Principles of PET/CT
Quality Control and Calibration

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Educational Objectives

- Review principles of PET and PET/CT imaging
- Overview of PET performance testing
  - NEMA NU-2 2001/2007 and ACR
- PET/CT Image Quality and Artifacts
- Recent advances in PET/CT

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Principles of PET Imaging

- Positron decay physics
- PET detectors design
- PET Lines-of-Response and Sinograms
- PET event types
  - prompt, true, scatter, random
- PET data processing
  - normalization, attenuation, scatter, randoms
- PET/CT
- PET calibration and SUV
- PET 2D/3D acquisitions

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Positron Decay

- Nuclei with low a neutron-to-proton ratio converts a proton to a neutron via emission of positron (β^+)

$p = n + \beta^+ + \upsilon$; ${}^{A}X_{Z} = {}^{A}Y_{Z-1} + \beta^+ + \upsilon$

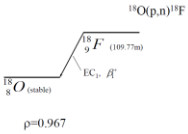
- Cyclotron (generator) for production of β^+ emitters

${}^{14}N(p,\alpha){}^{11}C$ ${}^{16}O(p,\alpha){}^{13}N$ ${}^{13}C(p,n){}^{13}N$ ${}^{14}N(d,n){}^{15}O$
${}^{15}N(p,n){}^{15}O$ ${}^{16}O(p,pn){}^{15}O$ ${}^{18}O(p,n){}^{18}F$ ${}^{20}Ne(d,\alpha){}^{18}F$

- Electron capture competes with positron decay

${}^{A}X_{Z} = {}^{A}Y_{Z-1}$ + X-rays

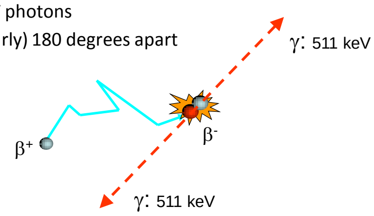
  - Branching Ratios
  - ${}^{18}F = 0.967$



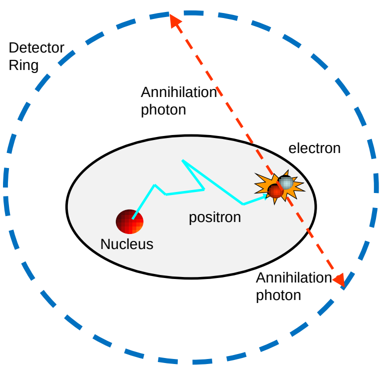
Reproduced From MIRD: Radionuclide Data and Decay Schemes

Annihilation Photons

- Energy spectrum of β^+ emission is continuous
- β^+ range depends on energy
  - ${}^{18}F$: E_{max} = 0.64 MeV, Range ~1 mm
  - ${}^{82}Ru$: E_{max} = 3.15 MeV, Range ~2 mm
- β^+ annihilation results in simultaneous emission of
  - Two 511 keV photons
  - Emitted (nearly) 180 degrees apart

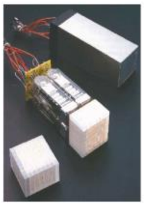


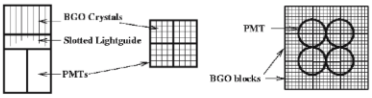
Schematic of a PET scanner

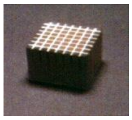


PET detectors

Scintillator	Relative light output [NaI(Tl) = 100]	Decay time (ns)	Thickness for 90% efficiency at 511 keV (cm)
BGO	15	300	2.4
GSO	25	60	3.3
LSO, LYSO	80	40	2.7







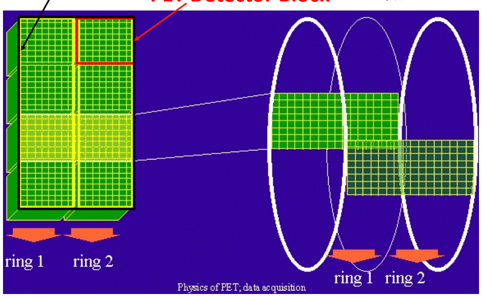
PET Detector Block

PET Detector Module and Rings

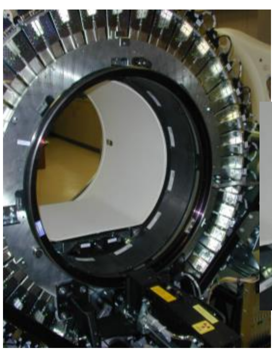
PET Detector Module

PET Detector Block

http://www.nucmed.buffalo.edu

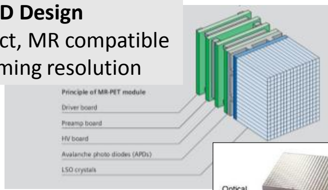


PET Scanner – Covers Off



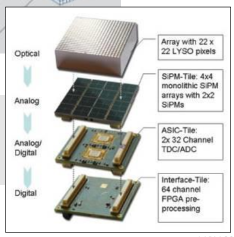
New PET Detector Concepts

PET APD Design
Compact, MR compatible
Poor timing resolution



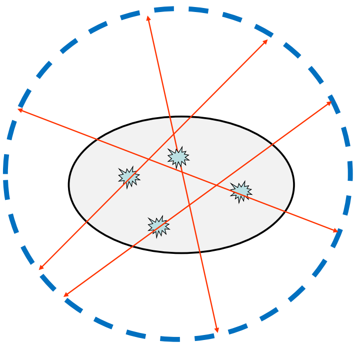
Siemens PET-MR

PET GM-APD or SiPM
Compact, MR compatible
Good timing resolution



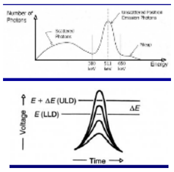
http://www.hybrid-pet-mr.eu

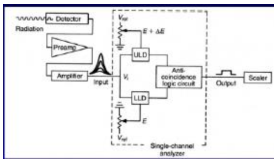
PET Detector Ring



PET Signal Processing – Singles

- Detector block/module (scintillator/PMT) converts gamma ray energy to voltage pulse
- PHA: Event trigger and energy thresholds to select 511 keV (450-650 keV)
- Location of event in crystal block/module (Anger logic) and event time

