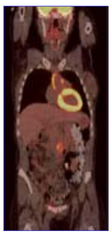
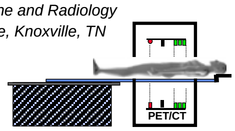
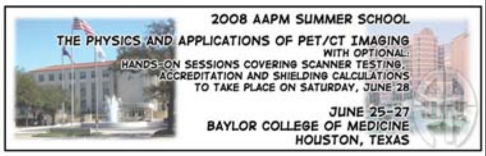
PET/CT Scanner Designs and Characteristics

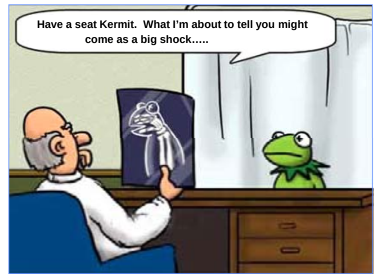
David W Townsend PhD
Departments of Medicine and Radiology
University of Tennessee, Knoxville, TN



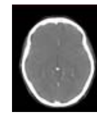




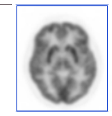
Making a diagnosis from imaging



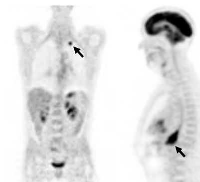
FDG brain scan



Normal CT



Normal PET



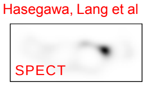
FDG-PET

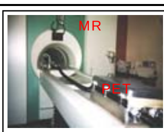
Diagnosis from anatomy…..

Diagnosis from function..

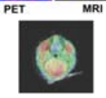
Dual-modality prototypes: 1995 - 1998

SPECT/CT
Hasegawa, Lang et al





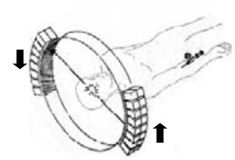
PET/MR
Cherry, Marsden et al



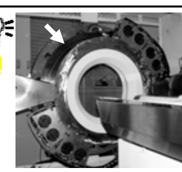
Mouse

PET/CT
Beyer, Nutt et al

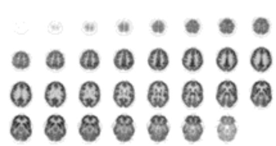
The Geneva PRT Camera Project 1990 - 1992



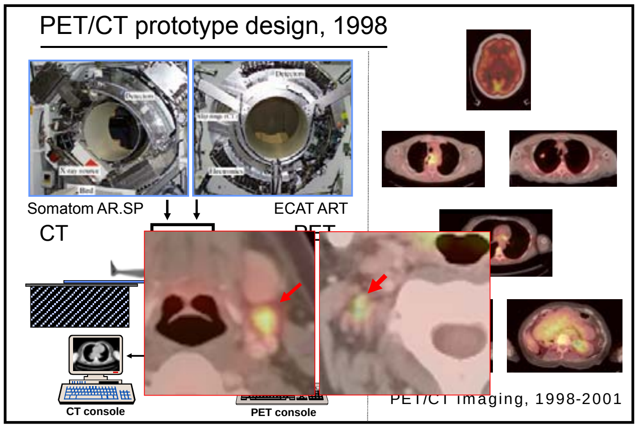
PRT-1

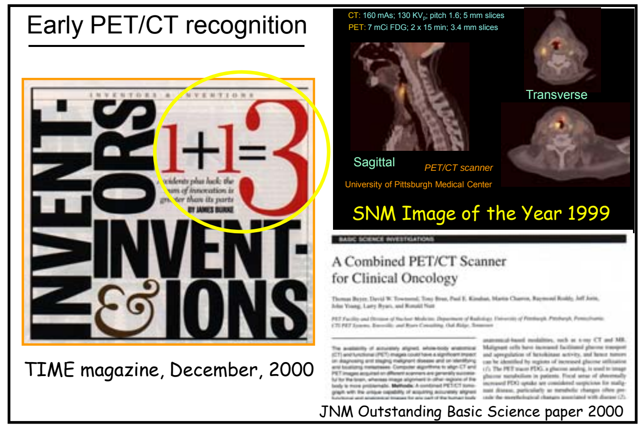


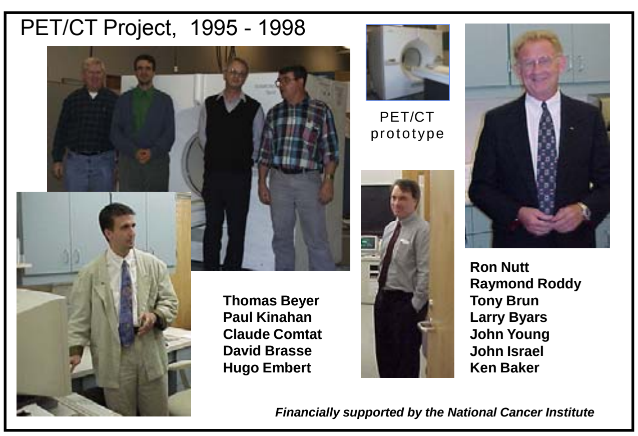
First FDG brain study on PRT-1, May 1991



PET/CT: artist's impression







As always…..*the skeptics*

"I think fusion is overblown in reputation. Good nuclear physicians can correlate just as well using internal landmarks."

