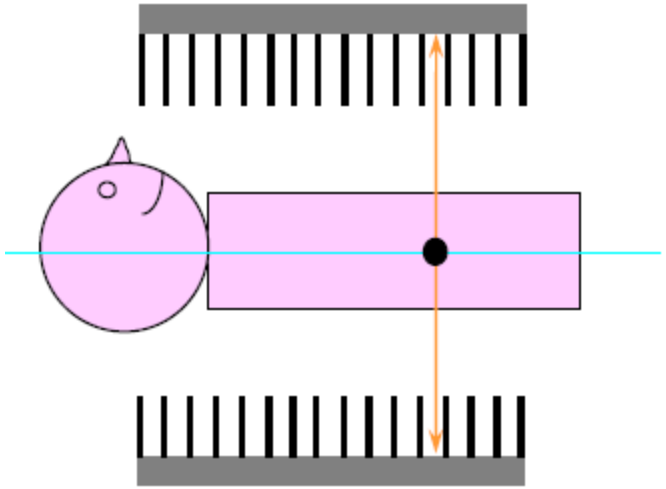


Type of Events in PET



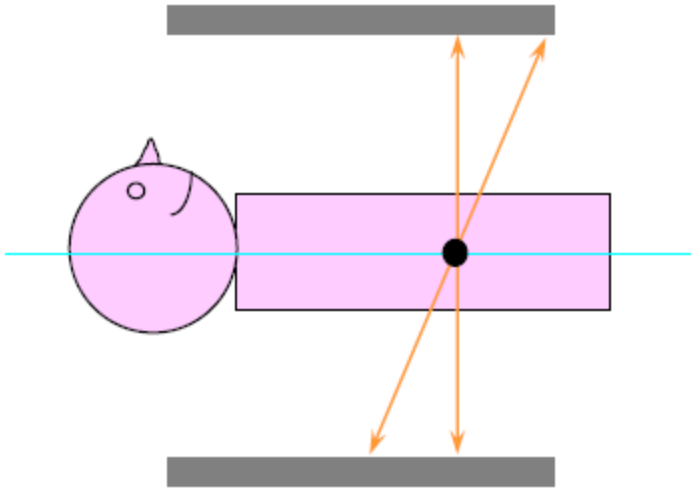
Acquisition Modes

- 2D



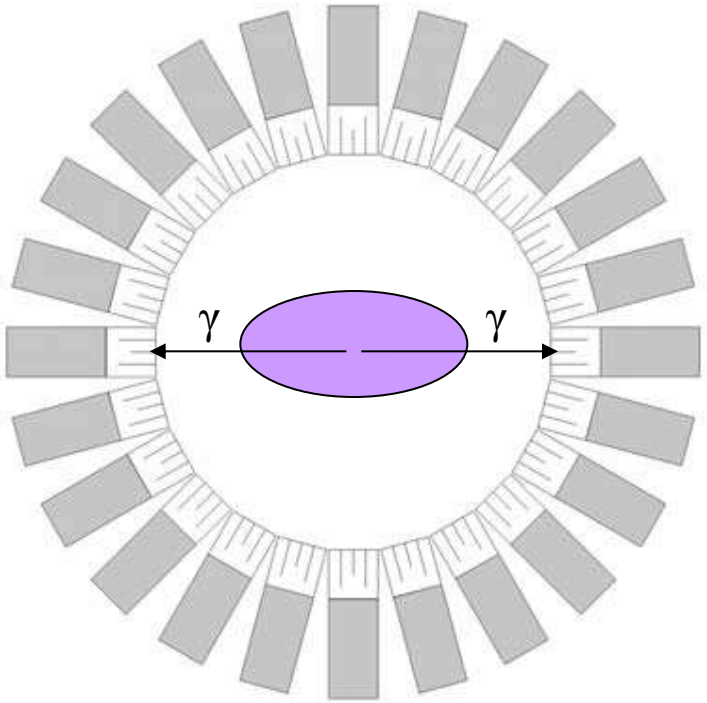
- Less randoms and scatter, but reduced sensitivity