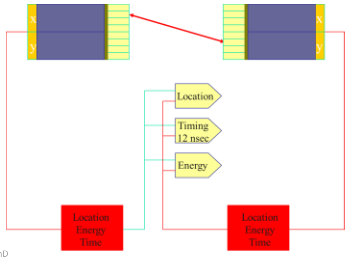




Cherry, Sorenson, & Phelps, Physics of Nuclear Medicine, 2003

Record the Line-of-Response

- Fundamental prerequisite to PET imaging
  - Photon (Singles) detection and processing
  - Coincidence assessment of singles events
  - Data storage and processing



LOR to Sinograms

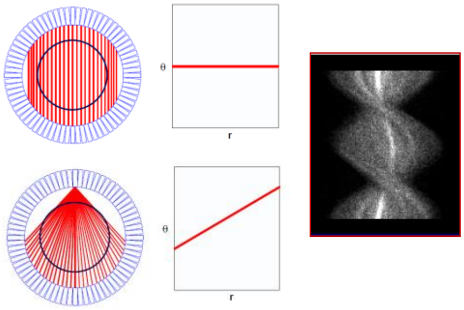
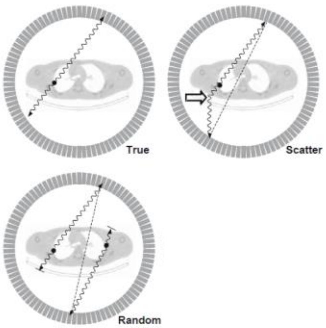


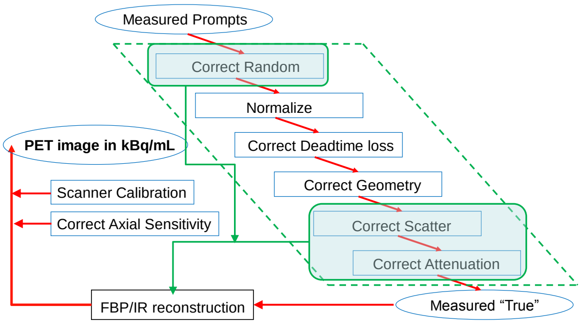
Image Courtesy: Magnus Dahlbom

PET Coincident Events – Prompts



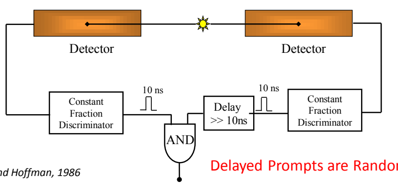
Bailey, Townsend, Valk, Maisey, "Positron Emission Tomography," Springer-Verlag, 2005

PET data corrections



Randoms Correction

1) Randoms Rates from Singles Rates, R = 2τ x S1 x S2
   - Randoms are proportional to S^2
   - Statistically more accurate since S>>R
2) Randoms Rates from Delayed Prompts (Δt >> 10 ns)
   - Real-time subtraction
   - Identical deadtime characteristics to Prompts channel
   - Requires more memory and statistically less accurate



Casey and Hoffman, 1986

Delayed Prompts are Randoms

Normalization (uniformity correction)

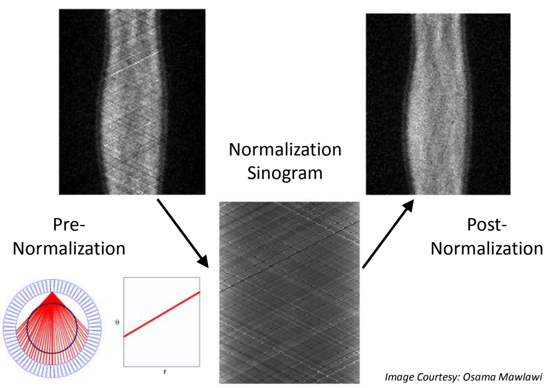
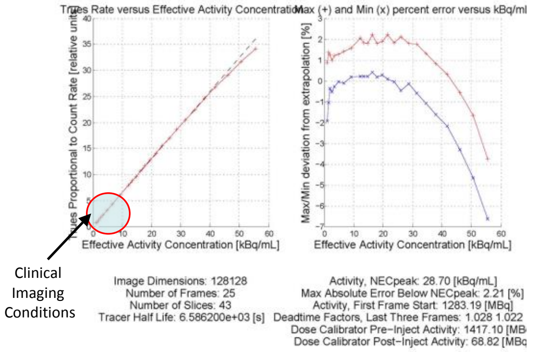


Image Courtesy: Osama Mawlawi

Deadtime Correction (Siemens mCT)



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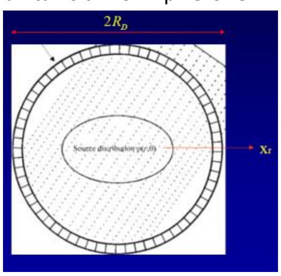
Geometry Correction

