PET & PET/CT Instrumentation: Performance & Quality Control

Prepared by James R. Halama, PhD
Loyola University Medical Center
Maywood, IL

1. **Positron and Negatron Decay:**

   a) $p^{+} \longrightarrow n^{0} + \beta^{+} + \nu$ (positron decay). Proton-heavy nucleus converts a proton to a neutron and emits a positron (β+) and neutrino (ν)

   b) $n^{0} \longrightarrow p^{+} + \beta^{-} + \nu$ (negatron decay). Neutron-heavy nucleus converts a neutron to a proton and emits a negatron (β^{-}) and anti-neutrino (ν)

2. **Commercial Production of Positron Emitters**

Isotope	Half-life	Method
^{18}F	110 Min.	$^{18}O(p,n)^{18}F$*
^{11}C	20 Min.	$^{14}N(p,\alpha)^{11}C$
^{13}N	10 Min.	$^{13}C(p,n)^{13}N$
^{15}O	2 Min.	$^{14}O(d,n)^{15}O$
^{82}Rb	76 Sec.	$^{82}Sr/^{82}Rb$ Gen.

*** ^{18}F-FDG manufactured commercially**

3. **Positron Emitting Radiopharmaceuticals**

Radiopharmaceutical	Half-life	Physiological Measurement
F-18 FDG	110 Min.	Glucose Metabolism
C-11 Acetate	20 Min.	Prostate Cancer diagnosis
N-13 ammonia	10 Min.	Blood Flow
O-15 Oxygen	2 Min.	Oxygen Metabolism
Rb-82 chloride	76 Sec.	Cardiac Blood Flow

4. Positron Properties

a) Positively charged electron (the negatron) with the same mass

b) When emitted during positron decay, has a spectrum of kinetic energies up to the energy of decay, E_{max} of the β^+ particle

c) **Anti-electron** – when paired with an electron annihilates the electron, and vice versa

d) **Positronium** – paired electron orbits positron to form an atom-like structure for 87 psec $t_{1/2}$ before annihilation

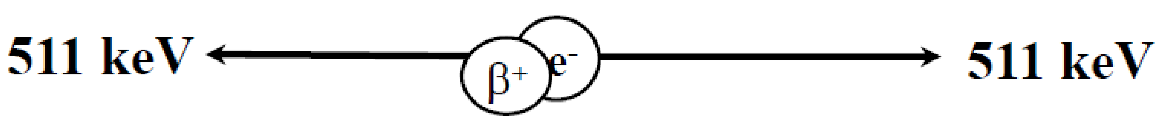
5. Positron-Electron Annihilation

a) Simultaneous emission of two 511 gamma rays leaving in opposite directions.

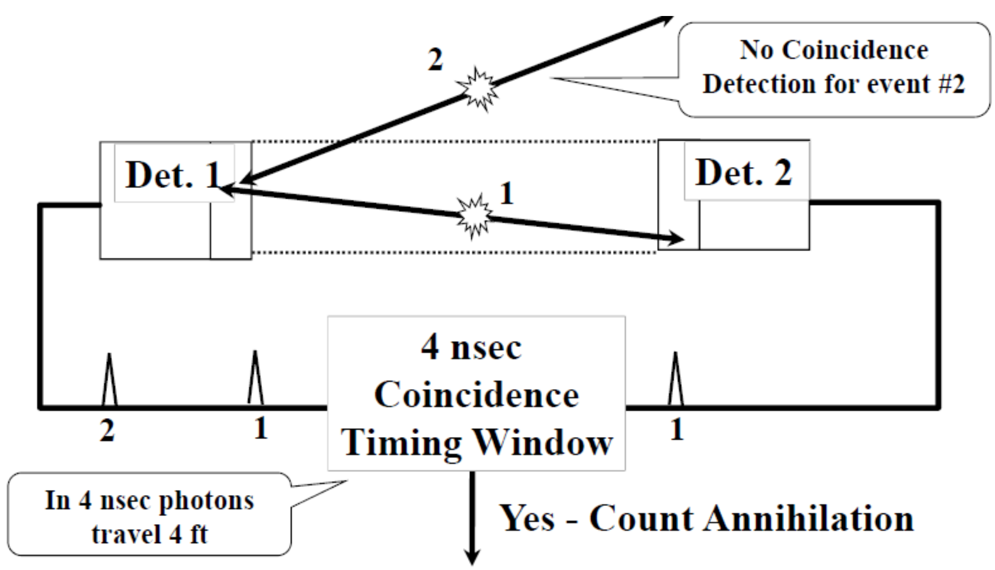
b) Satisfies conservation of energy law.

c) Satisfies conservation of momentum law – gamma rays have momentum.

d) diagram:



6. Count Annihilations by Coincidence Detection

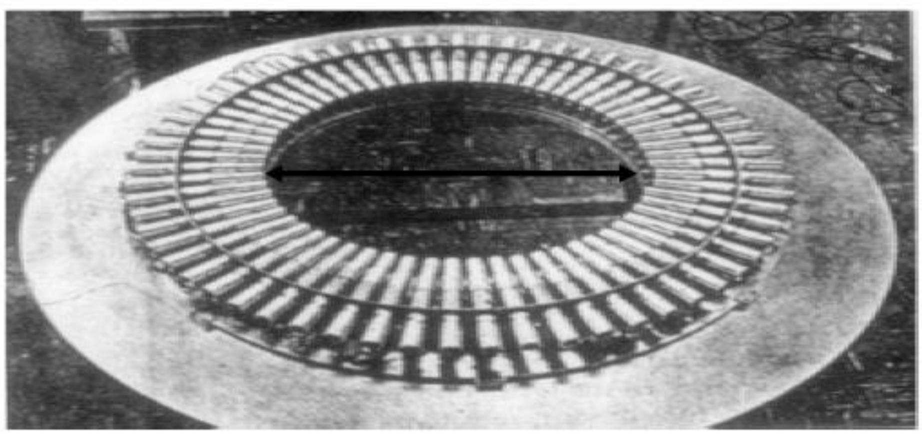


7. **Power of Coincidence Detection**

a) Sensitive only to annihilations in the volume between two detectors – provides spatial resolution
b) Electronic collimation - No lead collimation required
c) Higher sensitivity – 100 times more counts for the same activity compared to the gamma camera

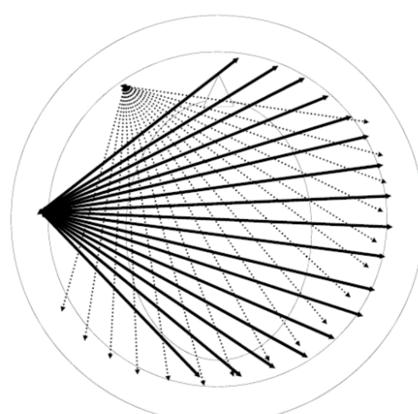
8. PET Scanner Design

a) Tomographic device with a complete ring of detectors
b) A single ring samples one slice in the patient
c) Detector material – Bismuth Germanate (BGO) chosen for high stopping power of 511 keV γ's