- 3D

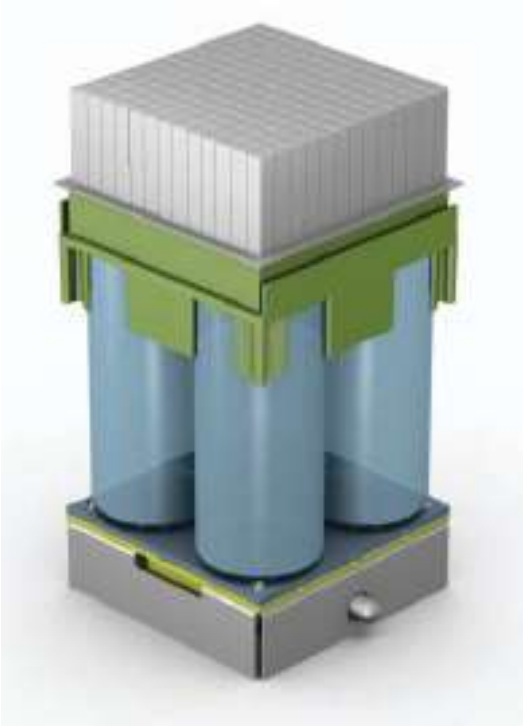


- Highest sensitivity but high randoms and scatter

PET Crystal Array

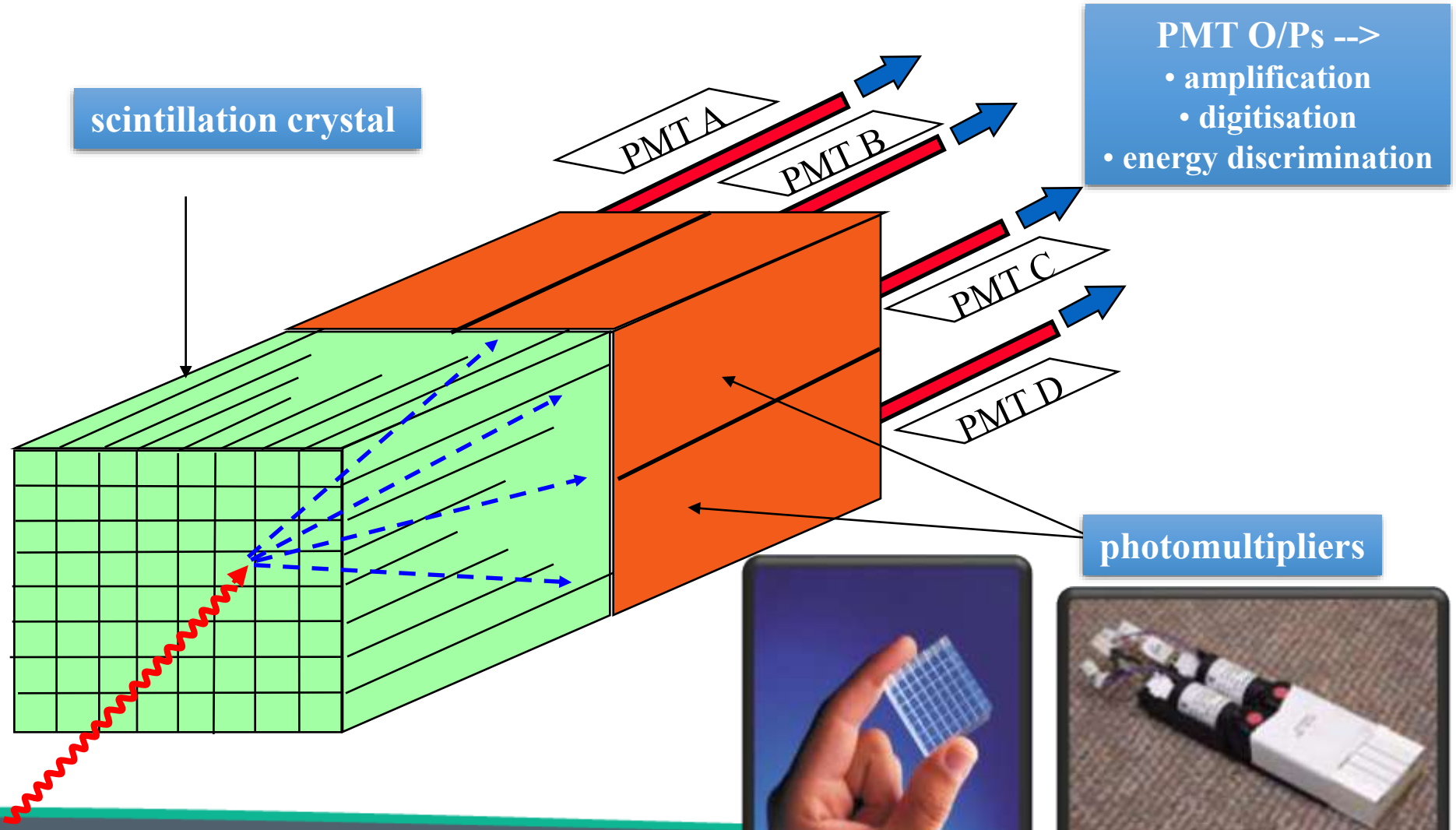


Annular Detector Array



Detector Block

PET Detector Block



Scintillator Crystals

Crystal	Relative Light Output (%)	Decay Time (ns)	Density (g/cm^3)	Effective Atomic Number (Z)	Energy Resolution at 511 keV (%)
NaI(Tl)	100	230	3.7	51	7.8
BGO	15	300	7.1	75	10.1
LSO	75	40	7.4	65	10.0
GSO	35	60	6.7	59	9.5

All crystals emit light with wavelengths ranging from 410 to 480 nm

Detectors based on BGO are still common, but crystals such as LSO and GSO (and those with similar properties) are increasingly being used. Both potentially offer improved count rate performance due to shorter decay times and improved energy resolution