"As one user of PET, I'm strongly willing to use the PET/CT fused imaging system. However, I have concern that the issue of sectionalism between radiologists and nuclear medicine physicians would prevent development of this special system."

"I hate to say it, but radiologist and nuclear medicine docs don't work as a team now most of the time, and getting the two types of images from one device won't change this characteristic."

"The PET business will go to the radiologist who will in fact own / control the CT."

THE JOURNAL OF NUCLEAR MEDICINE • Vol. 40 • No. 9 • October 1999 *skepticism*: *an attitude of doubt or a disposition to incredulity either in general or toward a particular object (e.g. PET/CT)*

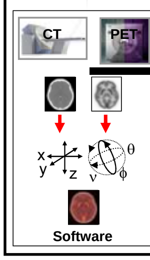
▶ 2008

v costs less than PET-only
jority perform PET/CT scans
T/CT now takes 5-10 min total
AC now used routinely
v dual certified PET/CT techs
ndard low dose CT protocols
re dual-boarded physicians
ny places generate one report

• NM and radiology conflicts

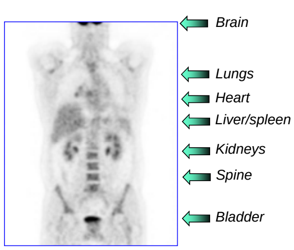
• progress resolving most issues….

Fusing images



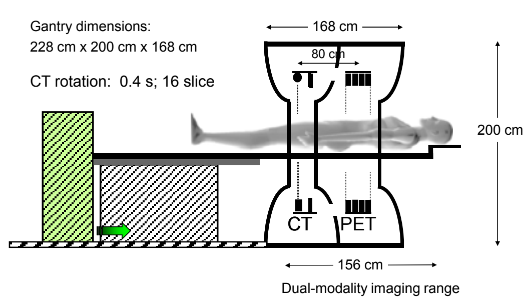
• image different aspects of disease
• localize functional abnormalities
• give added value to CT and PET
• identify non-specific tracer uptake

Specific biomarkers:



FDG: non-specific biomarker
➡ functional anatomy

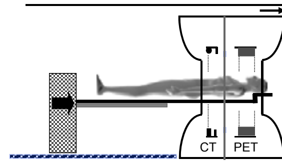
Anatomy of a PET/CT scanner



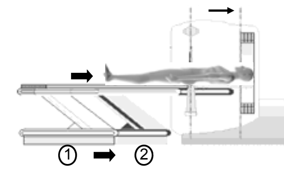
PET/CT design choices

CT parameters		PET parameters	
detectors:	ceramic; 1 – 24	scintillator:	BGO; GSO; LSO; LYSO
slices:	4, 6, 8, 16, 40, 64	detector size:	4 x 4 mm; 6 x 6 mm
trans. FOV:	45 – 50 cm	trans. FOV:	55 – 60 cm
rotation speed:	0.3 – 2.0 s	resolution:	~ 4 – 6 mm
tube current:	80 – 280 mA	axial extent:	15 – 22 cm
heat capacity:	3.5 – 6.5 MHU	septa:	2D/3D; 3D only
topogram:	128 – 2000 cm	attenuation:	CT-based
time /100 cm:	13 – 90 s	patient port:	70 cm
slice width:	0.5 – 12 mm	peak NECR:	63 @ 12 kBq/ml
patient port:	70 cm	(3D)	– 160 @ 31 kBq/ml

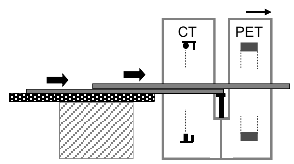
PET/CT patient support designs



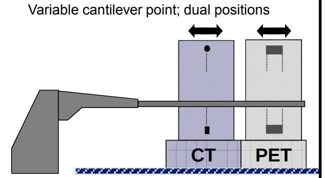
Fixed cantilever point; floor-mounted rails



Variable cantilever point; dual positions



Variable cantilever point; support in tunnel



Stationary bed; gantries travel on rails

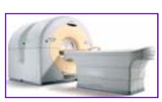
PET/CT scanner status in 2008

Discovery
ST, STE, RX

BGO, LYSO
4.7 x 6.3 x 30 mm^3
4.2 x 6.2 x 30 mm^3
2D/3D (septa)
8, 16, 64 slice CT
70 cm port
15.7 cm axial FOV
11.7 ns coincidence
dual-position bed

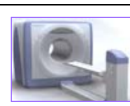
Biograph
6, 40, 64

LSO
6.4 x 6.4 x 25 mm^3
4 x 4 x 20 mm^3
3D only (no septa)
6, 40, 64 slice CT
70 cm port
21.8 cm axial FOV
4.5 ns coincidence
bed on rails



Gemini
GXL, TF

GSO, LYSO
4 x 4 x 30 mm^3
4 x 4 x 22 mm^3
3D only (no septa)
6, 10, 16, 64 CT
71.7 cm port
18 cm axial FOV
6 ns coincidence
bed supported in tunnel



SceptreP3

LSO
6.4 x 6.4 x 25 mm^3
3D only; rotating
4 slice CT

Aquiduo

LSO
4 x 4 x 20 mm^3
16 slice CT
gantry on rails

High performance PET/CT scanner design

Advances in CT:

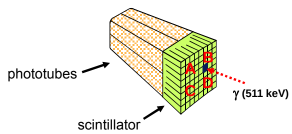
Straton x-ray tube

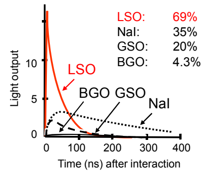
- increased number of axial slices
- faster gantry rotation times
- incorporation of dual Straton x-ray tubes
- very fast scan times for cardiac applications
- improved use of the radiation dose (TCM, AEC)

Advances in PET:

- new faster scintillators (LSO, LYSO)
- higher spatial resolution detectors
- increased sensitivity from extended AFOV
- overall improved count rate performance
- iterative reconstruction, accurate system model
- improved SNR from Time-of-Flight (TOF)

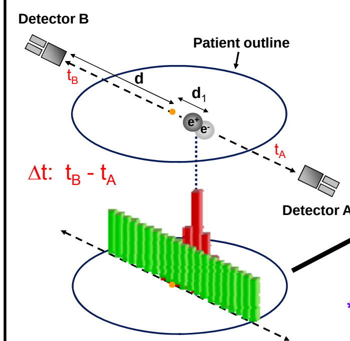
Advances in scintillators





	BGO	GSO	LSO	LYSO
Density (g/ml)	7.13	6.7	7.4	7.1
Effective Z	74	61	66.4	65.4
Decay (ns)	300	30-60	35-45	41
Timing (ps)			500	585
Light (ph/MeV)	8,200	10,000	30,000	30,000
% NaI	15	25	80	80

Improving signal-to-noise: time-of-flight (TOF)



$\Delta t = [(d+d_1) - (d-d_1)]/c$; $d_1 = c\,\Delta t/2$

$SNR_{TOF} = \sqrt{(D/\Delta d)} \cdot SNR_{non\text{-}TOF}$

δt (ps)	δx (cm)	SNR*
100	1.5	5.2
300	4.5	3.0
500	7.5	2.3
1200	18.0	1.5

*** SNR gain for 40 cm phantom = SNR_{TOF} / $SNR_{non\text{-}TOF}$**

PHILIPS GEMINI TF

Courtesy Matthias Egger PhD, Philips

PET detector design

- Detector design: PIXELAR with continuous lightguide
- Crystals: 28,336; LYSO: 4 mm x 4 mm x 22 mm
- Coincidence time window: 3.8 ns
- Lower level discriminator: 440 keV
- Acquisition mode: Sustained high-rate listmode

TOF PET performance

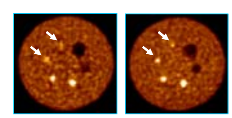
- Timing resolution: 650 ps ➡ localization accuracy of 9.75 cm
- Sampling rate: 25 ps
- Effective sensitivity gain: 2 – 4 x depending on patient size
- Effective system sensitivity: > 14,400 cps/MBq @ 10 cm
- Peak effective NEC (1R): > 210 kcps* @ 16 kBq/ml

**assuming TOF SNR gain (non-TOF: 105 kcps)*

Gemini TF

Courtesy Joel Karp PhD, University of Pennsylvania

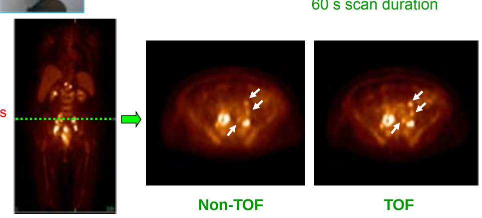
LYSO
4 x 4 x 22 mm^3 (LYSO)
3D only (no septa)
Brilliance 16 CT
70 cm port
18 cm axial FOV
585 ps timing



Non-TOF **TOF**
60 s scan duration

Rectal carcinoma, with metastases located in the mesentery and bilateral iliac chains more clearly seen with TOF.

114 kg; BMI = 38.1
12 mCi; 2 hr pi
3min/bed position



Non-TOF **TOF**

Discovery STE

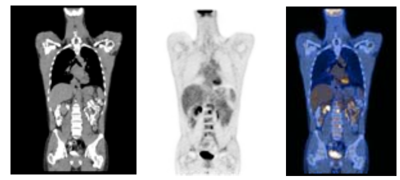
Courtesy Osama Malawi PhD, MD Anderson Cancer Center

Crystal dimensions, mm	4.7 x 6.3 x 30
Crystal detectors/block	6 x 8
Number of blocks	280
Number of block rings	4
Detector blocks/ring	70
Number of crystals/ring	560
Number of detector rings	24
Ring diameter	88.6 cm
Total number of crystals	13,440
Number of slices	PET: 47; CT: 8,16
Plane spacing	3.27 mm
Number of PMTs	280 quad PMTs
Physical axial FOV	15.7 cm
Transverse FOV	70 cm
Effective AFOV (cm)	12.5 (3D), 13.7 (2D)
Detector material	BGO
511 keV Stopping power	95%
Hygroscopic	No

Transverse resolution @ 1 cm (mm)	5.1 (2D), 5.2 (3D)
Transverse resolution @ 10 cm (mm)	5.6 (2D), 5.6 (3D)
Axial resolution @ 1 cm (mm)	4.7 (2D), 5.4 (3D)
Axial resolution @ 10 cm (mm)	6.0 (2D), 6.0 (3D)
System sensitivity – 3D	8.47 cps/kBq
System sensitivity – 2D	2.2 cps/kBq
Peak NECR – 2D (kcps)	87.9 kcps @ 44.9 kBq/cc
Peak NECR – 3D (kcps)	75.1 kcps @ 12.8 kBq/cc
Scatter fraction – 2D	21%
Scatter fraction – 3D	34%
Coincidence window	9.6 nsec
Energy window setting, keV	375-650 (2D) 425-650 (3D)