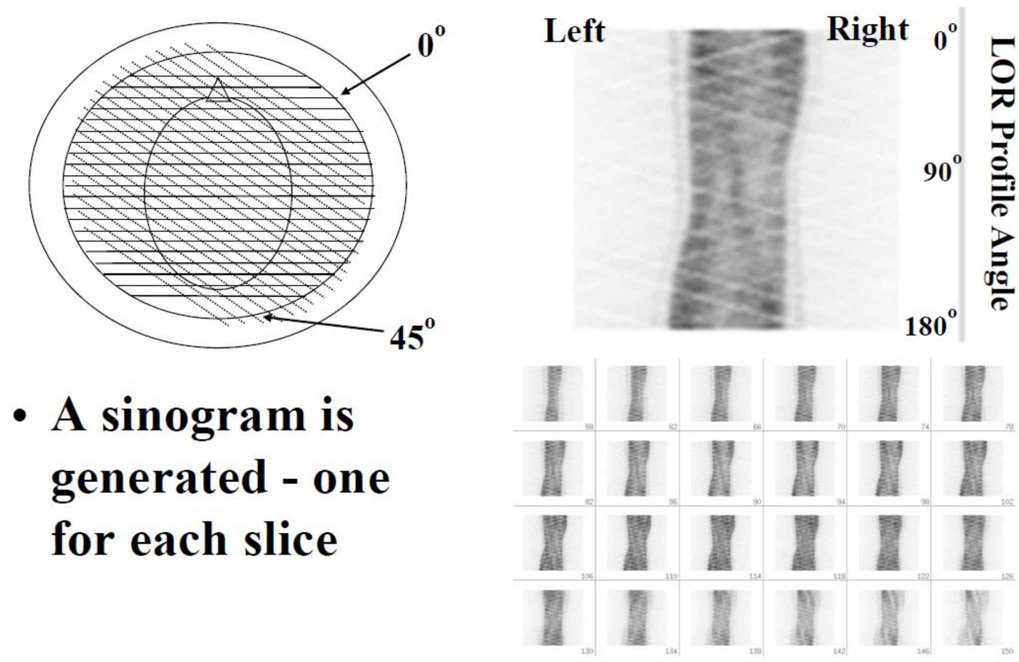


9. **One Detector Operated in Coincidence with Many Detectors**

a) Each detector is operated in coincidence with many detectors on the opposite side of the patient.
b) Acquisition geometry identical to fanbeam X-ray CT.
c) Lines-of-response measured over 360 degrees give complete projection image set for reconstruction.



10. Raw Data Stored as Sinogram



11. Tomographic Image Reconstruction

a) Filtered backprojection – not preferred

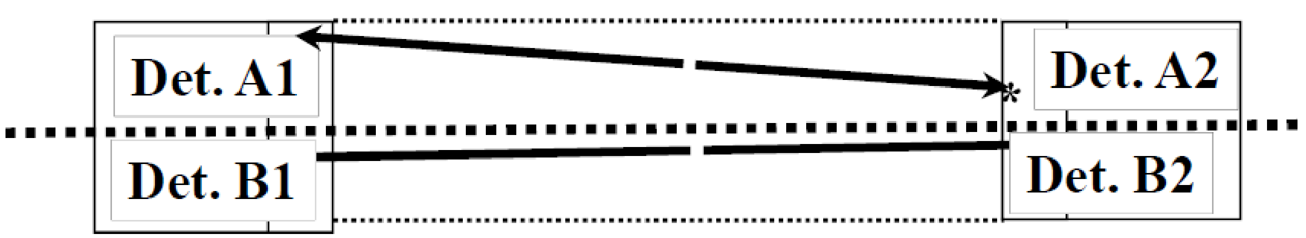
b) Iterative reconstruction by OSEM is preferred – it incorporates, random, scatter, and attenuation corrections

12. Better Spatial Resolution with Smaller Detectors

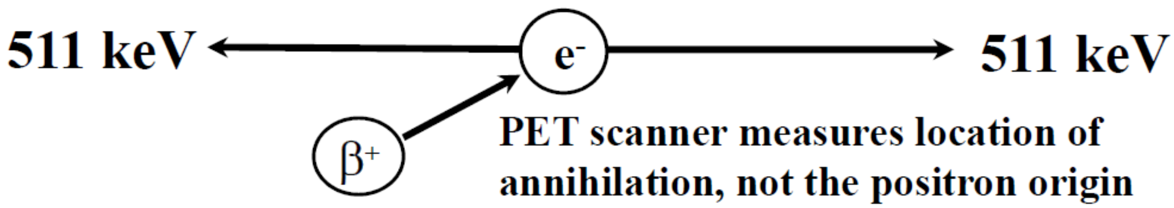
a) Resolution best with small detector elements.

b) Dividing detectors in half doubles the spatial resolution

c) Resolution best at object center.



13. **Positron Range Reduces Spatial Resolution**



Nuclide	Half-Life	Max β+ energy (MeV)	Max β+ range (mm) in soft tissue
^{11}C	20.3 min	0.97	4.1
^{13}N	9.96 min	1.19	5.1
^{15}O	122 sec	1.73	7.3
^{18}F	109.8 min	0.64	2.4
^{68}Ga	68.3 min	2.92	8.0
^{82}Rb	75 sec	3.38	10

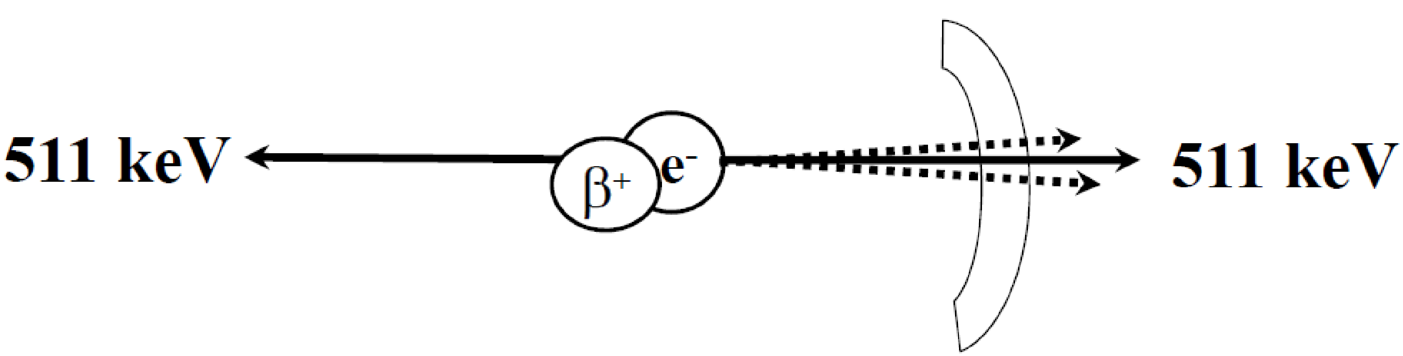
14. **Angular Variation Reduces Spatial Resolution**

a) 180° ± 1/4° variation in angular departure.

b) Resolution loss depends on separation distance of the two detectors

c) R_{loss} ~ 0.0024 * D where D is the diameter of the PET ring

d) For 50 cm diameter ring, R_{loss} ~ 1.2 mm.

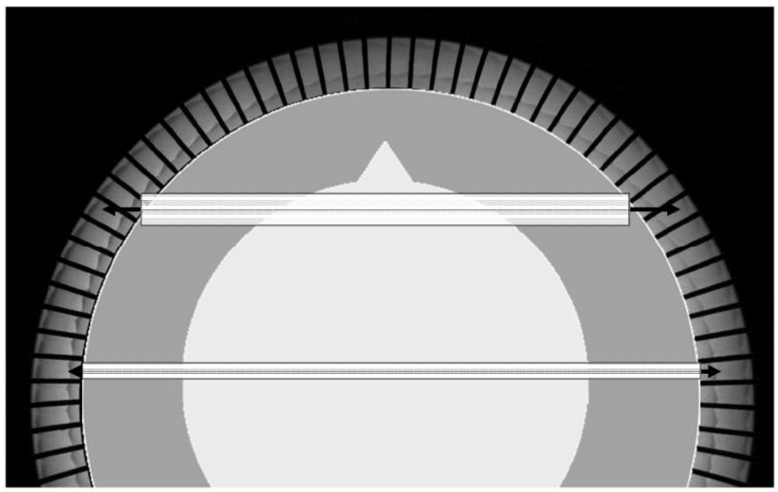


15. Parallax Error Reduces Spatial Resolution

a) Depth of interaction in crystal not accounted for.