- Ring detector introduces non-uniform sampling of LOR away from isocenter
- Geometry correction maintains uniform pixel size in transverse plane

$$\boxed{\Delta x_r = \Delta d_t \sqrt{1-(x_r / R_D)^2}}$$



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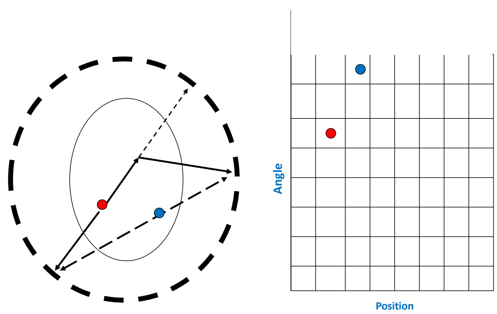
Scatter mis-positions LOR in Sinograms



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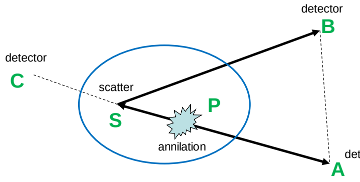
Model-based Scatter Estimation



Idea: To estimate the number of scattered coincidence along a specific LOR

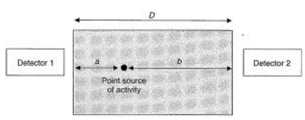
(LOR AB in figure)

Ollinger, Phys. Med. Biol. 41 (1996) 153-176

Assume an annihilation at point P,
- Compute probability the photons originate along AC
- Compute the probability that the one of the photon is detected at A
- Compute the probability of second photon scattering at location S
- Compute the fraction of events scattered toward B (Klein-Nishina formula)
- The probability that the scattered photon is detected at B

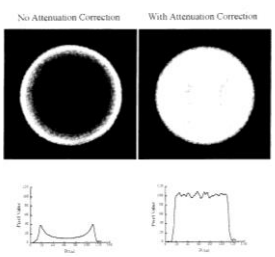
Input: PET emission image, CT transmission image, LOR AB
Output: Scatter along LOR AB

PET Signal Attenuation



$P = P_1 \times P_2$
$= e^{-ua} \times e^{-ub}$
$= e^{-u(a+b)}$
$= e^{-uD}$

Attenuation of PET coincident events depends on total object thickness only – it is independent of source location



Nuclear Medicine: Diagnosis and therapy, Harbert, Eckelman, & Neumann

CT-based Attenuation Correction

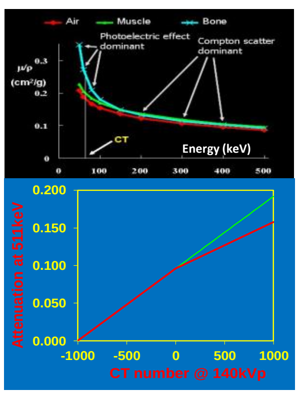
$$HU_x = \frac{\mu_x(E_{CT}) - \mu_w(E_{CT})}{\mu_w(E_{CT})} \times 1000$$

$$\mu_x(E_{CT}) = \left(1 + \frac{HU_x}{1000}\right) \times \mu_w(E_{CT})$$

$$\mu_x(E) = \left(1 + \frac{HU_x}{1000}\right) \times \mu_w(E) \times \overbrace{\left(\frac{\mu_w(E_{CT})}{\mu_x(E_{CT})} \times \frac{\mu_x(E)}{\mu_w(E)}\right)}^{K}$$

- Photon energies different between CT and SPECT
- K≈1 for Compton Scatter dominates low Z at ECT (low HU)
- K≠1 for Photoelectric pertinent for high Z at ECT (high HU)
- HU-to-µ transform is piece-wise linear (bi-modal)

LaCroix et al., IEEE TNS 41, 1994
Kinahan et al, Med Phys 25, 1998



PET/CT w/ and w/o AC

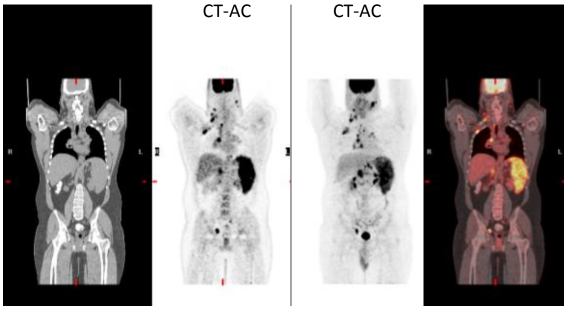
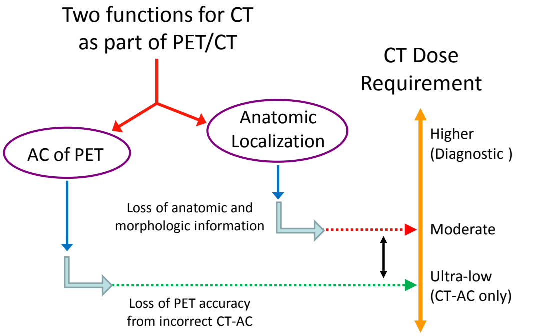


Image Courtesy: Osama Mawlawi

Role of CT in PET/CT



PET Scanner Calibration

- Perform PET scan with low known activity
  - Low scatter and deadtime conditions
  - Uniform cylinder – simple attenuation correction
- Convert PET true count rate (cps) into activity concentration (Bq/mL)
- PET Standard Uptake Values $\left[\frac{Bq/mL}{Bq/mg}\right]$

$$\mathrm{SUV} = \frac{\text{decay-corrected dose/ml of tumor}}{\text{injected dose/patient weight in grams}}$$