GE HealthCare

PET/CT SCANNER

DISCOVERY™ MI DR

- for whole-body scintigraphy
- for whole-body tomography



Canon

PET/CT SCANNER

CARTESION PRIME

- for whole-body tomography



BASDA

PET/CT SCANNER

BPT-40

- for whole-body tomography
- 16-slice



PET/CT SCANNER

SCINTCARE PET/CT 720T

- for whole-body scintigraphy
- 128-slice
- wide-bore



Neusoft

PET/CT SCANNER

NEUSIGHT

- for whole-body scintigraphy
- for whole-body tomography
- 64-slice



Mediso

PET/CT SCANNER

ANYSCAN®

- SPECT/CT scanner
- for whole-body scintigraphy
- for whole-body tomography



UNITED IMAGING

PET/CT SCANNER

UMI PANORAMA GS

- for whole-body scintigraphy
- for whole-body tomography
- wide-bore



MiE

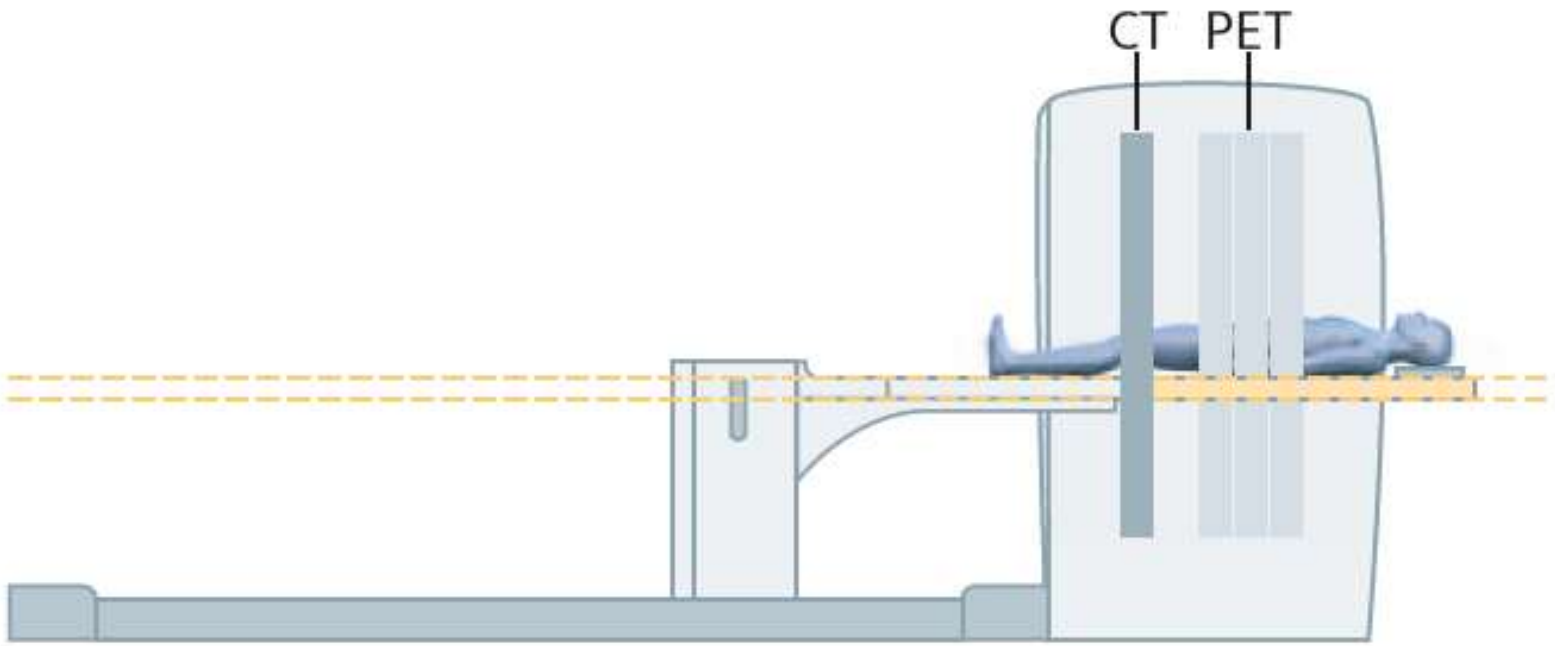
PET/CT SCANNER

UMI 550

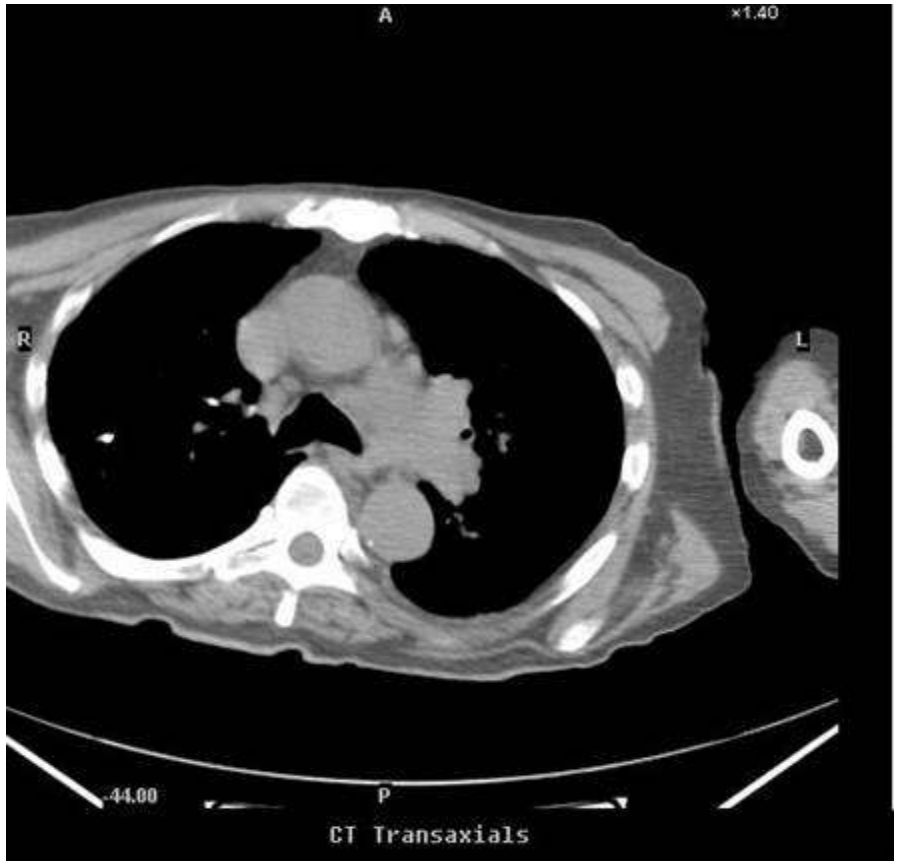
- for whole-body scintigraphy
- for whole-body tomography
- 80-slice

Current PET ≈ PETCT

Current PET ≈ PETCT

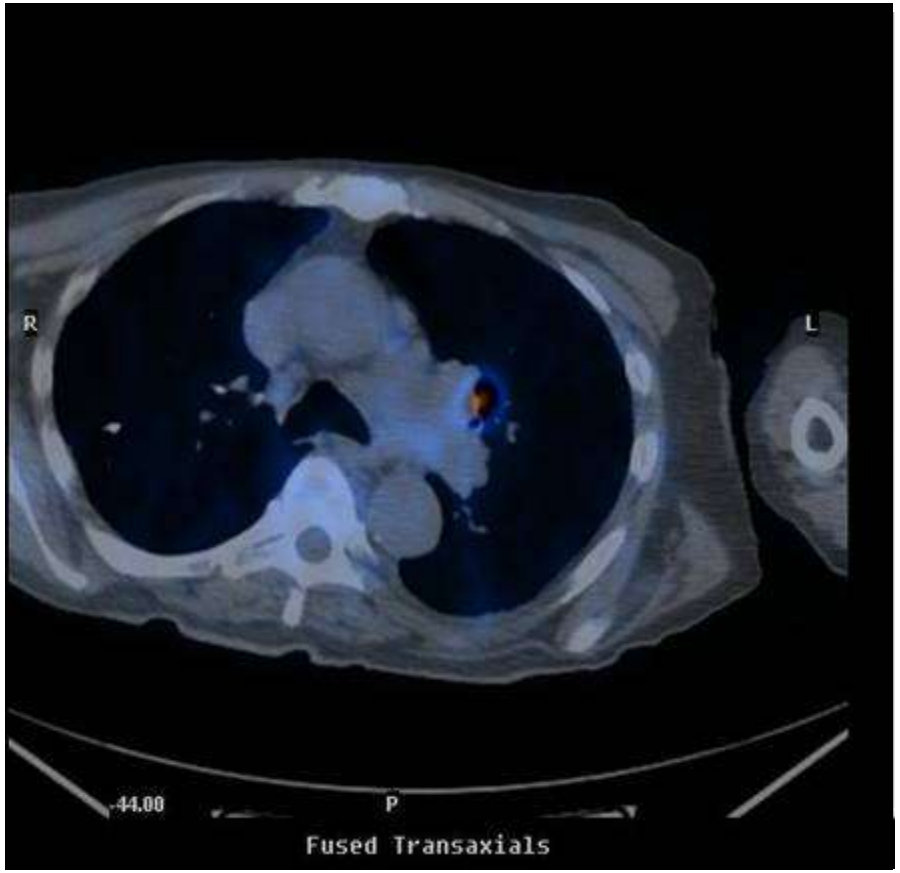


Computed Tomography (CT)