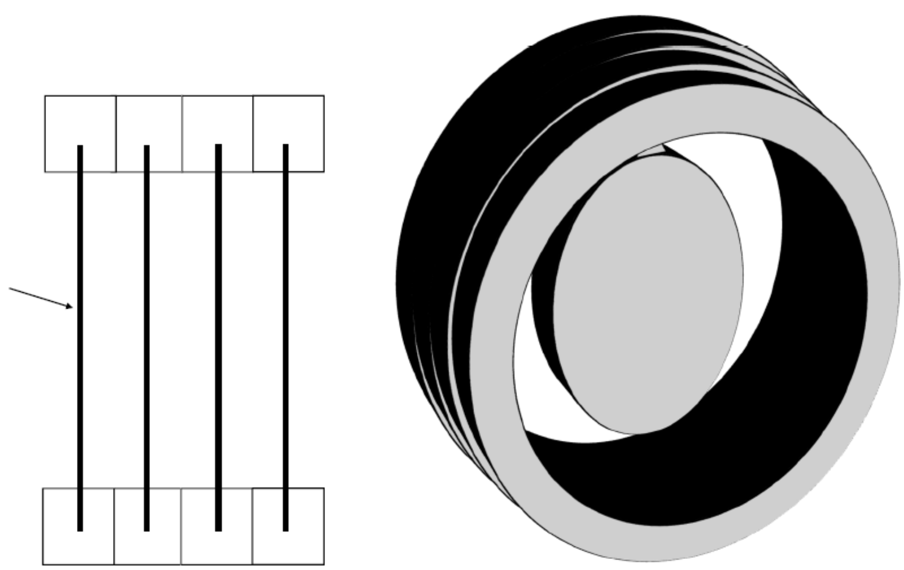
b) Leads to loss of spatial resolution at the periphery.

c) Best at the center.

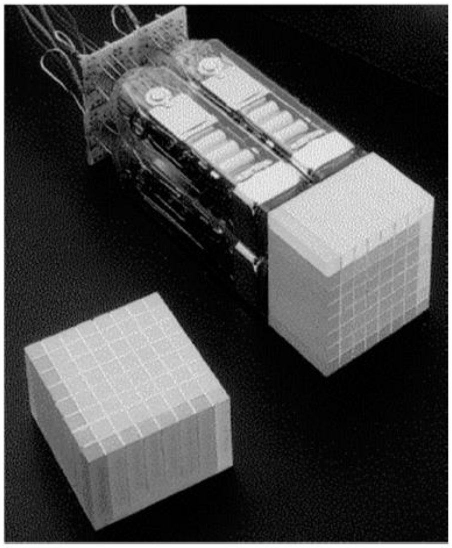


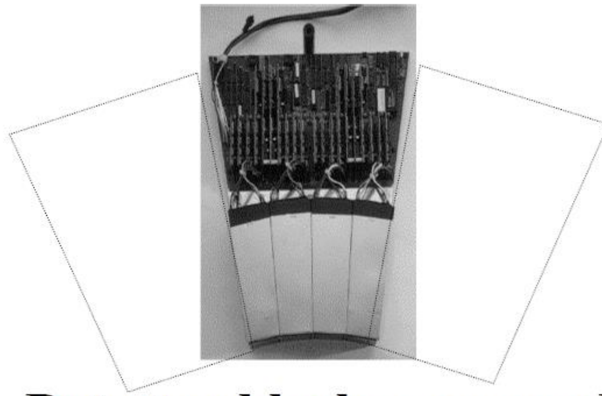
16. Multi-Slice Scanner with Multiple Detector Rings

Slice planes defined by each detector ring



17. PET Scanner Crystal Block Design



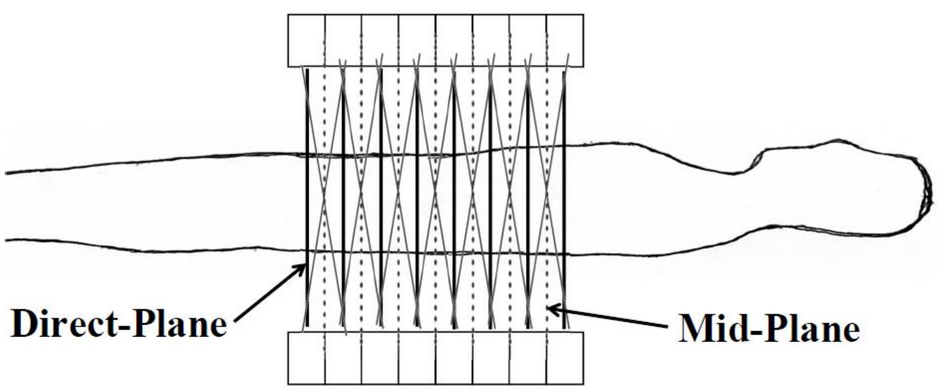


- **Detector blocks arranged to form a circle**
- **8x8 blocks in a circle form 8 rings of crystals**

18. 2D Acquisition Method

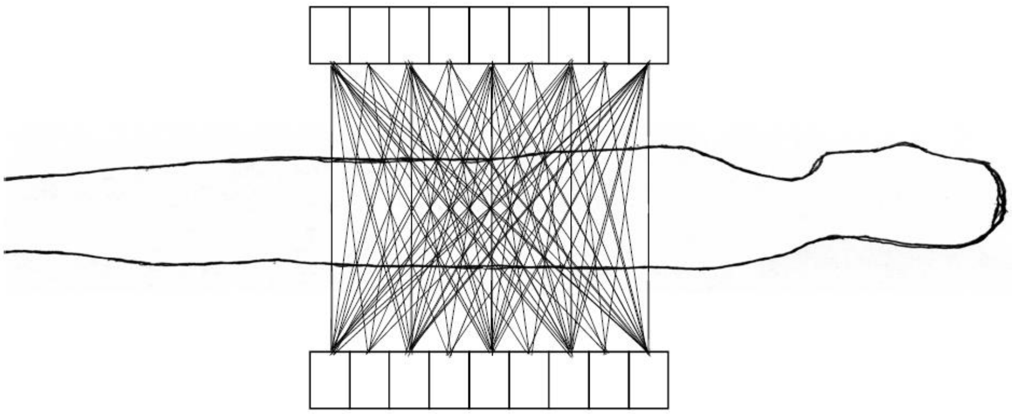
a) The system counts annihilations from within the direct plane of each detector ring and across adjacent rings & then sums to form a mid-plane slice with twice as many counts.

b) For an 8 ring scanner, 15 slices are acquired (2N-1)



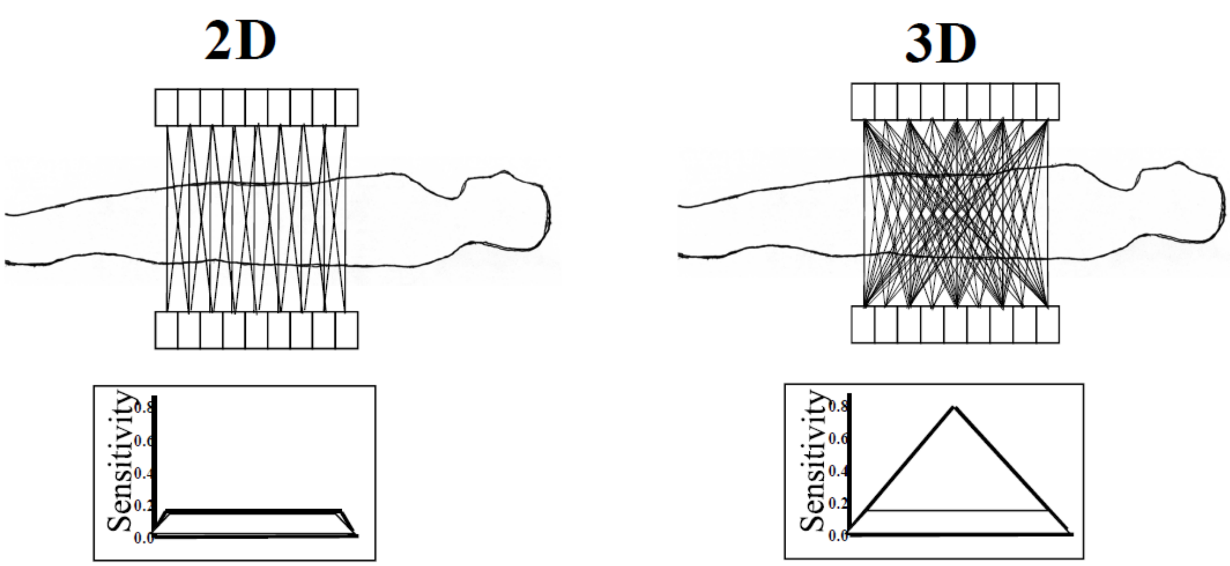
19. 3D Acquisition Method

a) Count annihilations across all possible slice-ring combinations. Five times more sensitive