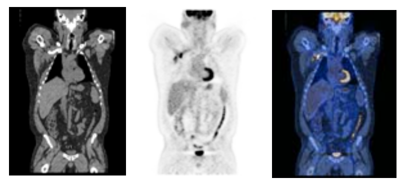
Discovery STE

Courtesy Osama Malawi PhD, MD Anderson Cancer Center



Low BMI

Scan duration: 18 min
6 beds; 3 min/bed
17.7 mCi; 60 min pi; 2D
71 kg (156 lb) patient



High BMI

Scan duration: 18 min
6 beds; 3 min/bed
19.2 mCi; 60 min pi; 2D
113 kg (249 lb) patient

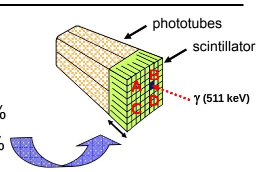
Improved sensitivity with *Biograph* TrueV

- *thicker LSO crystals*

  20 mm → 30 mm

  - LSO volume increase: 50%
  - sensitivity increase: 40%

  ★ **planar sensitivity**

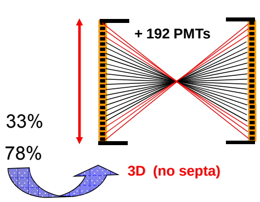


- *extended axial FOV*

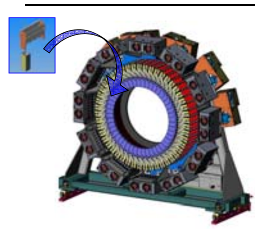
  16.2 cm → 21.8 cm

  - LSO volume increase: 33%
  - sensitivity increase: 78%

  ★ **volume sensitivity**

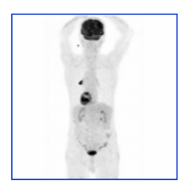


Biograph PET•CT with TrueV



- cylindrical scanner geometry
- 4 rings of 13 x 13 LSO block detectors
- 4 mm x 4 mm x 20 mm pixels
- 32,448 individual pixels
- 109 transaxial image planes
- 21.8 cm axial field-of-view

- patient port: 70 cm
- timing: 4.5 ns
- resolution: 4.2 mm
- NEC_{max}: 160 kcps
- LLD: 425 keV



Total PET scan duration: 3 min
6 beds; 0.5 min/bed; HD recon
10.5 mCi; 105 min post-injection

NEMA NU-2 2001 performance measurements

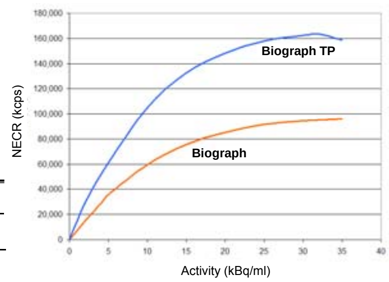
Scatter (%) (425 keV – 650 keV)

	Scatter fraction
Biograph	34
Biograph TP	34

Peak NECR (kcps)

	Peak NECR
Biograph	96 @ 34 kBq/ml
Biograph TP	161 @ 31 kBq/ml

Noise Equivalent Count Rate



Spatial resolution (Γ)

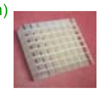
Γ = 1.25 √ {(d/2)² + (0.0022D)² + r² + b²}

d = detector size (6.4 mm or 4.0 mm)

D = detector ring diameter (mm)

r = 'effective' positron range (mm)

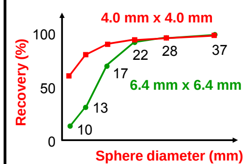
b = block decoding factor (~ 1 mm)

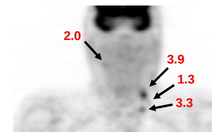


8 x 8

13 x 13

Recovery Coefficients





8.6 mCi; 60 min uptake

6.4 mm x 6.4 mm

11.2 mCi; 90 min uptake

4 mm x 4 mm

Improving the imaging system model

Attenuation-weighted OSEM

$$i_j^{k+1} = i_j^k \cdot \frac{1}{\sum_i p_{i,j} \cdot \frac{1}{a_i}} \cdot \left[\sum_i p_{i,j} \cdot \frac{s_i}{\sum_j p_{i,j} \cdot i_j^k} \right]$$

s_i: {(P - R)•N – S}

a_i: attenuation

Ordinary Poisson OSEM

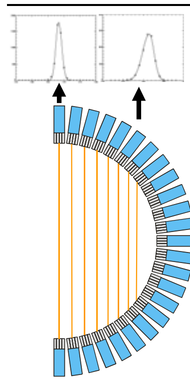
$$i_j^{k+1} = i_j^k \cdot \frac{1}{\sum_i \left(p_{i,j} \cdot \frac{1}{n_i \cdot a_i} \right)} \cdot \sum_i \left[p_{i,j} \cdot \frac{s_i}{\left(\sum_j p_{i,j} \cdot i_j^k \right) + a_i \cdot (r_i \cdot n_i + c_i)} \right]$$