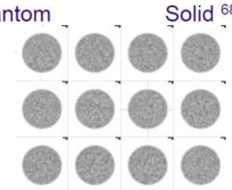
$$\mathrm{SUV}_{\mathrm{lean}} = \frac{\text{decay} - \text{corrected dose/ml of tumor}}{\text{injected dose/patient lean body mass in grams}}$$

PET Calibration Phantoms

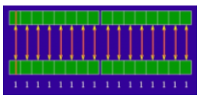
Water Phantom

Solid ^{68}Ge Phantom

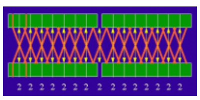
NIST traceable F-18 STD
"S" vial geometry



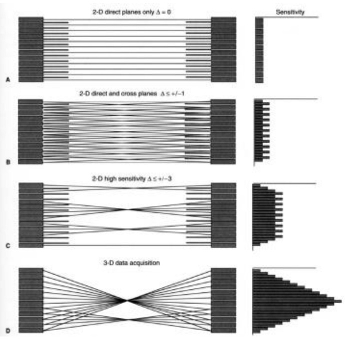
2D versus 3D PET



Detector Center Plane
Δ = 0; Planes = 1; Images = 16



Detector in-between Planes
Δ = 1; Planes = 2; Images = 15
Δ = 2; Planes = 3; Images = 14
Δ = 3; Planes = 4; Images = 13



Cherry, Sorenson, & Phelps, Physics of Nuclear Medicine, 2003

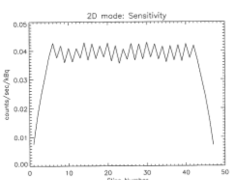
PET Sensitivity NEMA (GE DRX)

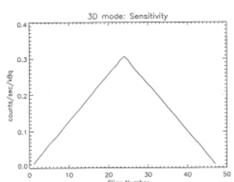
2. NEMA NU2-2001: Sensitivity (8-23-2006)

Activity:
Line: 211.2 uCi @ 17:01

Table of sensitivity (cps/kBq)

	2D @ 0 cm	2D @ 10 cm	3D @ 0 cm	3D @ 10 cm
Sensitivity	1.693	1.711	7.371	7.623



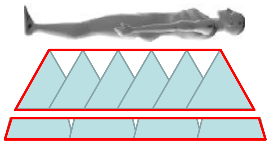


2D versus 3D PET

- 2D PET: Collimation septa present between detector planes in axial direction
  - Reduces scatter; Uniform AX sensitivity (1 cm bed overlap)
- 3D PET: No collimation present except at end of ring
  - Sensitivity 3D > 2D → lower activity needed
  - Randoms & Scatter 3D > 2D; Improvements in modeling of the random and scatter events → Standard Acq. mode
  - Triangular AX sensitivity profile (~50% detector overlap)

3D PET: Higher Sensitivity + Greater No. of Beds

2D PET: Lower Sensitivity + Fewer No. of Beds



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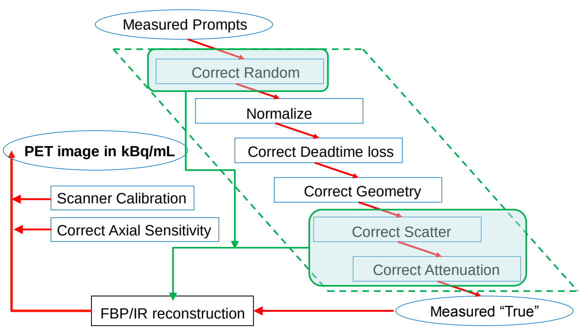
PET data corrections



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SAM Question 1

The attenuation of PET coincident events emitted from the patient depends on the:

38% A. Patient diameter or size

33% B. Location of annihilation event in the patient

19% C. Radiopharmaceutical administered

10% D. CT scan technique

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SAM Question 1: Answer

- The attenuation of PET coincident events emitted from the patient depends on the:
  A. Patient diameter or size
  B. Location of annihilation event in the patient
  C. Radiopharmaceutical administered
  D. CT scan technique
- **Answer: A – Patient diameter or size**
- *Reference: SR Cherry, JA Sorenson, ME Phelps, "Physics in Nuclear Medicine, 3rd Edition," Saunders Elsevier, 2003*

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SAM Question 2

The well counter calibration for a PET scanner is used to:

15% A. Correct for variations in image uniformity
23% B. Correct for variations in detector gains
15% C. Correct for differences in detector coincidence timing
8% D. Convert count rate (cps) to activity concentration (kBq/mL)

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SAM Question 2: Answer

- The well counter calibration for a PET scanner is used to:
  A. Correct for variations in image uniformity
  B. Correct for variations in detector gains
  C. Correct for differences in detector coincidence timing
  D. Convert count rate (cps) to activity concentration (kBq/mL)
- **Answer: D – Convert count rate (cps) to activity concentration (kBq/mL)**
- *Reference: SR Meikle, RD Badawi, "Quantitative Techniques in PET," in Positron Emission Tomography, eds. DL Bailey, DW Townsend, PE Valk, and MN Maisey, Springer-Verlag (London), 2005*

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PET NEMA NU2-01/07 (2D/3D)

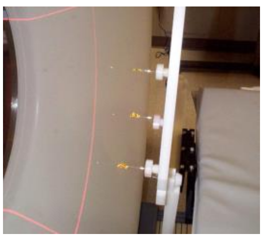
NEMA Tests

- Spatial Resolution
- Sensitivity
- Scatter Fraction/Count Rate Performance
- Image Quality
- Accuracy of correction for count losses and randoms