20. Axial Sensitivity Profiles

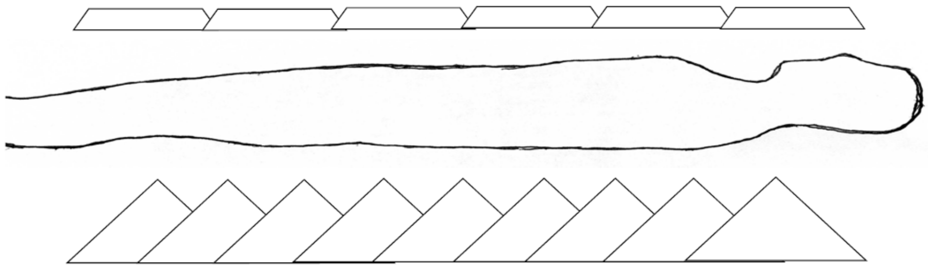
b) 3D sensitivity is peaked at the center



21. Whole Body Multiple Scan Protocols

a) 2D Acquisition with 10% Overlap at 5 min./stop. 30 min. acquisition for 6 stops

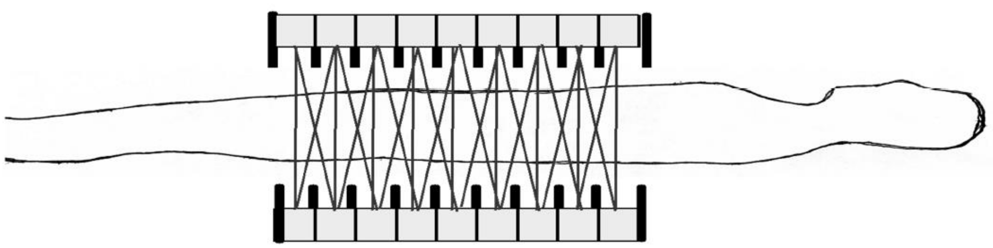
b) 3D Acquisition with 50% Overlap at 2 min./stop. 18 min. acquisition for 9 stops



22. 2D Septal Shielding

a) Lead septa inserted between each ring; allow only annihilation events to be counted from within the direct and adjacent slice planes.

b) Septa reduce dead time losses and scatter from the patient.



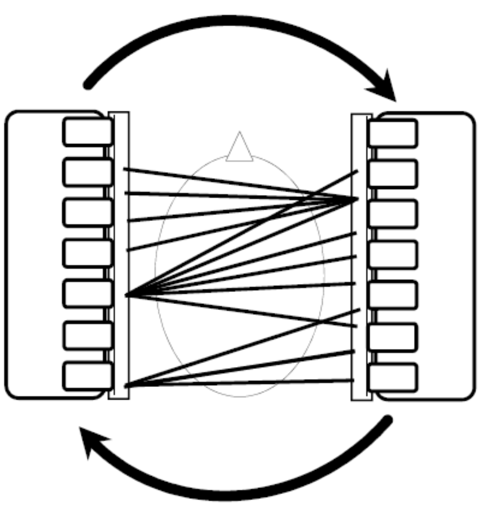
23. PET Detector Crystals

	NaI	BGO	LSO
Stopping Power	0.34/cm	0.92/cm	0.87/cm
Light Output	100%	15%	75%
Energy Resolution	10%	25%	15%
Decay Time	240 ns	300 ns	40 ns

24. Current PET Scanners

	GE PET/CT Discovery VCT	Siemens Biograph TruePoint PETCT	Philips GEMINI TF 64
Detectors	13,440 4.7x6.3x30 mm BGO	32448 4.0 x 4.0 x 20 mm LSO	28,336 4.0 x 4.0 x 22 mm LYSO
Stopping Power	95%	High	72%
Axial FOV (cm)	15.7	21.6	18
Number of rings	23	54	45
Acquistion Modes	2D / 3D	3D	3D
Slice Spacing (mm)	3.3	2	2.0 or 4.0
Resolution @ 10 cm (mm)	5.0	4.2	4.7

25. NaI Gamma Camera Coincidence Imaging Systems



	Philips/ADAC MCD	Philips/ Marconi PCD	Siemens e.cam Duet
Detectors	2 500x380x16 mm NaI(Tl)	2 or 3 470x593x19 mm NaI(Tl)	2 530x390x25 mm NaI(Tl)
Axial FOV (cm)	38	38	38
Number of planes	98	128	80
Spacing (mm)	3.9	3	4.8
Resolution @ center (mm)	4.8	4.8	4.7

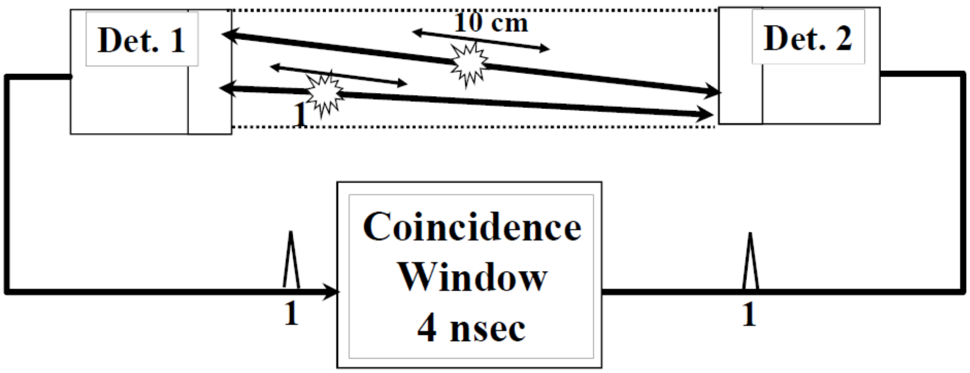
26. Time-of-Flight PET

a) In addition to recording the PET detector crystal pair, can also record the difference in arrival time (TOF).

b) Requires events to be stored in list mode

c) with each coincidence event, the detector pair and difference in arrival time are recorded

d) If timing resolution is 0.3 nsec, can measure origin to within 10 cm.

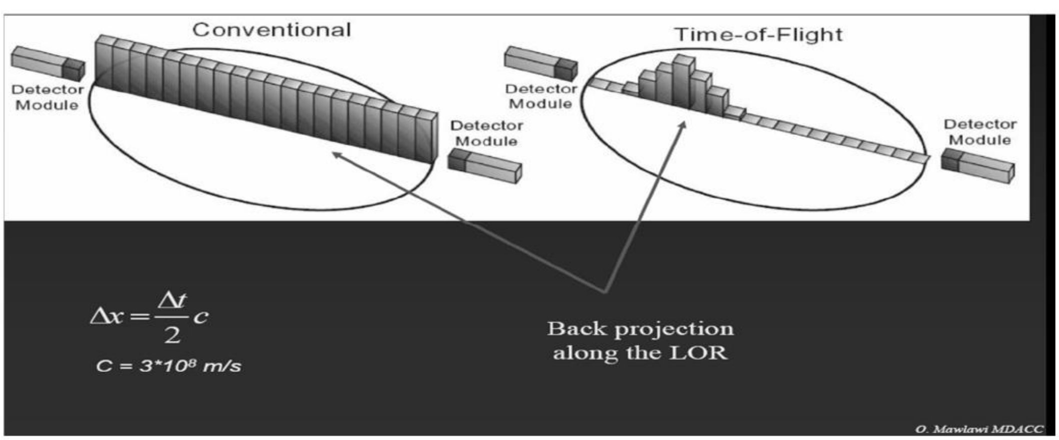


27. Time-of-Flight Reconstruction

a) In back projection a probability function for the annihilation origin is used to improve the reconstruction and image quality. Increased Signal/Noise ratio.

b) Perceived improvement in sensitivity because fewer counts may be needed.

c) Best for large patients. There is no advantage in children for scanner with 0.5 nsec timing resolution or greater.