- Anatomical detail
- Cannot differentiate between active and benign disease
- Better resolution than PET

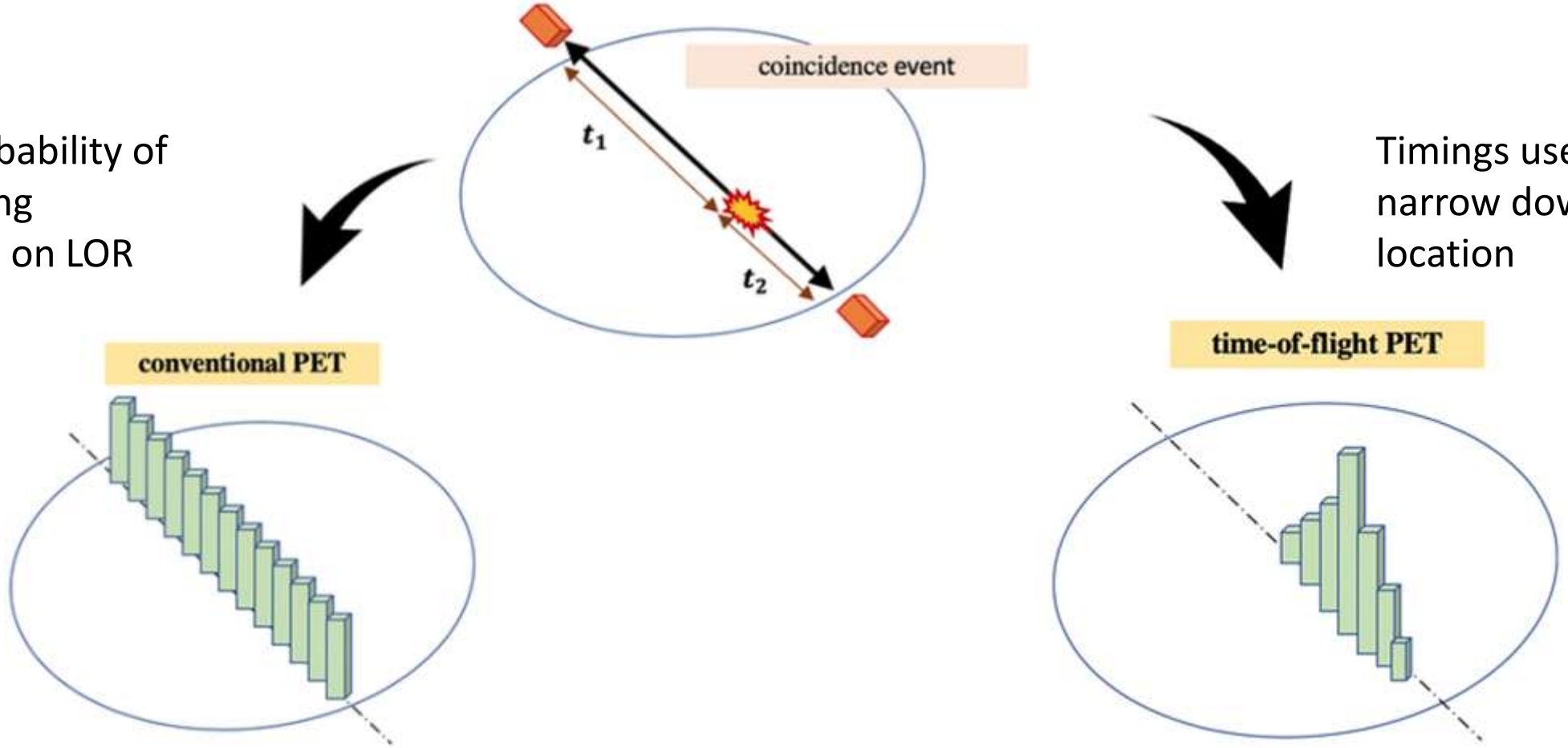
PET/CT – Best of Both Worlds



- Combines function with anatomy
- Accurate anatomical registration
- Higher diagnostic accuracy than PET or CT alone

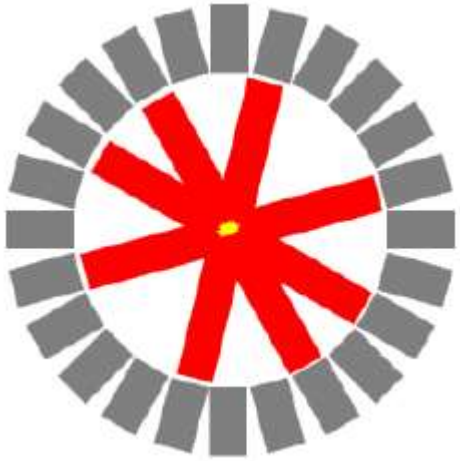
PET Imaging – Time of Flight (TOF)