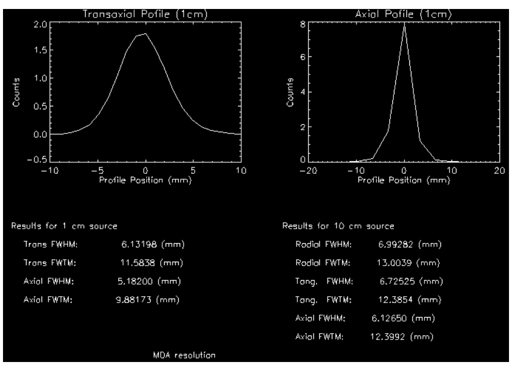
Daube-Witherspoon M. et al JNM, 43(10) 1398-1409, 2002

NU2-01/07 Spatial Resolution Setup

- Point Sources are located at (0,1), (0,10), (10,0) cm
- 6 mCi/cc, Capillary tube sources ~ 1 µL active volume
- Reconstruct FBP, 256x256 matrix, 25 cm FOV, apply all correction but no filtration



NU2-01/07 Spatial Resolution



NU2-07 Spatial Resolution

NEMA 2007 Resolution Test Results
Image Size: 256 x 256
Scanner Model 1103
Date Processed: Tue Aug 27 14:06:57 2013

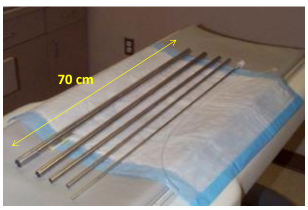
Average Net Trues : 2874152.4 counts
Corrections Applied :
normalization
deadtime
radial-arc-correction
decay-correction
frame-length-correction
fore
randoms-subtraction

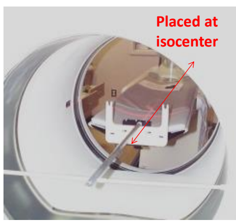
Method of Reconstruction : FORE+FBP
Image Size : 256 x 256 x 81
Image Zoom : 1.0
XY Filter : 0.0 mm
Z Filter : 0.0 mm

Radial Distance (cm)	Direction	FWHM (mm)	FWTM (mm)
1	Transverse	4.75	9.44
1	Axial	4.06	8.07
10	Transverse Radial	5.66	10.55
10	Transverse Tangential	5.53	11.26
10	Axial Resolution	5.43	10.35

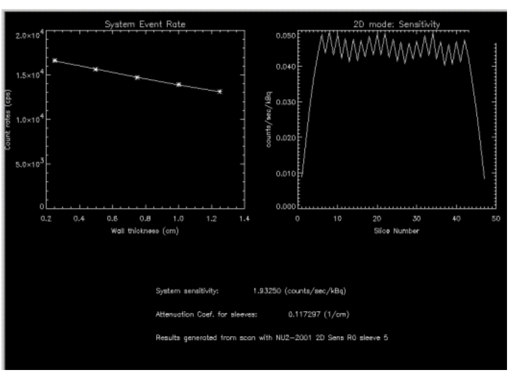
NU2-01/07 Sensitivity Setup

- Detected coincidence count rate per unit activity in FOV
- 250 µCi in ~70 cm 2.4 mL line source → 5 Aluminum Sleeves
- Sensitivity measured with increasing amounts of attenuating material and extrapolated to no attenuation





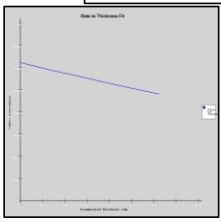
NU2-01/07 Sensitivity: 2D @ R=0

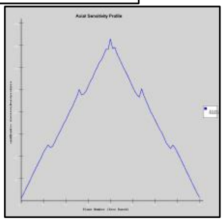


NU2-07 Sensitivity: 3D @ R=0

NEMA 2007 Sensitivity Test Results
Scanner Model 1103
Date Processed: Tue Aug 27 16:58:53 2013

Nuclide :	F18
System Sensitivity (STOT) :	5851.8 cps/MBq
Detector Efficiency :	0.59 %
Effective mu :	0.207 cm^-1
Lower Level Discriminators :	435 keV
Upper Level Discriminators :	650 keV
Initial Activity :	4.081 MBq
	0.110 mCi
Average Net Trues :	5659855.6 Counts

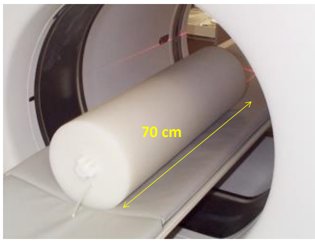




NU2-01/07 SF & CR Performance Setup

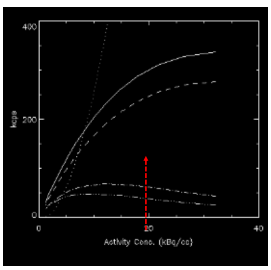
- SF measures the sensitivity of scanner to coincidence events caused by scatter
- CR measures the performance of the PET scanner across a range of radioactivity levels
- ~40 mCi (3D) in 70 cm 4.8 cc line source

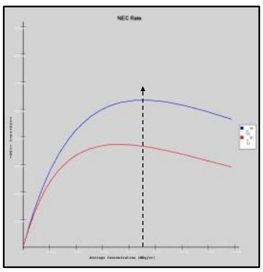
- Dynamic data acq. as 4x15min and 14x25min with 25 min delays
- Total time is ~13 hr
- Analysis performed on sinograms with no corrections applied