28. Commercially Available PET/CT Scanners

a) Siemens Biograph (CT 16-64 slice)

b) GE ST Discovery (CT 8-64 slice)

c) Philips Gemini (CT 16-64 slice)

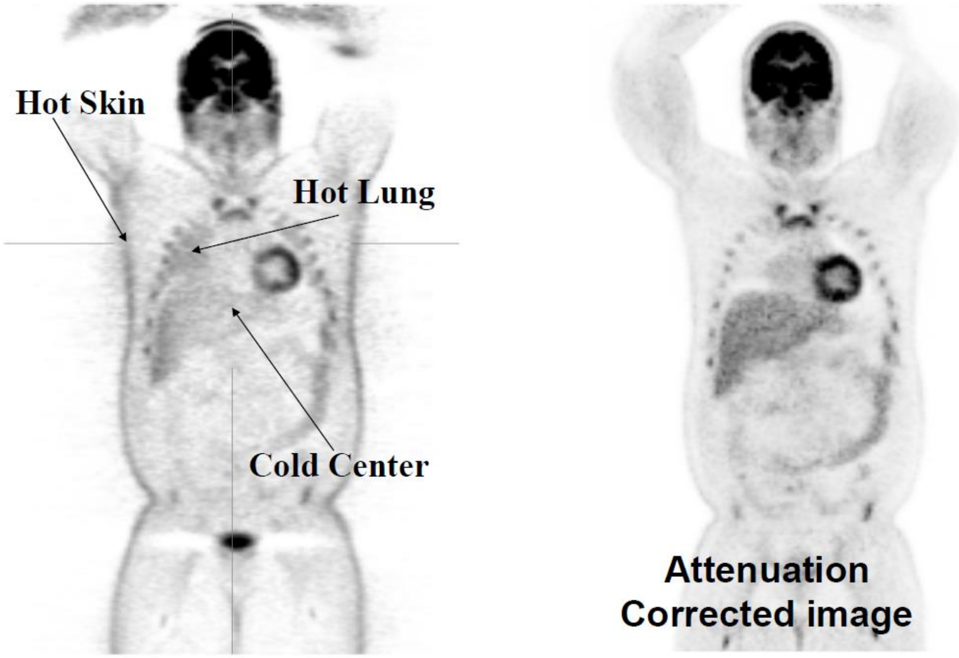
29. Fused PET/CT Image

a) 44-year-old female post hysterectomy and oophorectomy for cervical cancer

b) Fused PET/CT shows recurrence in the periaortic nodes

c) Fused on a single device

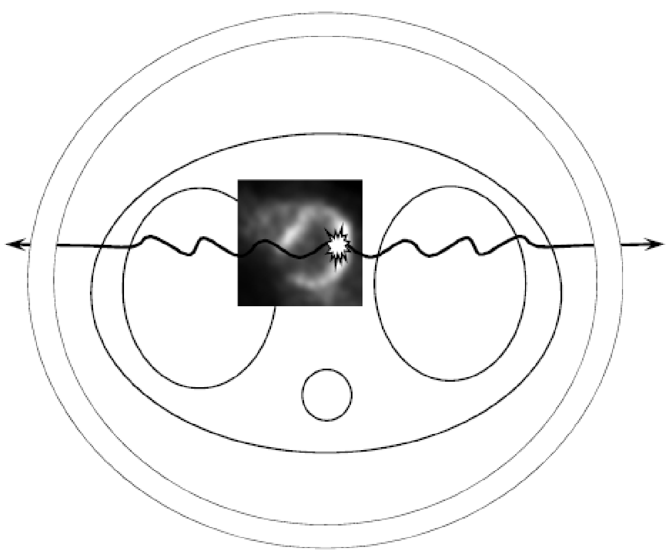
30. Attenuation Artifacts



31. Coincidence Detection Requires Both Photons to Exit

a) Combined path is total thickness of patient, leading to large artifacts.

b) Can calculate attenuation correction factors based on total patient thickness. Easy to apply a correction.



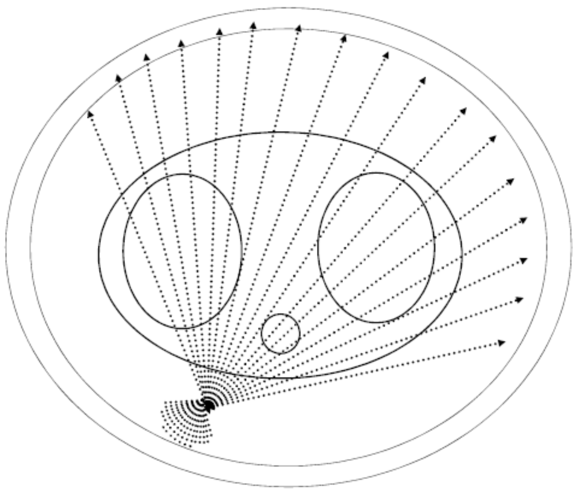
32. **Transmission Imaging with External $^{68}Ge/^{68}Ga$ source**

a) Measure transmission of 511 KeV annihilation photons from $^{68}Ge/^{68}Ga$ using rotating $^{68}Ge/^{68}Ga$ Source

b) ^{68}Ga – Positron emitter; $t_{1/2}$ = 1 hr

c) ^{68}Ge – Electron Capture; $t_{1/2}$ = 271 d

d) Required 5 min acquisition per bed position



33. **Transmission Imaging with Helical CT**

a) Continuous rotating x-ray tube and detectors based on slip-ring technology

b) Complete whole-body CT scan < 1 min

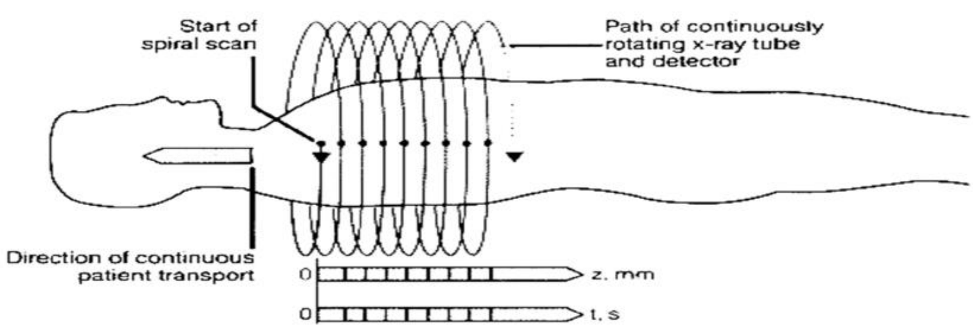
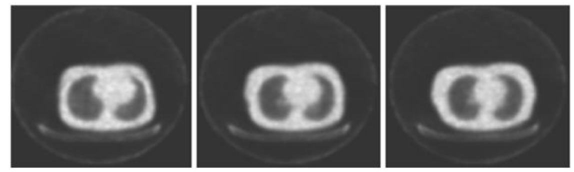


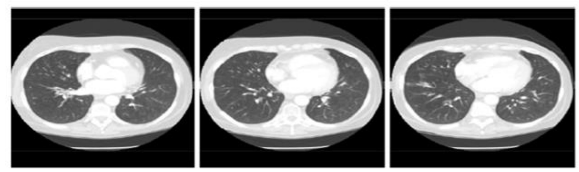
FIGURE 6–3. First step in spiral-helical CT: data acquisition. This figure illustrates that as the patient is transported through the gantry aperture, the x-ray tube traces a spiral path around the patient, collecting data as it rotates. (Courtesy of Siemens Medical Systems, Inc.)