Equal probability of event being anywhere on LOR

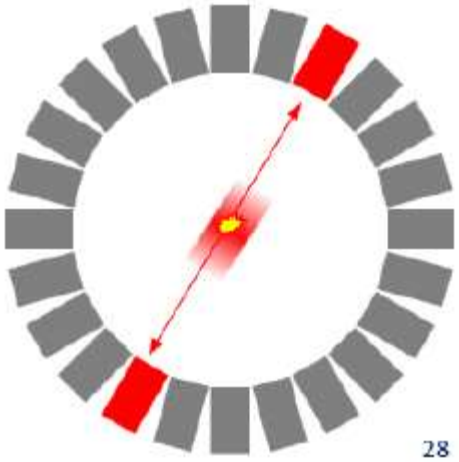


Timings used to narrow down location

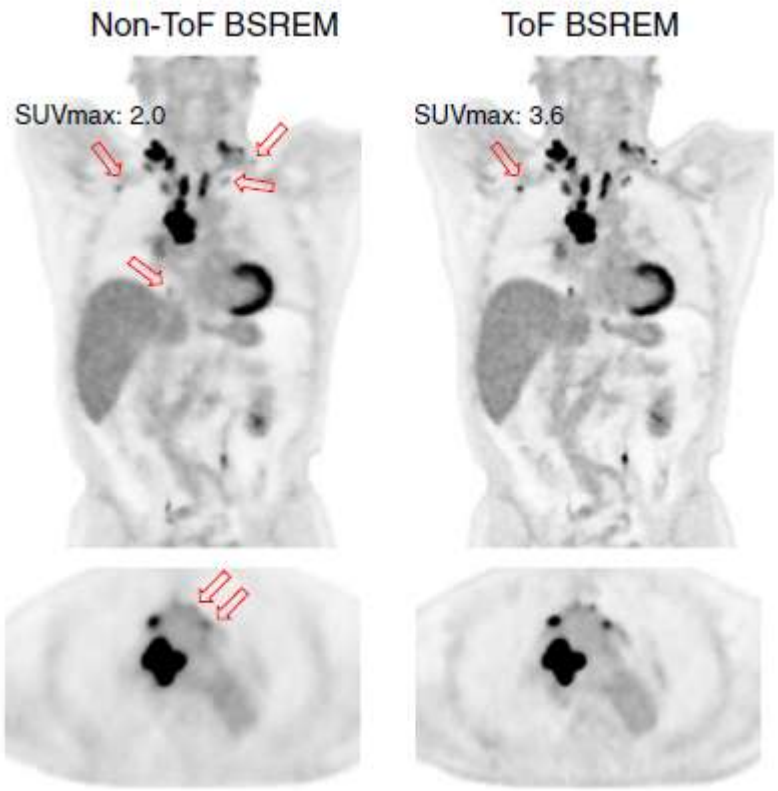
PET Imaging – Time of Flight (TOF)



Conventional



Time of flight



TOF improves image contrast by more accurately determining point of annihilations. We get a higher signal-to-noise ratio.

PET Imaging – Standard Uptake Value (SUV)

- Semi quantitative analysis based on:
  - Region of interest (ROI) values
  - A way of comparing what is in the region of interest against what was given to the patient in the injection.

- Definition:

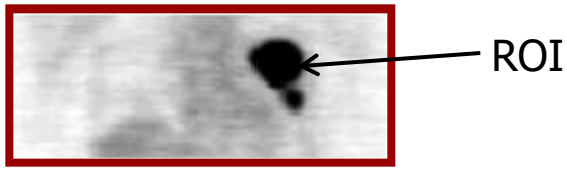
$$SUV = \frac{Concentration\ of\ radiotracer\ (^{MBq}/_{ml})}{Injected\ dose\ (MBq)\ /\ patient\ weight\ (kg)}$$

In the ROI

Standardised Uptake Value (SUV)

- Semi quantitative analysis based on
  - region of interest values
  - applying activity (kBq/ml) in the region of interest to patient weight and dose:

$$SUV = \frac{Uptake\ (\frac{kBq}{ml})}{activity\ (MBq)/weight(kg)}$$



before chemotherapy
SUV = 17.2



chemotherapy day 7
SUV = 3.9



chemotherapy day 42
SUV = 1.8

PET Imaging – Factors Impacting SUV



- Technical factors:
  - Calibration between PET scanner and dose calibrator
    - Part of QA – next lecture
  - Error in measurement of activity on calibrator (and residual)
  - Synchronisation of clocks (decay correction)
  - Quality of administration





PET Imaging – Factors Impacting SUV

- Patient factors:
  - Patient movement and breathing
  - Uptake period – impact on distribution
  - Glucose levels (FDG specific)
    - if high then less FDG uptake as is a glucose analogue (FDG patients fast before scan),
    - high blood glucose = low contrast image (little difference between uptake areas and tissue



PET Imaging – FDG scans common problems



Normal uptake



Patient hasn't fasted



Patient exercised before scan



Patient chewing gum

What do you think caused this?

PET Imaging – Clinical Examples

- Oncology Uses:
  - Differentiate benign from malignant disease
  - Staging of disease (and restaging)
  - Treatment response
  - Radiotherapy treatment planning



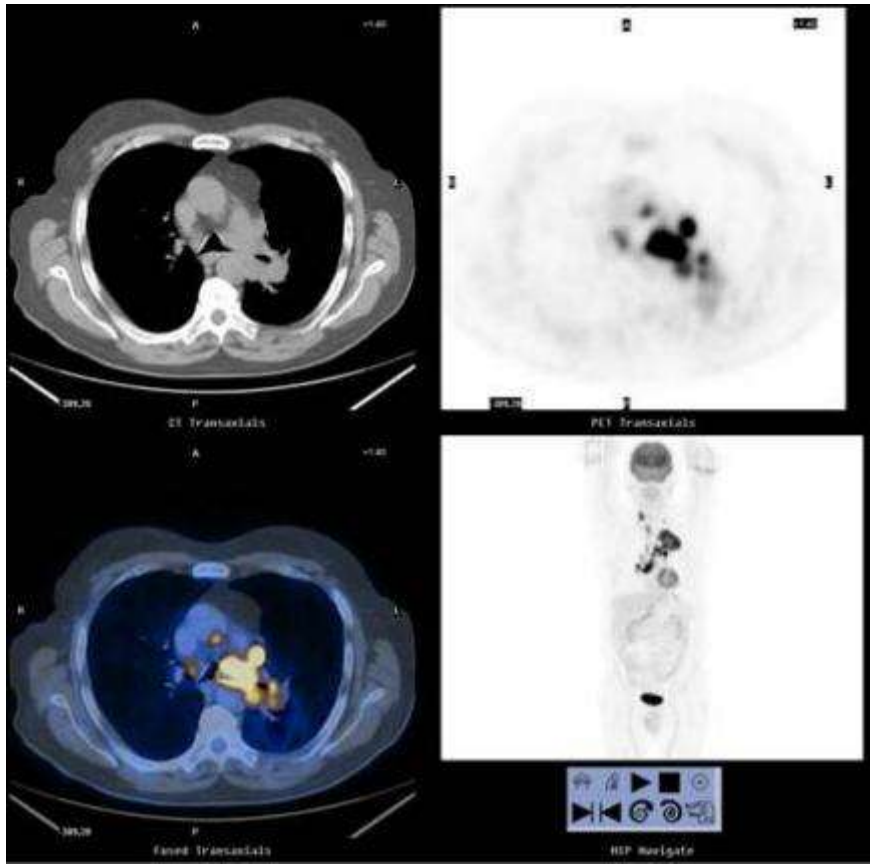
NHS
Hull University Teaching Hospitals
NHS Trust