$p_{i,j}$: includes geometric distortions

s_i: Prompts (P)

n_i: normalization; a_i: attenuation; r_i: randoms; c_i: scatter

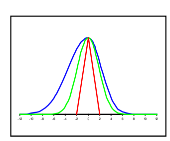
Distortions from a circular geometry



Lines-of-response become more closely spaced as distance from center increases

Point spread function for the central LORs is symmetrical

Point spread function for lines-of-response at large radius are asymmetrical and broader due to tilt of the crystal and depth of interaction

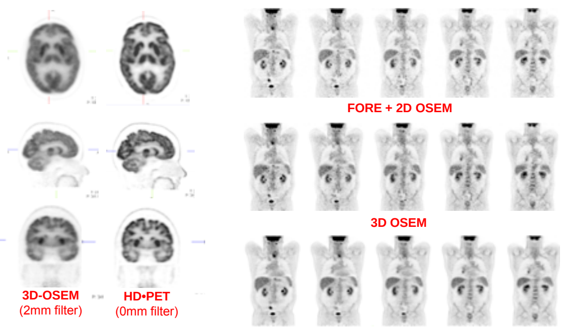


AW-OSEM linearly interpolates between sinogram bins (red)

PSF interpolates between sinogram bins with measured spatially-variant point spread functions (green — blue)

The inclusion of the point spread function allows the simulation to better match the data with the effect of improving resolution and lowering noise

HD PET: modeling the system PSF

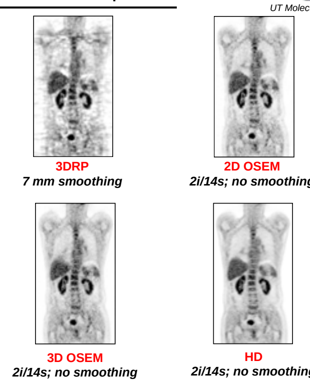


Brain Whole body

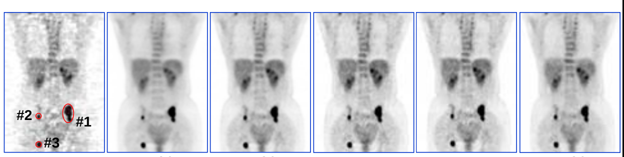
Advances in reconstruction techniques

UT Molecular Imaging

88 kg (194 lbs), BMI = 25
Scan duration: 18 min
6 beds; 3 min/bed
10.1 mCi; 88 min post-injection
168 x 168 matrix; CT-AC



Reconstruction algorithms and SUV



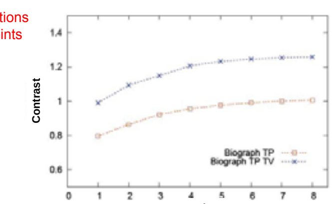
SUV_{max} / SUV_{mean}

Tumor	FBP	2D: 1i / 8s	2D: 3i / 8s	2D: 5i / 8s	2D: 3i / 16s	3D: 3i / 8s
#1	9.7 / 6.6	8.7 / 6.1	9.5 / 6.4	9.8 / 6.6	9.9 / 6.6	9.6 / 6.5
#2	5.9 / 4.2	3.8 / 2.8	5.2 / 3.8	5.9 / 4.2	5.6 / 4.1	5.7 / 3.9
#3	10.0 / 6.4	8.2 / 5.0	9.0 / 5.7	10.1 / 6.2	9.9 / 6.6	10.0 / 5.9

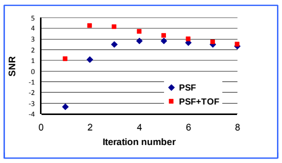
Reconstruction method	SUV @ 60 min	SUV @ 90 min
2D AWOSEM 4i/8s 168 (5 mm)	4.59	6.94
2D AWOSEM 4i/16s 168 (5 mm)	4.55	7.04
3D AWOSEM 4i/8s 168 (5 mm)	4.46	7.18
3D AWOSEM 4i/8s 336 (5 mm)	5.19	7.18
3D AWOSEM 4i/8s 336 (none)	5.47	8.00

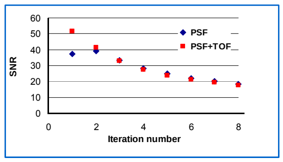
- 29% SUV change for different reconstructions
- 40% SUV change at two different time points

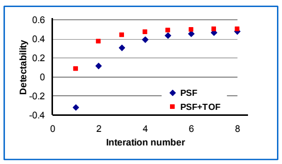
$$\text{Contrast} = \frac{\textit{Mean ROI hot spot}}{\textit{Mean ROI background}}$$