34. Attenuation Correction Density Maps

Density map of chest using isotope; low resolution and noisy

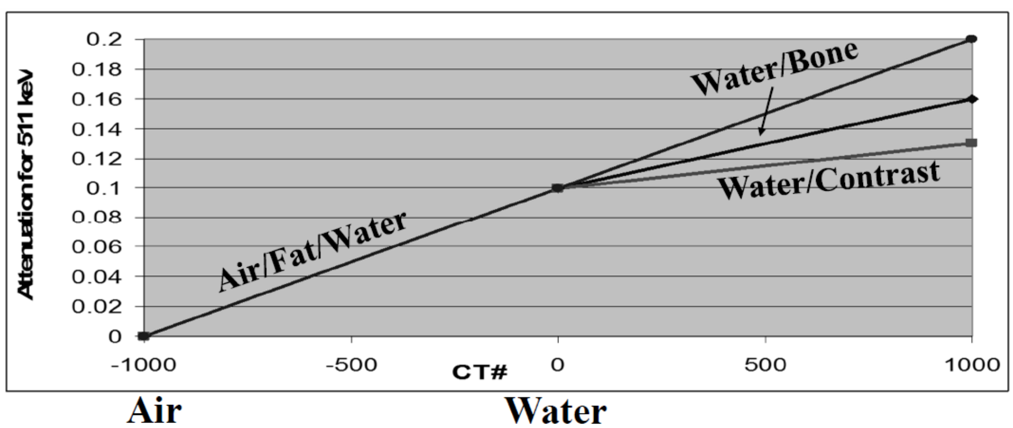


X-ray CT of Chest; much higher resolution



35. X-ray CT Attenuation Mapping

a) **Attenuation scale factors for bone and contrast media different than soft tissue.**
b) **Bi-linear mapping with lower slope for CT#'s > 0.**



36. Artifacts from CT Contrast

a) Presence of CT contrast during CT scan will cause artifacts in PET attenuation corrected images.
b) Linear attenuation coefficients at 60-70 keV of CT do not scale accurately to 511 keV for contrast media or other objects of high density.
c) CT contrast creates hot spot lesions in PET images.
d) Reference: Blodgett_ClinImag11_49.pdf

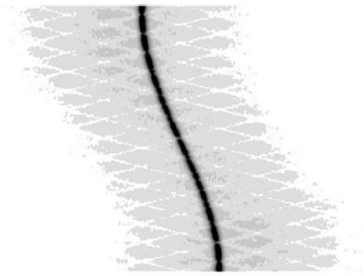
37. Quantitative PET

a) Measures uptake of a PET radiopharmaceutical, e.g., F-18 FDG in tissues and tumors.
b) Requires scan output to be recorded in units of activity concentrations (Bq/ml).
c) Requires several scanner corrections to be applied:
   i. Scatter
   ii. Randoms
   iii. Dead time
   iv. Attenuation

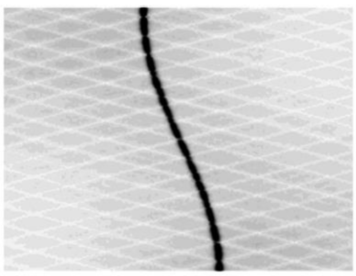
38. Total Coincidence Counts

a) Scatter accounts for ~ 15 (2D) - 40% (3D) of Total coincident counts. Can only be estimated.
b) Random counts may exceed the True counts. Can easily be measured by delay coincidence channel.
c) Scatter and Randoms add a background to the reconstructed images resulting in less contrast.

39. Distribution of Scatter & Randoms



Sinogram of line source with scatter. Scatter coincidence counts observed along-side the sides of the source.

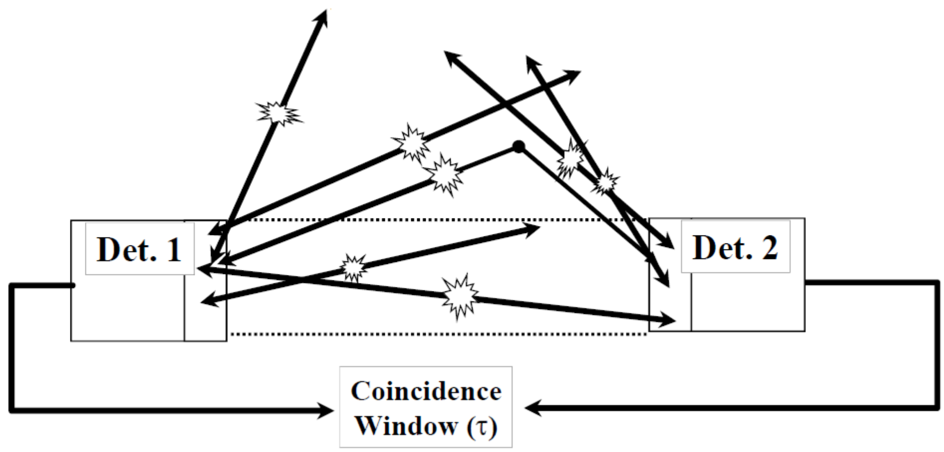


Sinogram of line source with scatter and randoms. Random counts uniformly added over the entire imaging volume.

40. Single Detector Count Rate

a) Singles Rate –Photon count rate on a single detector.

b) Singles/Coincidence Ratio is ~ 50:1



41. Random Count Rate

a) Random counts occur when two or more positron-electron annihilations occur.

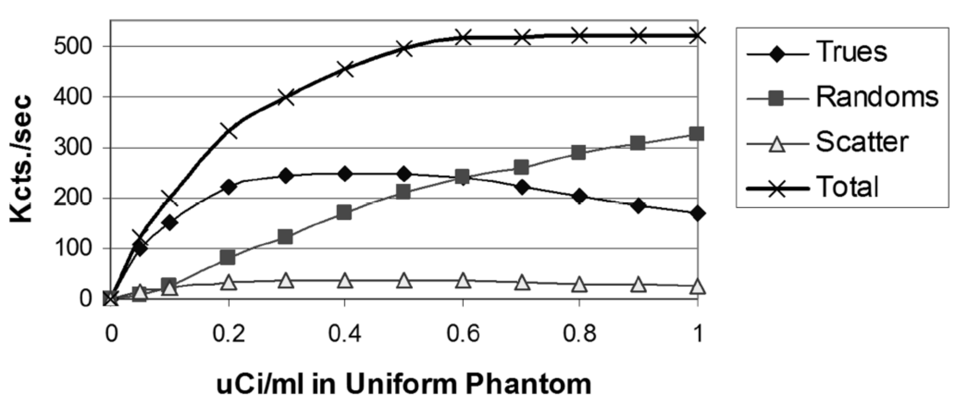
b) Random Rate = (Det 1 * Det 2) x t

c) Random Rate ~ (Singles Rate)^2 x t

42. Dead-Time Correction

a) Count rate response curve used to correct for count losses due to dead time.

b) Acquired over a 12-hr period.



43. Standardized Uptake Value

a) A unit-less value – g/ml; assume tissue density of 1 ml/g

b) Lean Body Mass may be used instead of Body Mass (SUV_{lbm})

c) SUV > 1 implies active uptake

d) SUV < 1 implies an exclusion of uptake

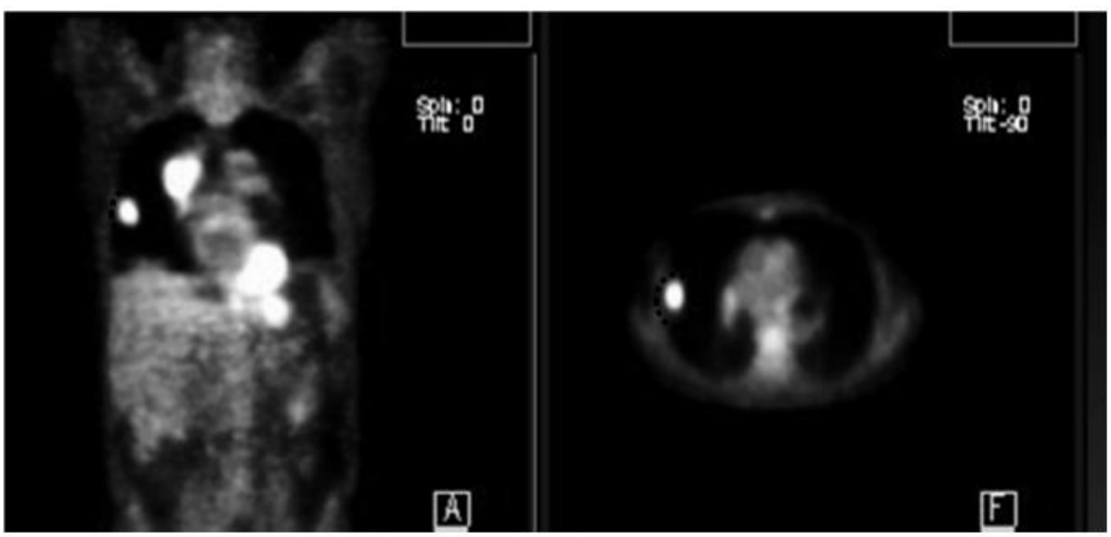
$$\text{SUV} = \frac{\text{Tissue FDG Concentration (Bq/ml)}}{\text{Injected Dose (Bq)/Body Mass (g)}}$$