PET Applications

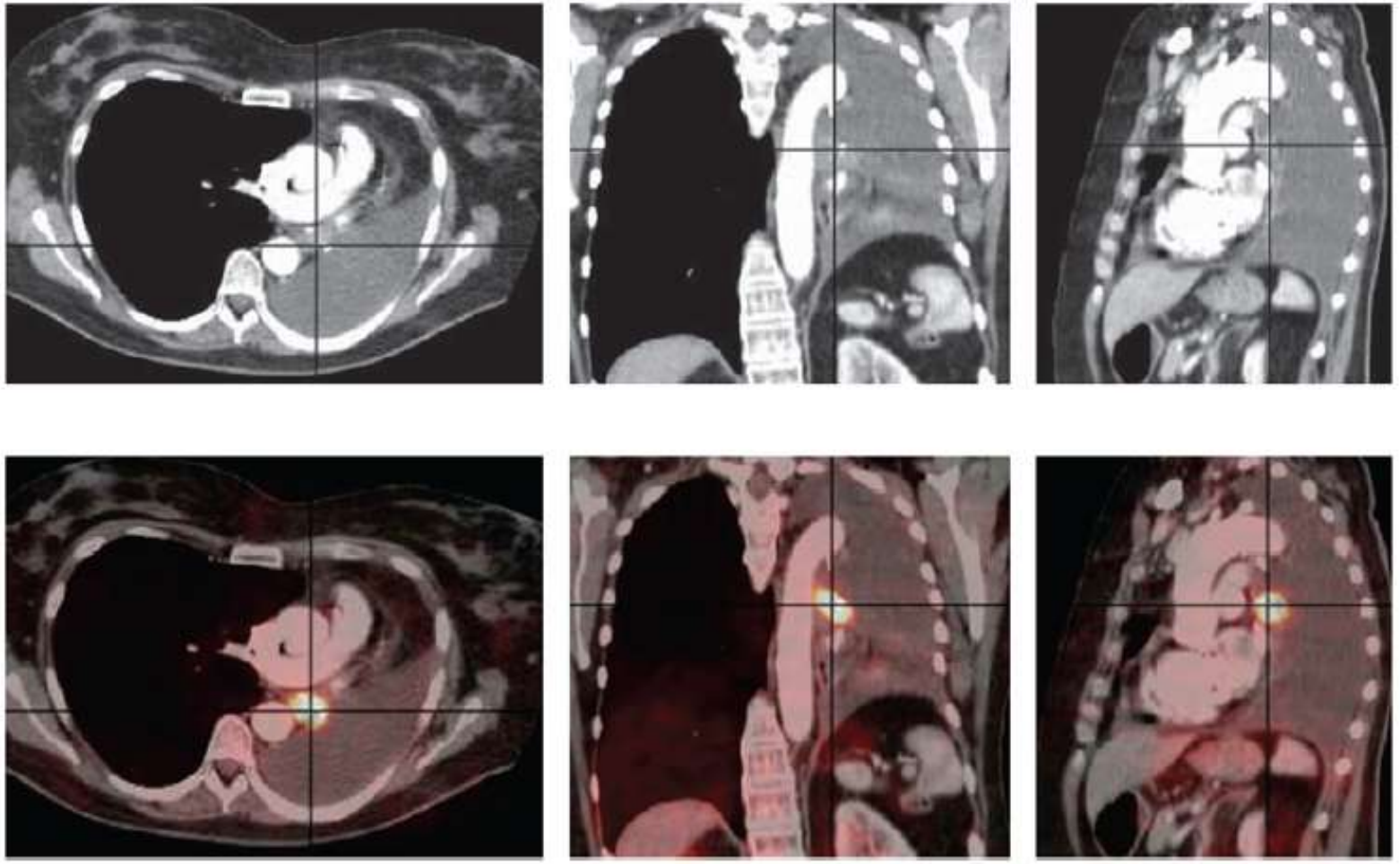
Oncology

^{18}FDG in Oncology

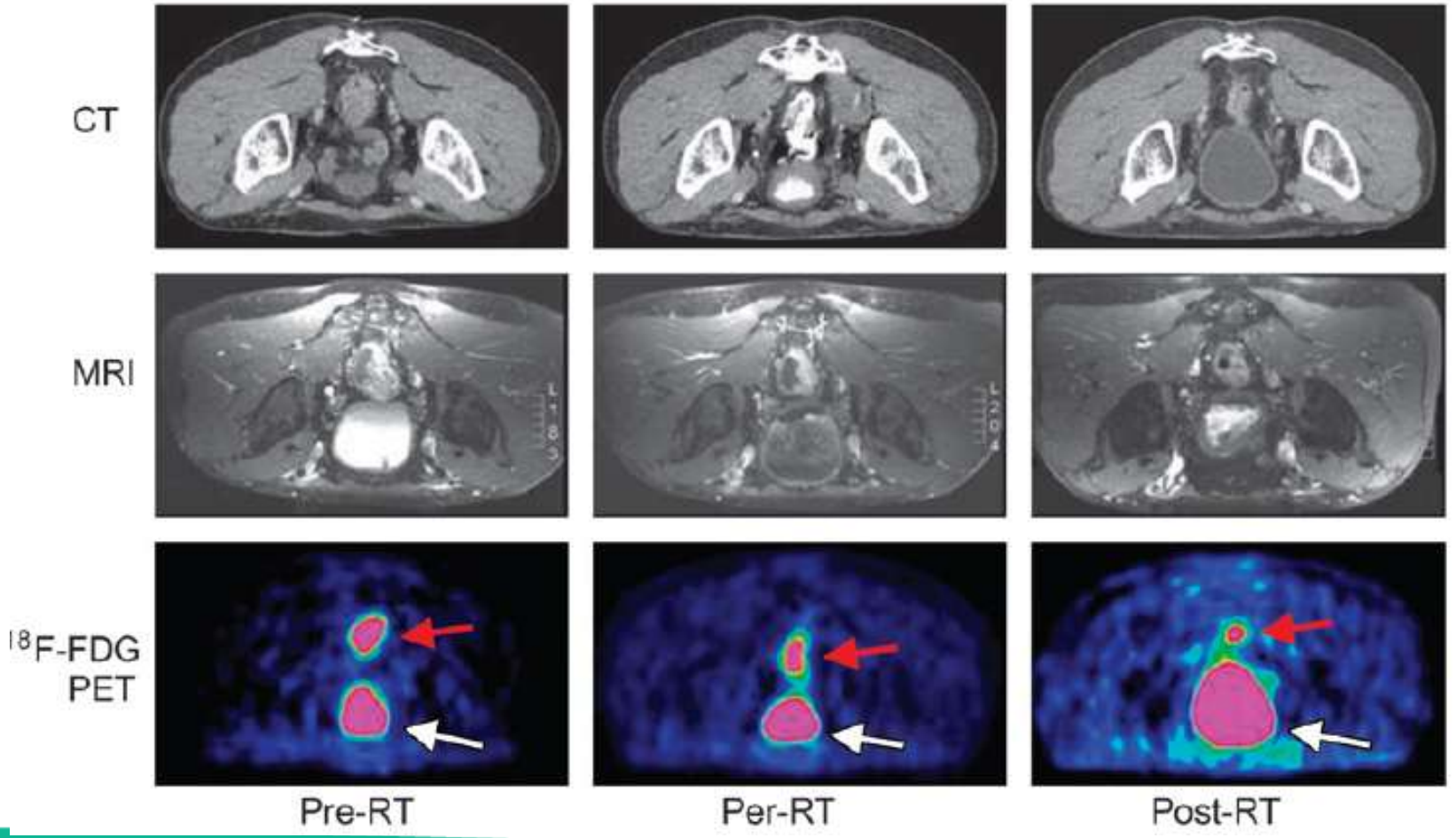
- Differentiate benign from malignant disease
- Staging of disease
- Treatment response
- Radiotherapy treatment planning