TOF prototype: SNR and detectability







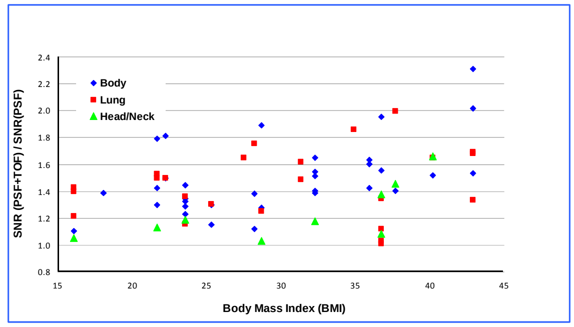
SNR

$(\langle S \rangle - \langle B \rangle) / \sigma_B$

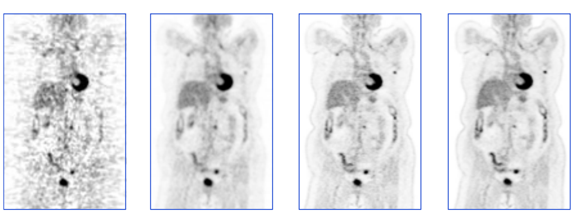
Detectability

$(\langle S \rangle - \langle B \rangle) / \sqrt{(\sigma_S^2 + \sigma_B^2)}$

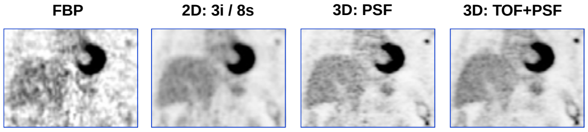
SNR gain as a function of BMI (SNR$_{TOF}$ / SNR$_{non\text{-}TOF}$)



Reconstruction algorithms with TOF

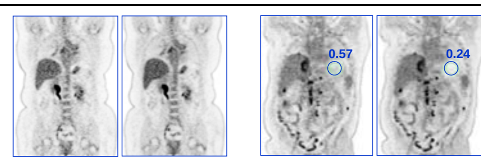


FBP | 2D: 3i / 8s | 3D: PSF | 3D: TOF+PSF



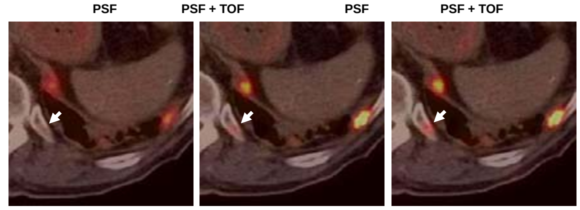
Patient studies

105 kg
BMI: 41



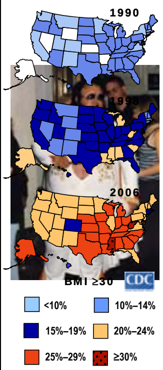
88 kg
BMI: 30

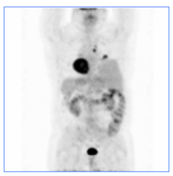
PSF | PSF + TOF | PSF | PSF + TOF



FORE + OSEM | PSF | PSF + TOF

Imaging large patients



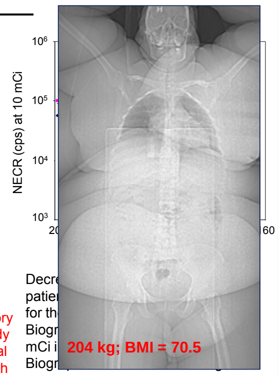


10.7 mCi, 93 min pi

3 min/bed, 6 beds

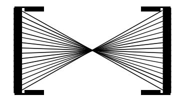
260 lbs (118 kg) male

59 year-old male with history of lymphoma. PET/CT study shows hilar and mediastinal foci that are compatible with metastases.



The 2D vs 3D debate…..

- *GEMINI* PET/CT scanners are fully 3D
- *Biograph* PET/CT scanners are fully 3D
- *Aquiduo* and *SceptreP3* are fully 3D
- *Discovery* STE (BGO) and RX (LYSO) are 2D and 3D

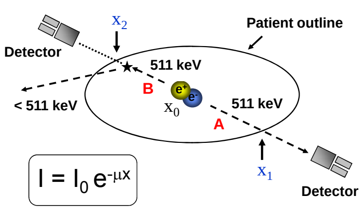


Discovery RX (LYSO)

Strobel K, Rudy M, Treyer V, et al. Objective and subjective comparison of standard 2-D and fully 3D reconstructed data on a PET/CT system. *Nucl. Med. Comm.* 2007; 28(7):555-559.

Kemp BJ, Lowe VJ, Nathan MA, et al. Clinical evaluation of sequentially acquired 2D and 3D whole-body PET/CT scans. *J Nucl. Med.* 2007; 48(2):433P (abstract).

Attenuation



$$I = I_0 e^{-\mu x}$$

$$P_A = \exp\left[-\int_{x_1}^{x_0} \mu(x)\, dx\right]$$

$$P_B = \exp\left[-\int_{x_0}^{x_2} \mu(x)\, dx\right]$$

$$I = I_0 (P_A \cdot P_B) = I_0 \left\{\exp\left[-\int_{x_1}^{x_2} \mu(x)\, dx\right]\right\}$$

$$I_0 = I \left\{\exp\left[+\int_{x_1}^{x_2} \mu(x)\, dx\right]\right\} = I \cdot \text{ACF}$$

CT-based attenuation correction

PET: $\mu(E_{511}) = \rho_e \sigma_c(E_{511})$

CT: $\mu(E_{70}) = \rho_e\{\sigma_c(E_{70}) + \sigma_{pe}(E_{70}, Z_{eff})\}$

ρ_e = electron density; $\sigma_c(E)$ = Compton; $\sigma_{pe}(E)$ = photoelectric

