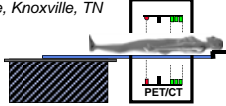
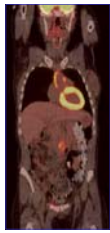


PET/CT Scanner Designs and Characteristics

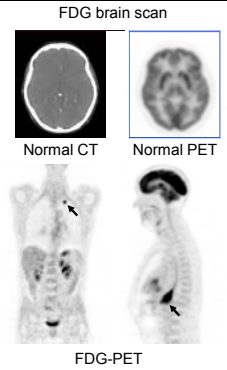
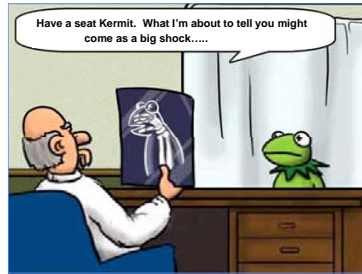
David W Townsend PhD
 Departments of Medicine and Radiology
 University of Tennessee, Knoxville, TN



2008 AAPM SUMMER SCHOOL
 THE PHYSICS AND APPLICATIONS OF PET/CT IMAGING
 WITH OPTIONAL HANDS-ON SESSIONS COVERING SCANNER TESTING, ACCREDITATION AND SHIELDING CALCULATIONS TO TAKE PLACE ON SATURDAY, JUNE 28

JUNE 25-27
 BAYLOR COLLEGE OF MEDICINE
 HOUSTON, TEXAS

Making a diagnosis from imaging



Diagnosis from anatomy.....

Diagnosis from function..

Dual-modality prototypes: 1995 - 1998

<p>SPECT/CT Hasegawa, Lang et al</p> <p>SPECT</p>	<p>PET/MR Cherry, Marsden et al</p> <p>PET MRI muscle brain Mouse</p>	<p>PET/CT Beyer, Nutt et al</p> <p>CT PET</p>
-------------------------------------------------------	-----------------------------------------------------------------------------------	---------------------------------------------------

The Geneva PRT Camera Project 1990 - 1992

PRT-1

PET detectors (BGO)

CT detectors (Xe)

PET/CT: artist's impression

First FDG brain study on PRT-1, May 1991

PET/CT prototype design, 1998

Somatom AR.SP CT ECAT ART PET

CT console PET console

PET/CT imaging, 1998-2001

Early PET/CT recognition

CT: 160 mAs, 120 kVp, pitch 1.0, 5 mm slices
PET: 7 mCi FDG, 2 x 15 min, 3.4 mm slices

Sagittal PET/CT scanner
University of Pittsburgh Medical Center

SNM Image of the Year 1999

A Combined PET/CT Scanner for Clinical Oncology

Thomas Byers, David W. Townsend, Tony Brun, Paul K. Kinoshita, Maria Charnak, Raymond Roddy, Jeff Ains, John Young, Larry Brasse, and Ronald Tsai

PET Center and Division of Nuclear Medicine, Department of Radiology, University of Pittsburgh, Pittsburgh, Pennsylvania
PET PET Systems, Knoxville, and North Carolina, Oak Ridge, Tennessee

TIME magazine, December, 2000

JNM Outstanding Basic Science paper 2000

PET/CT Project, 1995 - 1998

PET/CT prototype

Thomas Beyer
Paul Kinahan
Claude Comtat
David Brasse
Hugo Embert

Ron Nutt
Raymond Roddy
Tony Brun
Larry Byars
John Young
John Israel
Ken Baker

Financially supported by the National Cancer Institute

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)*



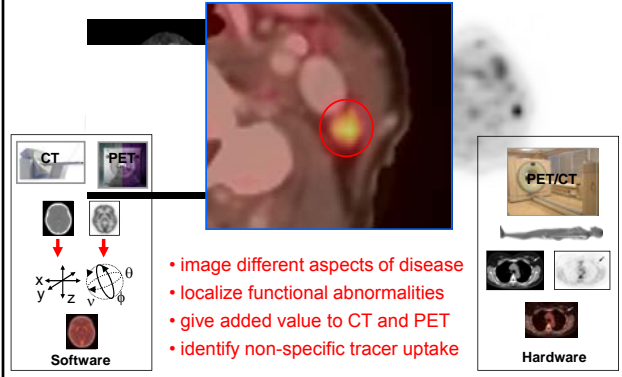
• NM and radiology conflicts

2008

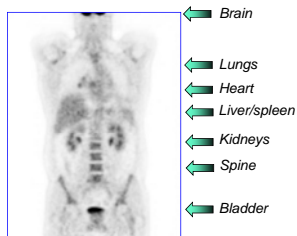
- costs less than PET-only
- majority perform PET/CT scans
- PET/CT now takes 5-10 min total
- PAC now used routinely
- dual certified PET/CT techs
- standard low dose CT protocols
- dual-boarded physicians
- many places generate one report

• progress resolving most issues....