Volume Delineation



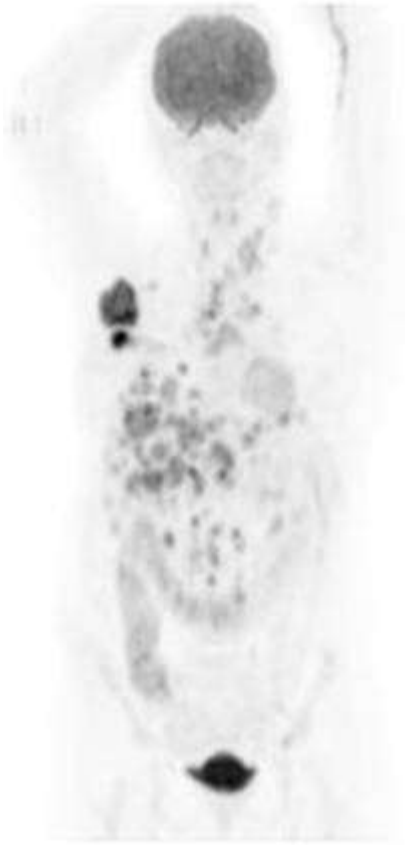
Volume Delineation



Disease Progression

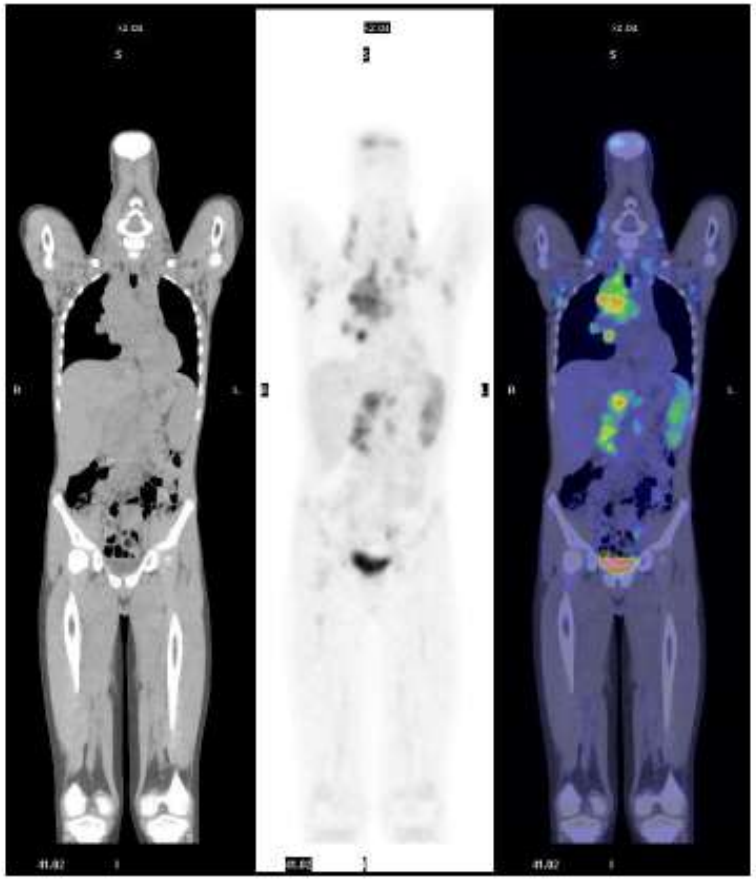


2004



2005

Oncology – Glucose Metabolism (^{18}FDG)





PET Imaging – Oncology Example

- Ga68-PSMA (Prostate Specific Membrane Antigen)
- Ga-68 half-life 68.3 min
- Patients who have biological recurrence (high PSA) after prostatectomy/ radiotherapy/ brachytherapy
- Patients being considered for Lu-177 PSMA therapy
- F-18 PSMA also used

PET Imaging – Oncology Example

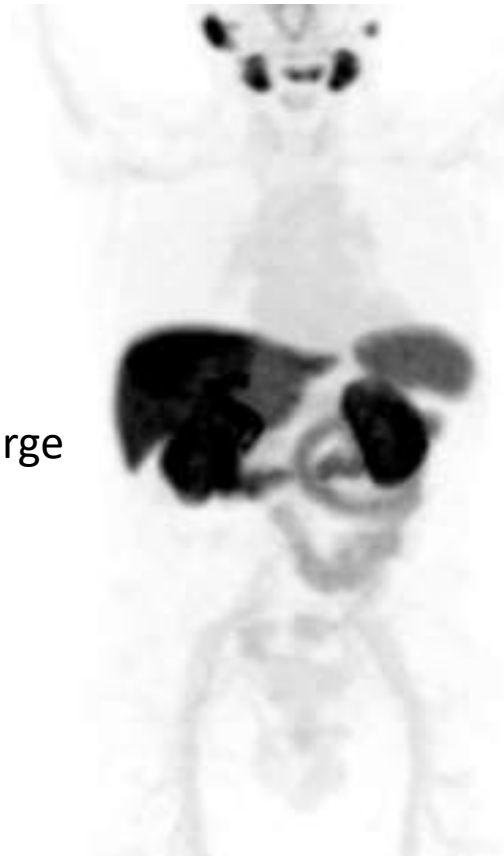


Ga-68 PSMA

Normal uptake:
salivary/lacrimal glands,
liver, spleen, small and large
bowel, kidneys, **bladder**