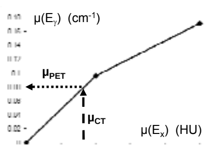
Z_{eff} = effective atomic number

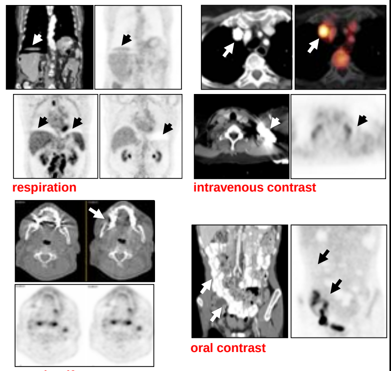
CT-based attenuation correction

Algorithm

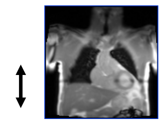
- bi-linear scaling
- bone threshold: 80 HU
- resample CT images
- scale individual pixels
- re-project scaled image

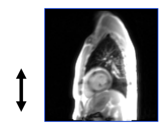
Scaling function





Respiration and CT-AC


Coronal

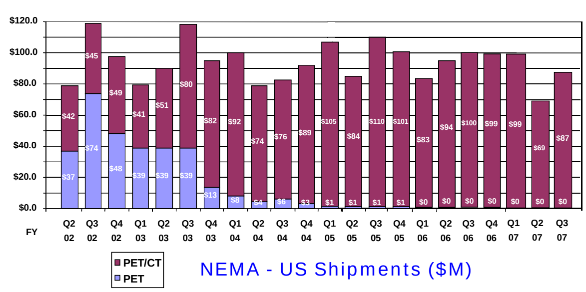

Sagittal

Respiration strategies:

- continuous shallow breathing
- limited breath hold (over diaphragm)
- breath hold CT at partial inspiration
- slow the rotational speed of CT
- cine CT scan (4DCT)
- respiratory gated CT scan
- breath hold CT; gated PET scan
- gating both CT and PET scans
- breath hold CT; "breath hold" PET

MR respiration movies courtesy of Jim Hamill PhD

PET/CT market impact



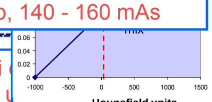
PET/CT scan protocol

- arms up (except neck)
- acquired with breath hold
- partial inspiration
- 10 – 15 s scan time
- intravenous +/- oral contrast
- 120 kVp, 140 - 160 mAs

gram
spiral CT

sed attenuation correction

- bi-linear scaling model
- threshold at ~ 60 HU
- kVp-dependent scaling
- correction for oral contrast
- some error from iv contrast
- use CT or non-corrected PET
- respiration protocol
- ACF error < 15%
- validated in human tissue



- 10 mCi
- 90 min u
- 2 - 3 mi
- 4 - 11 be
- 10 - 30 min scan durati
- respiratory gating

- 2D-OSEM, 4i/8s; fully 3D-OSEM
- 5 mm axial smoothing

PET/CT:

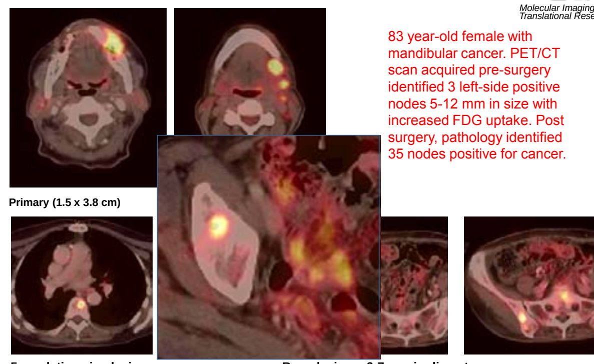
- for staging disease
- for therapy planning
- for monitoring response

Mandibular cancer

biograph 16

Molecular Imaging and Translational Research

83 year-old female with mandibular cancer. PET/CT scan acquired pre-surgery identified 3 left-side positive nodes 5-12 mm in size with increased FDG uptake. Post surgery, pathology identified 35 nodes positive for cancer.



Primary (1.5 x 3.8 cm)

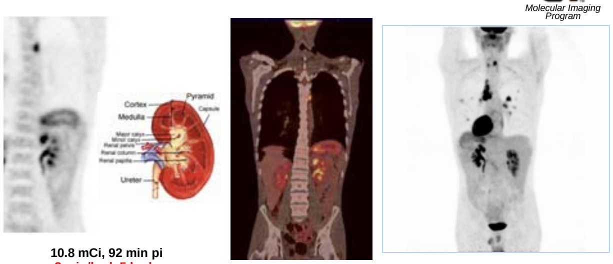
5 mm lytic spine lesion

Bone lesions, 6-7 mm in diameter

Lung cancer

Biograph 6 TrueV

Molecular Imaging Program



10.8 mCi, 92 min pi
2 min/bed, 5 beds
3i / 8s; 5 mm
130 kVp; 50 mAs

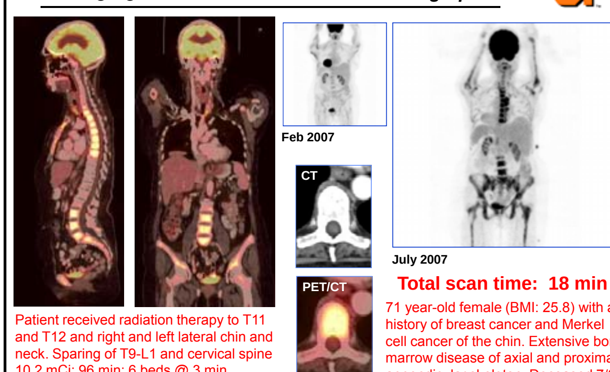
PET/CT

Scan duration: 10 min

44 year-old male (6', 118 lbs) with recent diagnosis of lung cancer. Smoker for 26 years. Loss of voice and hoarseness. Shortness of breath and 25 lb weight loss in one month. Recent chest pain. Uptake in lymph node obstructing breathing and left pulmonary artery.