44. VOI Extraction of SUV

a) Extract maximum counts, Bq/ml, or SUV in VOI.

b) Reduces errors in drawing of VOI, but subject to statistical variation within VOI.

c) SUV_{peak} with average of the nearest neighbors to reduce statistical variations.



45. Accuracy of SUV

a) Requires accurate

   i. Sensitivity calibration of the PET scanner.
   ii. measurement of patient weight.
   iii. measurement of injected activity and decay corrected to within 5 min.

b) Time dependent – SUV increases over time – for FDG, must scan patients within $\pm$ 10 min. time window.

c) Underestimated in small lesions of diameter < 3 x system resolution (~3 x 6 mm) due to partial volume averaging of normal tissue with lesion.

46. SUV - Other Patient Related Factors

a) Blood glucose levels

b) Patient activity

   i. patient remains in quiet sedentary state during uptake over a period of 60 min. or longer
   ii. Note prior muscular activity

c) Voiding of bladder prior to scanning

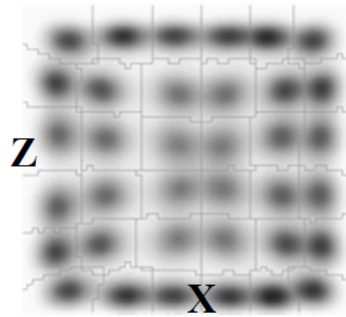
d) Radioactivity of prior NM study

e) Presence of contrast media

47. Calibrations & QC Tests

a) Energy and linearity
b) Normalization
c) Dead time & Timing
d) Sensitivity Calibration
e) Blank scan for attenuation correction (No CT)
f) PET/CT Calibrations

48. Anger Camera Logic Used in Multiple Crystal Blocked Detectors



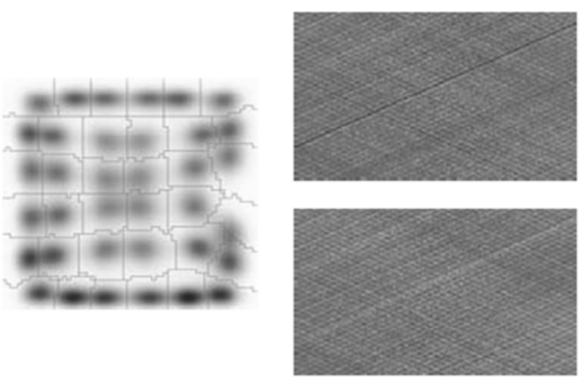
$$X = \frac{B+D}{A+B+C+D}$$

$$Z = \frac{C+D}{A+B+C+D}$$

Brad Kemp
Mayo Clinic

- **Each crystal produces a unique combination of signals in the PMTs.**
- **Refer *X* and *Z* to preset values in a 2D lookup table to map *X* and *Z* to a single crystal.**

49. PMT Gain, Energy & Linearity Calibrations



Erroneous mapping of crystals leading to errors in LOR mapping

- **New calibrations quarterly or that recommended by Vendor.**
- **PMT gain and energy stability checked daily.**

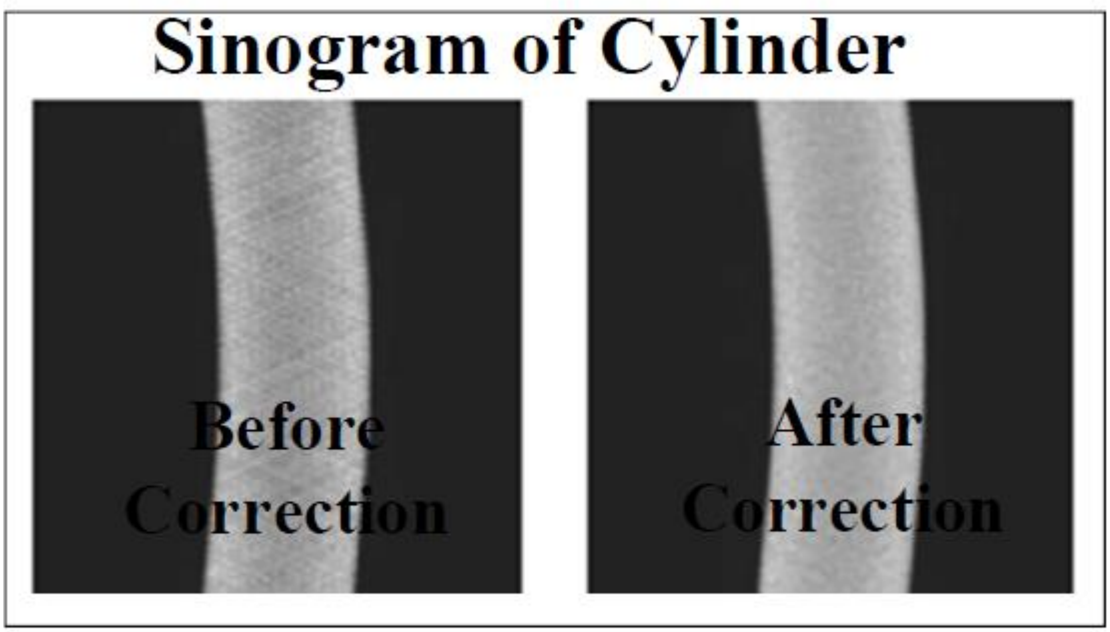
Brad Kemp
Mayo Clinic

50. Normalization – Uniformity Correction

a) Corrects for the variations in efficiency in LORs in the sinogram.

b) Measurement using a uniform source phantom

c) Acquired quarterly or after system maintenance.



Brad Kemp
Mayo Clinic

51. Timing & Dead Time Calibrations

a) Coincidence timing for every LOR – performed by FSE semi-annually or as specified by the Vendor.

b) Deadtime Calibration – Performed by FSE by scanning of 18F in a water filled phantom as the activity decays (~12 hours). Acquire semi-annually or as specified by the Vendor.