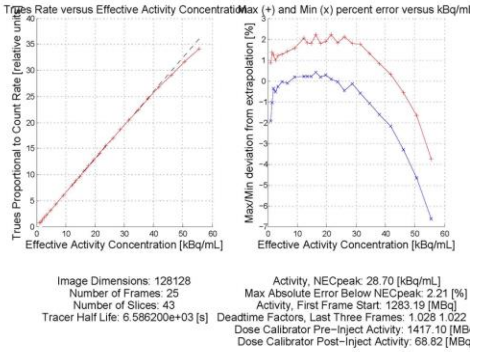
NU2-07 SF & CR Performance: 3D

- Peak NEC Rate: >100 kcps @ =< 30 kBq/mL



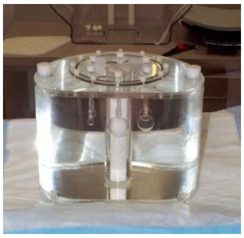


Deadtime Correction Accuracy

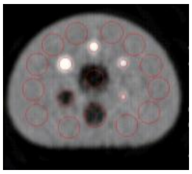


NU2-01/07 Image Quality Setup

- IEC Phantom: ~0.2μCi/mL background; ~0.8μCi/mL sphere
- ~5 mCi in the scatter phantom
- Clinical protocol used for data acquisition and reconstruction
- Draw ROIs on spheres and background regions



NU2-01/07 Image Quality



Sphere diameter (cm):	1.0	1.3	1.7	2.2	2.8	3.7
Hot Sphere Contrast (%):	27	53	63	82		
Cold Sphere Contrast (%):					66	73
Background Variability (%):	7	6	5	5	4	3
Average residual lung error (%):	21					

Results generated from imageset with PET AC

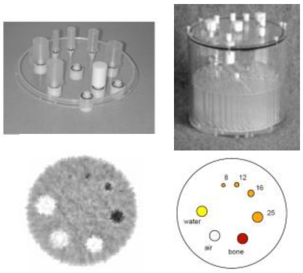
PET ACR Image Quality

- Specific instructions for phantom preparations
- Clinical protocol used for data acquisition and reconstruction
- Draw ROIs on cylinders and background regions

Phantom Dose Chart

Patient Dose	Dose A mCi	Dose B mCi
4 mCi	0.140	0.330
6 mCi	0.210	0.495
8 mCi	0.280	0.660
10 mCi	0.350	0.825
12 mCi	0.420	0.990
14 mCi	0.490	1.154
16 mCi	0.560	1.319
18 mCi	0.630	1.484
20 mCi	0.700	1.649

Cylinders Background



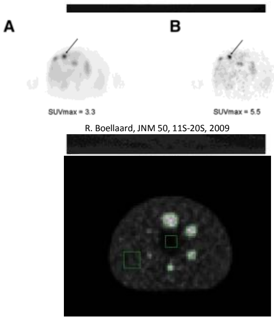
PET ACR Phantom Images

1. Image contrast and quantitation – cylinder SUV
2. Uniformity and artifacts – uniform section
3. Spatial resolution – cold rods

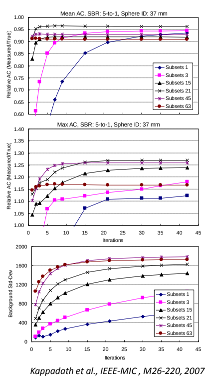
1 2 3

25, 16, 12, 8 mm 12.7, 11.1, 9.5, 7.9 mm

Iterative Reconstruction (^{18}FDG PET/CT)



R. Boellaard, JNM 50, 11S-20S, 2009



SUV mean

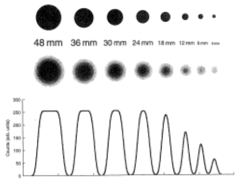
SUV max

Image Noise

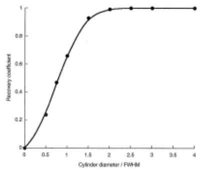
Kappadath et al., IEEE-MIC , M26-220, 2007

Partial Volume Effect

- Arises from the effects of finite spatial resolution on the reconstructed PET activity distribution
  - Smears the activity distribution
  - Lower signal for object size smaller than 2σ



The partial-volume effect



Recovery coefficient versus object size

Cherry, Sorenson, & Phelps, Physics of Nuclear Medicine, 2003

PET/CT: motion mis-registration

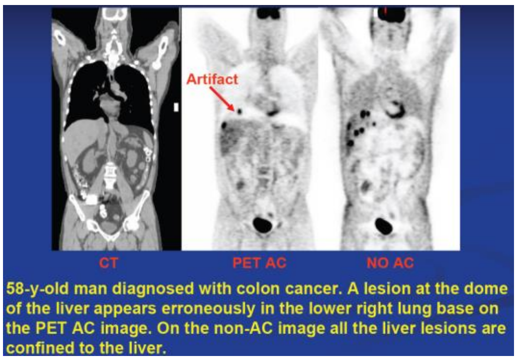
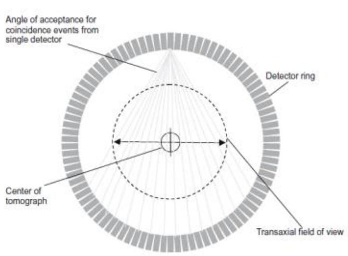


Image Courtesy: Osama Mawlawi

PET versus CT FOV registration



Bailey, Townsend, Valk, and Maisey, "Positron Emission Tomography," Springer-Verlag, 2005