Restaging breast cancer

Biograph 6



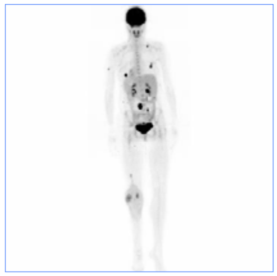
Total scan time: 18 min

Patient received radiation therapy to T11 and T12 and right and left lateral chin and neck. Sparing of T9-L1 and cervical spine
10.2 mCi; 96 min; 6 beds @ 3 min

71 year-old female (BMI: 25.8) with a history of breast cancer and Merkel cell cancer of the chin. Extensive bone marrow disease of axial and proximal appendicular skeleton. Deceased 7/07.

Staging melanoma

Biograph 6


Total scan time: 22 min

27 year-old female (123 lbs) with a history of metastatic melanoma on right lower leg. Evidence of disease progression between two scans

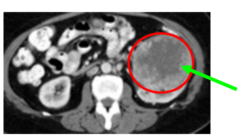
Has PET/CT made a real difference?

PET/CT compared to PET and CT: average over all cancers is **10-15%** improvement

- **Head and neck**
  Accuracy: 95% vs 83% PET; 73% CT
- **Thyroid**
  Accuracy: 93% vs 78% CT
- **Solitary lung nodules**
  Accuracy: 96% vs 81% CT
- **Lung cancer**
  Accuracy: 98% vs 80% PET (T stage)
- **Breast cancer**
  Accuracy: 90% vs 79%
- **Esophageal cancer**
  Accuracy: 92% vs 86% PET
- **Colorectal cancer**
  Accuracy: 89% vs 78% PET
- **Lymphoma**
  Accuracy: 93% vs 78% CT
- **Melanoma**
  Accuracy: 97% vs 93% PET
- **Unknown primary**
  No difference; 20-40% detected

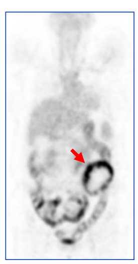
Czernin, Allen-Auerbach, Schelbert. J Nucl Med 48 (1, Supplement) 2007: 78S – 88S

Biological target volume (BTV_{FDG})



GTV_{CT}

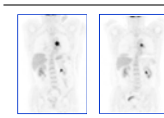
BTV_{FDG}

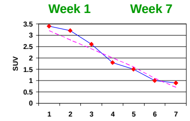


GTV defined from the CT

BTV_{FDG} defined as FDG-avid volume from PET

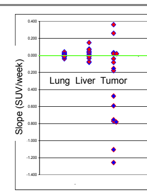
Can we predict response with FDG-PET?

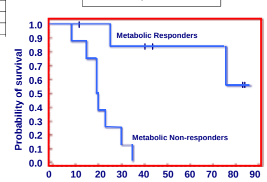


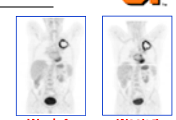


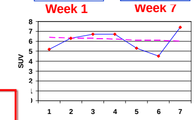
Responder

Patient alive 20 months after end of chemotherapy





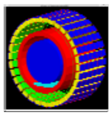




Non-responder

Patient survived 2 months after end of chemotherapy

SIEMENS Combining PET and MR: First studies



- Six 12 x 12 arrays of 2.5 x 2.5 x 20 mm
- LSO blocks read out by 3 x 3 APD array
- Total of 192 LSO APD block detectors
- FOV: 35.5 cm x 19.25 cm axial
- Siemens 3T TRIO MR scanner

Patient study

MR/PET

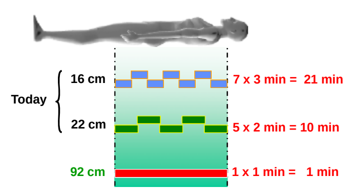
Client-owned dog

Challenges for MR/PET

- ✓ to develop MR-compatible PET detectors
- PET attenuation correction factors from MR images
- establish a role for MR/PET in research
- applications for simultaneous MR and PET
- establish a clinical role for MR/PET
- develop a whole-body MR/PET system

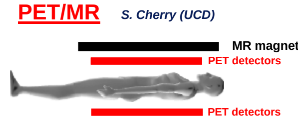
Into the future….

PET/CT



PET/MR

S. Cherry (UCD)



PET biomarkers

- glucose transport/utilization
- tumor hypoxia
- tumor blood flow
- angiogenesis
- amino acid synthesis
- cell proliferation
- apoptosis
- tumor receptors

UTGSM Molecular Imaging and Tracer Development Program

Acknowledgements:

Jon Wall, PhD
Karl Hubner, MD
Chris Guglielmo, MD
George Kabalka, PhD
Steve Kennel, PhD
Wenben Zeng, PhD
Weimin Miao, PhD
Bjoern Jakoby, MS
Cristina Lois, PhD
Josh Schaefferkoetter, BS
Misty Long, R.T. (R) (N)
Chris Carr, R.T. (R) CNMT
Alan Stuckey, CNMT
Pam Trentham

National Cancer Institute

...and now on your iPhone