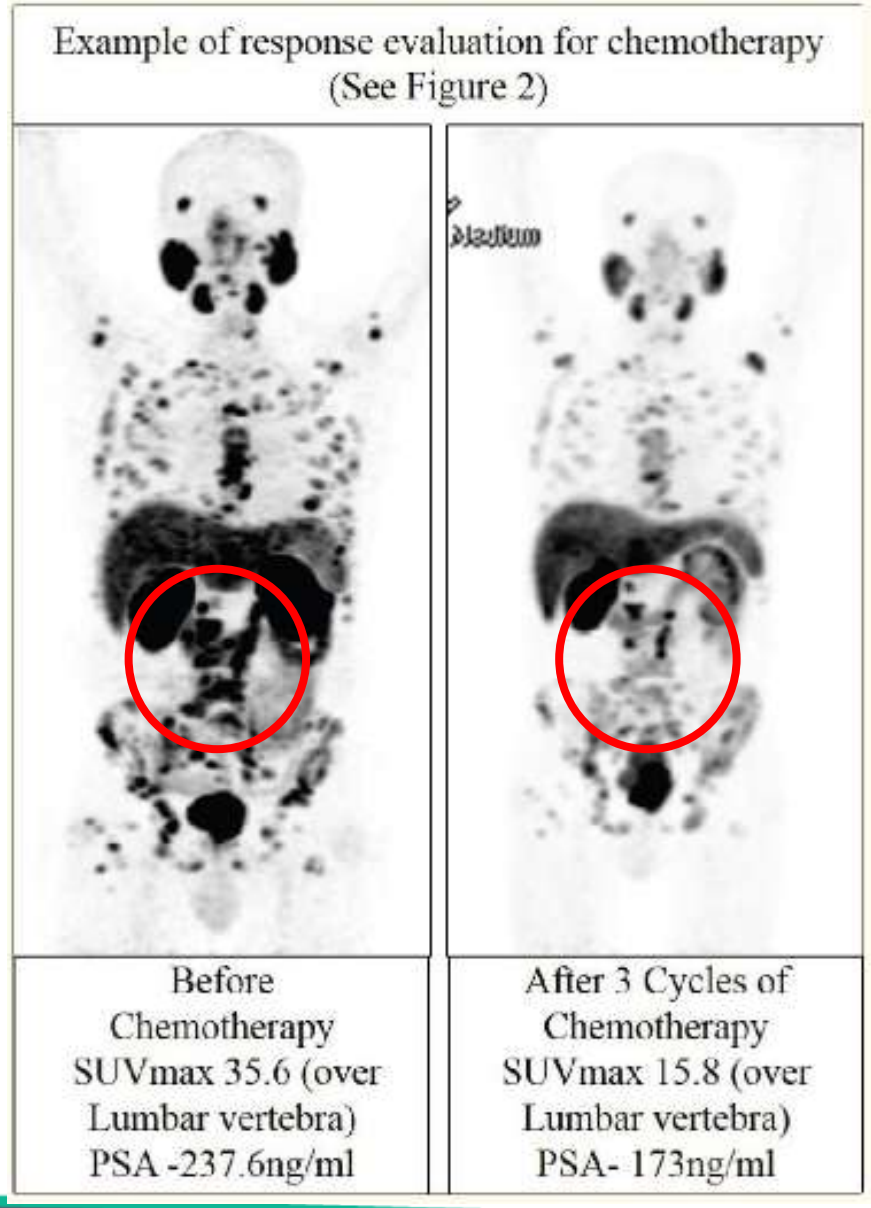
Normal uptake:
salivary/lacrimal glands,
liver, spleen, small and large
bowel, kidneys

Difference in hepatobiliary
and urinary excretion

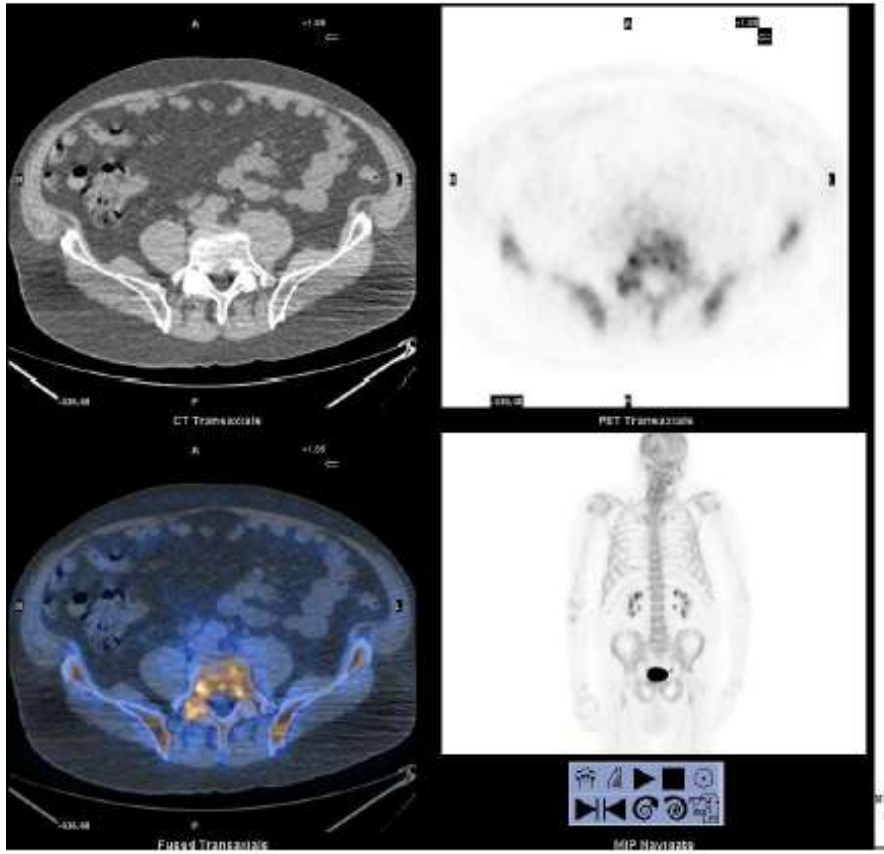


F-18 PSMA

Ga-68 PSMA example



$Na^{18}F$ example



Fluoride Bone Scan



Tc-99m HDP

Thank you for listening!