Truncation Artifacts

Image Courtesy: Osama Mawlawi

Metal and CT Contrast Artifacts

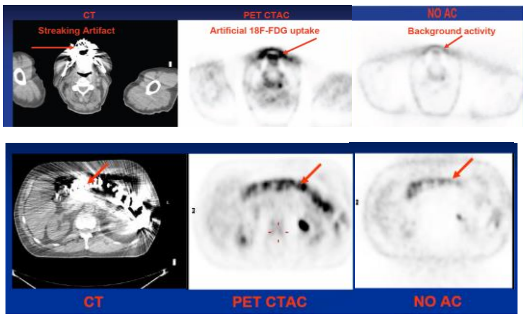


Image Courtesy: Osama Mawlawi

SAM Question 3

All of the following affect PET image quality except:

- 7% A. Reconstruction parameter
- 14% B. Scan duration
- 14% C. CT scan technique
- 7% D. Patient size

SAM Question 3: Answer

- All of the following affect PET image quality except:
  A. Reconstruction parameters
  B. Scan duration
  C. CT scan technique
  D. Patient size
- **Answer: C – CT scan technique**
- *Reference: O Mawlawi, SC Kappadath, T Pan, E Rohren, HA Macapinlac, "Factors affecting quantification in PET/CT imaging," Current Medical Imaging Reviews 4, 34-45, 2008*

SAM Question 4

The minimum CT dose appropriate for PET/CT examinations are constrained by:

0% A. Accuracy of CT-based attenuation correction
14% B. Radiologist preference for CT image quality
10% C. Equalize the CT dose to the PET dose
7% D. Accuracy of PET scatter correction

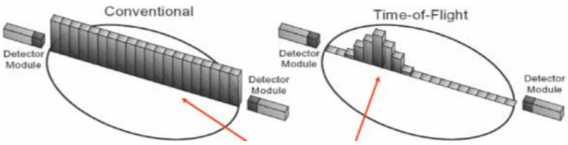
SAM Question 4: Answer

- The minimum CT dose appropriate for PET/CT examinations are constrained by:
  A. Accuracy of CT-based attenuation correction
  B. Radiologist preference for CT image quality
  C. Equalize the CT dose to the PET dose
  D. Accuracy of PET scatter correction
- **Answer: B – Radiologist preference for CT image quality**
- *Reference: FH Fahey, MR Palmer, KJ Strauss, RE Zimmerman, RD Badawi, ST Treves, "Dosimetry and adequacy of CT-based attenuation correction for pediatric PET: Phantom study," Radiology 243, 96–104, 2007*

Recent Advances in PET/CT

- Recent advances
  - TOF PET
  - PSF modeling
  - Extended axial FOV
  - Gating for motion correction
- More recent advances
  - Continuous bed motion (Siemens FlowMotion)
  - Digital detectors (Philips Vereos)
  - Regularized reconstruction (GE Q.Clear)

Time-of-Flight PET



Probability along LOR

Δt (ps)	Δx (cm)
600	9
100	1.5
0.33	0.5

$$\Delta x = \frac{\Delta t}{2} c$$

$$SNR_{TOF} \cong \sqrt{\frac{D_{obj}}{\Delta x}} SNR_{non-TOF}$$

TOF PET Image Quality

TOF PET Non-TOF PET

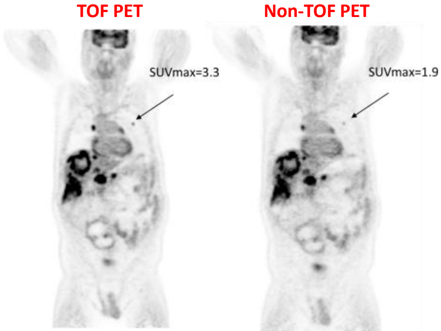
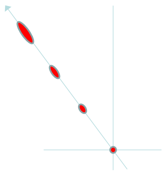
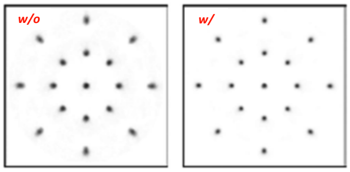


Image Courtesy: Osama Mawlawi

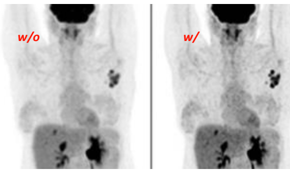
PSF Resolution Modeling



Lee et al., PMB 49, 2004



Pecking et al., Clin. Exp. Metastasis 29, 2012



- Goal is to improve image quality, contrast, and quantitative accuracy
- SharpIR (GE)
- TrueX (Siemens)
- Phillips ✓

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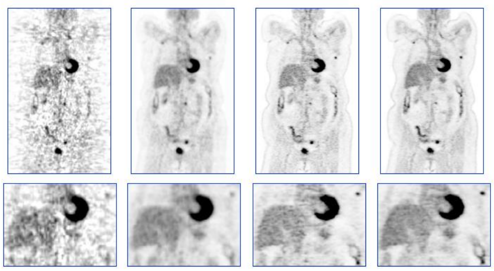
Improvements in PET Image Quality



(a) FBP (b) 2D: 3i / 8s (c) 3D: PSF (d) 3D: TOF+PSF

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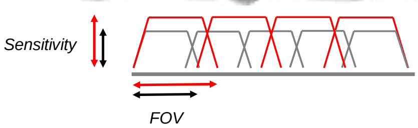
Advantages of Extended Axial FOV



- Fewer bed positions for same axial coverage
- Increased sensitivity → time/bed ↓ or counts/time ↑
- Net reduction in imaging time (or administered activity) for comparable image quality

Image courtesy: D Townsend

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SAM Question 5

The main advantage of a TOF PET scanner over a non-TOF PET scanner is:

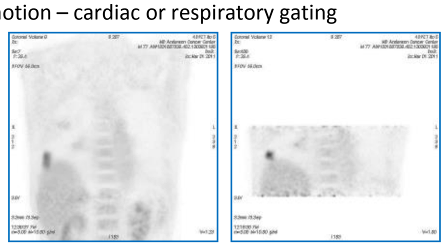
- 10% A. Higher intrinsic spatial resolution
- 10% B. Higher image contrast-to-noise ratio (CNR)
- 7% C. Higher count-rate performance
- 7% D. Lower number of detector elements needed

SAM Question 5: Answer

- The main advantage of a TOF PET scanner over a non-TOF PET scanner is:
  - A. Higher intrinsic spatial resolution
  - B. Higher image contrast-to-noise ratio (CNR)
  - C. Higher count rate performance
  - D. Lower number of detector elements needed
- **Answer: B – Higher image contrast-to-noise ratio (CNR)**
- *Reference: M Conti, "Focus on time-of-flight PET: the benefits of improved time resolution," EJNMMI 38, 1147-1157, 2011*

Gating and List Mode

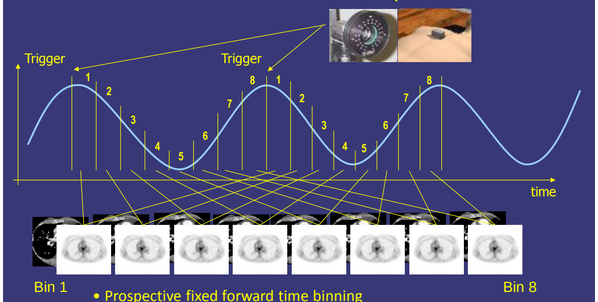
- Motion smears PET signal and reduced intensity
  - PET is motion averaged therefore use (motion) average CT
- Trigger to sort PET data into bins to correct for organ motion – cardiac or respiratory gating



SUV = 5.0 SUV = 8.5

Image courtesy: Tinsu Pan

Gated 4D PET and 4D CT Acquisition



- Prospective fixed forward time binning
- Single FOV Gated PET and Gated CT
- User defined number of bins and bin duration
- Images will be noisy unless acquired for longer durations

Image Courtesy: Tinsu Pan

Motion Correction Software

- Goal is to improve image quality, contrast, and quantitative accuracy – respiratory motion
- Q.Freeze (GE): Phase-matched 4D PET/CT
- Q.Static (GE) and HD.Chest (Siemens): Use PET data from end-expiration when motion is low
- Other vendors also have 4D PET solutions

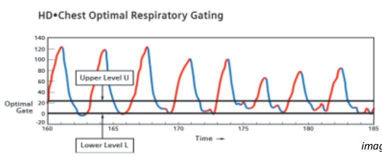


image courtesy: Siemens

Continuous Bed Motion

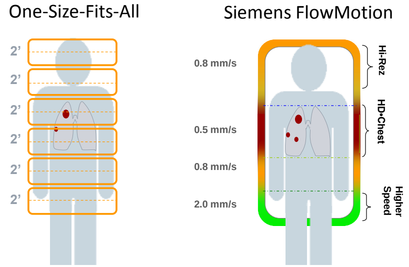


image courtesy: Siemens

Continuous Bed Motion

- Siemens FlowMotion mCT scanner

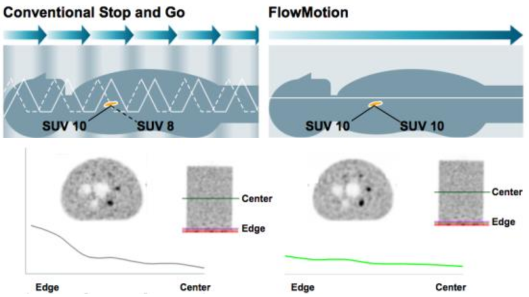
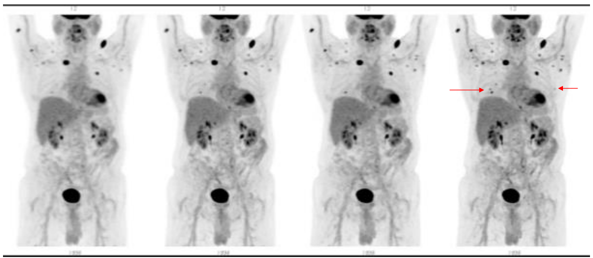


image courtesy: Siemens

Regularized Reconstruction – GE Q.Clear



77 years male with follicular lymphoma, 80 kg, 25 BMI, 9.4 mCi, 60 min post injection

Fully Digital PET/CT – Philips Vereos

- LYSO crystals + SiPM → Fully digital detectors
  - Fast and high sensitivity
- TOF, PSF modeling, 4D capability

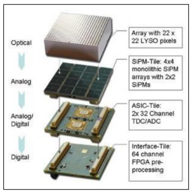


image courtesy: Philips

References

- SR Cherry, JA Sorenson, ME Phelps, “Physics in Nuclear Medicine, 3rd Edition,” Saunders Elsevier, 2003
- DL Bailey, DW Townsend, PE Valk, and MN Maisey, “Positron Emission Tomography,” Springer-Verlag (London), 2005
- M Conti, “Focus on time-of-flight PET: the benefits of improved time resolution,” EJNMMI 38, 1147-1157, 2011
- O Mawlawi, SC Kappadath, T Pan, E Rohren, HA Macapinlac, “Factors affecting quantification in PET/CT imaging,” Current Medical Imaging Reviews 4, 34-45, 2008
- FH Fahey, MR Palmer, KJ Strauss, RE Zimmerman, RD Badawi, ST Treves, “Dosimetry and adequacy of CT-based attenuation correction for pediatric PET: Phantom study,” Radiology 243, 96–104, 2007