52. Sensitivity Calibration [$True_{corr}$ (cpm) / Bq/ml]

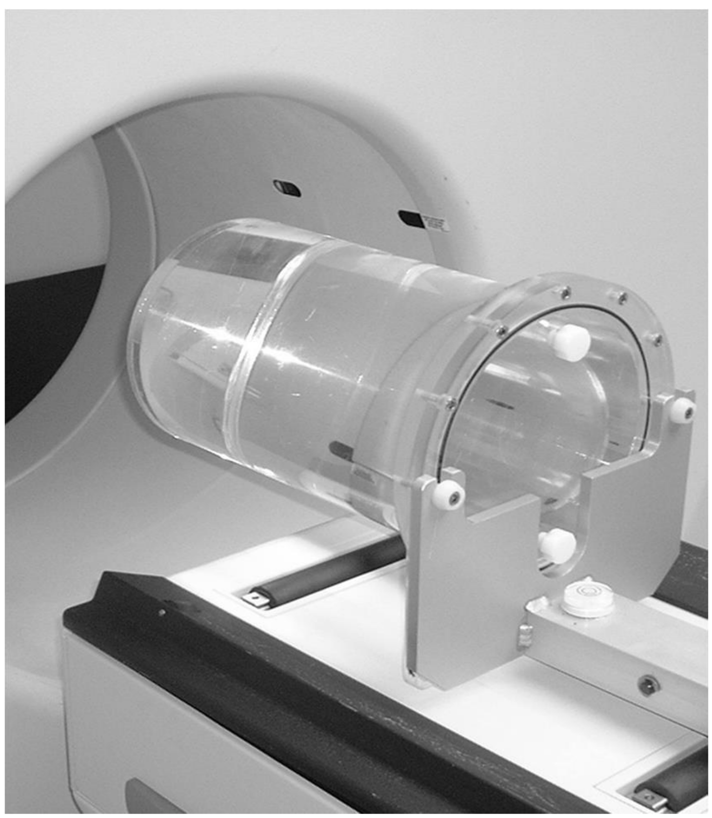
a) Fill water phantom with calibrated 18F activity. Decay correct to the minute to the time of image acquisition.

b) Calculate activity concentration in Bq/ml (9200 ml phantom).

c) Acquire and reconstruct image slice of phantom.

d) Measure counts in image slice and calculate sensitivity (cpm/Bq/ml).

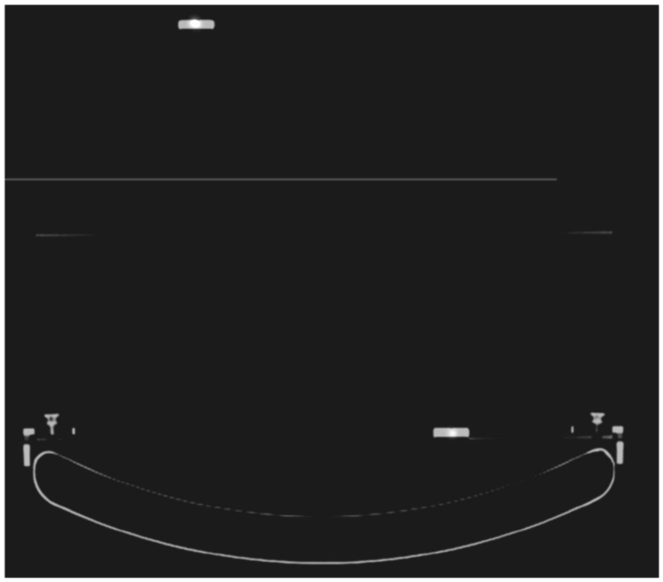
e) Expected SUV = 1.00



53. Test for PET/CT Alignment

a) Image 18F (or 22Na) point sources whose location seen on CT scan

b) Point source alignment to within 2 mm



54. CT Tests for PET/CT

a) Perform monthly CT# linearity test or that specified by the vendor.

b) Perform spatial & contrast resolution, slice thickness, & dose measurements as prescribed by CT department protocols.

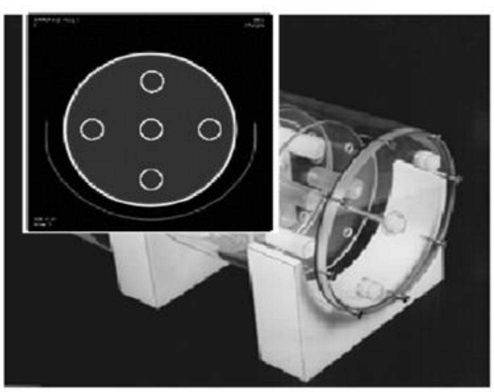
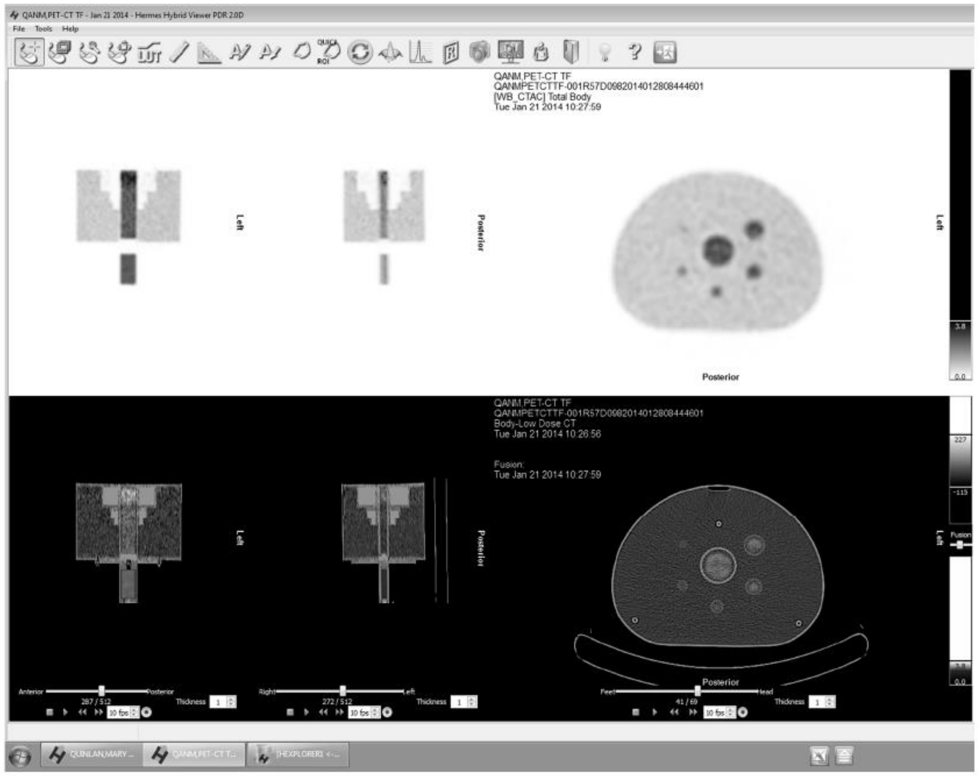


TABLE I. Phantom reference materials, corresponding linear attenuation coefficients and CT numbers.

Material	Attenuation coefficient	CT number
Ethylene	0.1790	− 87 ± 5
Styrene	0.1870	− 31 ± 5
Water	0.1932	0 ± 5
Lexan	0.2165	101 ± 5
Plexiglass	0.2165	121 ± 5

55. PET/CT Phantom



There is same activity concentration in the six spheres. Why does the SUV appear to differ?

PART 2. PET and PET/CT Shielding Requirements

56. Isotope Dose Rates

Isotope	γ-ray energy	photons/ 100 decays	Dose Rate (mSv-m^2/MBq-hr)
Tc-99m	140 keV	90	0.02
F-18	511 keV	193	0.143
F-18/Tc-99m Ratio	3.6	2.1	7.1

57. **Isotope Shielding Considerations**

Isotope	γ-ray Energy	HVL lead (11 g/cc)	HVL Tungsten (18 g/cc)
99mTc	140 keV	.27 mm	~ 0.2 mm
18F	511 keV	4.1 mm	2.9 mm
F-18/Tc-99m Ratio	3.6	15.2	14.5

58. **Radiation Dose – Areas of Concern**

a) Hot Lab

b) Patient Uptake Room

c) PET Scanner Room

59. **Hot Lab Shielded Dose Calibrator and 5 cm L-Block**

60. Handling the Isotope - Hand doses 100 times a patient dose

61. Whole Room Shielding

a) 0.5 inches lead for uptake room

b) 0.25 inches lead for scanner room

62. Portable Shields for Patients

a) Pb shields 2.5 and 5.0 cm thick are available

b) Dose reduction factors of 40 and 1900 respectively

c) Problems: Patient may move in relation to gantry and shield can limit access to patient

63. Shielding for CT

a) CT portion substantially the same as for any CT installation (~ 1/16" lead)

b) Techniques for CT - 140 kVp, 80 mAs and 125-150 cm axial length (non-diagnostic scan)

c) Patients/day less than CT only installation (may be increased for off hour use)

d) If shielded for PET – no additional shielding for CT

e) If not shielded for PET – shielding designed for CT may be required