Fusing images

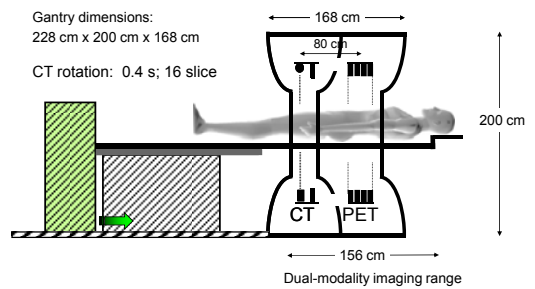


Specific biomarkers:



FDG: non-specific biomarker
 ➔ functional anatomy

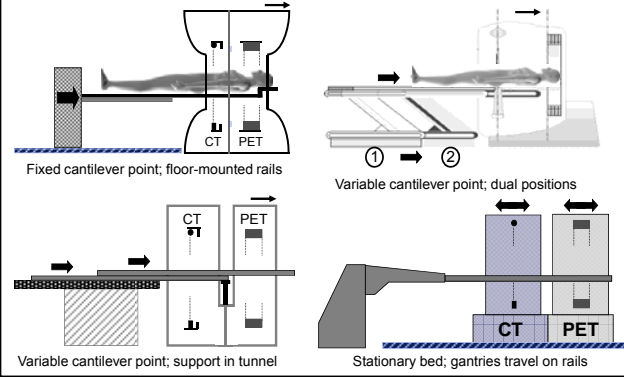
Anatomy of a PET/CT scanner



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



PET/CT scanner status in 2008



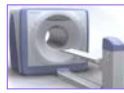
Discovery
ST, STE, RX



Biograph
6, 40, 64



Gemini
GXL, TF



SceptreP3

LSO
6.4 x 6.4 x 25 mm³
3D only; rotating
4 slice CT

BGO, LYSO
4.7 x 6.3 x 30 mm³
4.2 x 6.2 x 30 mm³
2D/3D (septa)
8, 16, 64 slice CT
70 cm port
15.7 cm axial FOV
11.7 ns coincidence
dual-position bed

LSO
6.4 x 6.4 x 25 mm³
4 x 4 x 20 mm³
3D only (no septa)
6, 40, 64 slice CT
70 cm port
21.8 cm axial FOV
4.5 ns coincidence
bed on rails

GSO, LYSO
4 x 4 x 30 mm³
4 x 4 x 22 mm³
3D only (no septa)
6, 10, 16, 64 CT
71.7 cm port
18 cm axial FOV
6 ns coincidence
bed supported in tunnel



Aquiduo

LSO
4 x 4 x 20 mm³
16 slice CT
gantry on rails

High performance PET/CT scanner design

Advances in CT:



- 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)



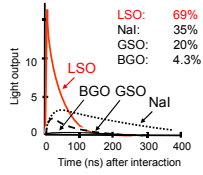
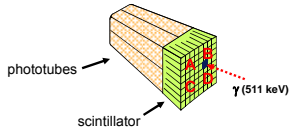
Advances in PET:



- 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)

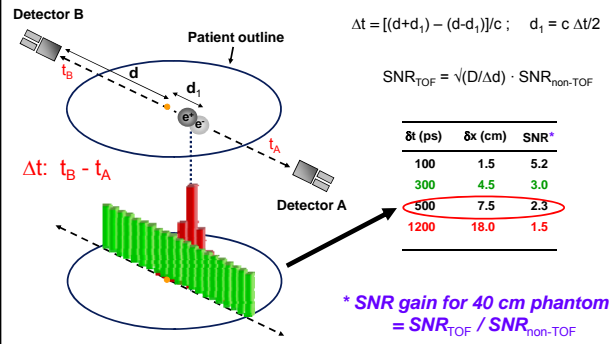


Advances in scintillators




	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)




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

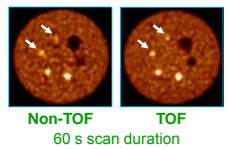
- Timing resolution: 650 ps → localization accuracy of 9.75 cm
- Sampling rate: 25 ps
- Effective sensitivity gain: 2 – 4 x depending on patient size
- Effective system sensitivity: > 14,400 cps/MBq @ 10 cm
- Peak effective NEC (1R): > 210 kcps* @ 16 kBq/ml

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

Gemini TF *Courtesy Joel Karp PhD, University of Pennsylvania*



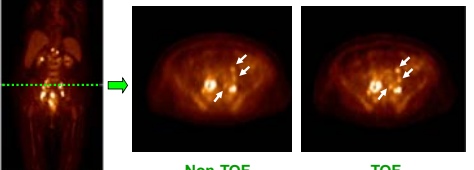
LYSO
4 x 4 x 22 mm³ (LYSO)
3D only (no septa)
Brilliance 16 CT
70 cm port
18 cm axial FOV
585 ps timing



Non-TOF TOF
60 s scan duration

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

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



Non-TOF TOF

Discovery STE

Courtesy Osama Malawi PhD, MD Anderson Cancer Center

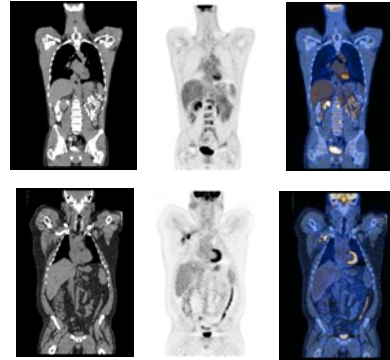
Crystal dimensions, mm	4.7 x 6.3 x 30
Crystal detectors/block	6 x 8
Number of blocks	280
Number of block rings	4
Detector blocks/ring	70
Number of crystals/ring	560
Number of detector rings	24
Ring diameter	88.6 cm
Total number of crystals	13,440
Number of slices	PET: 47; CT: 8,16
Plane spacing	3.27 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) @ 44.9 kBq/cc	87.9 kcps
Peak NECR - 3D (kcps) @ 12.9 kBq/cc	75.1 kcps
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%

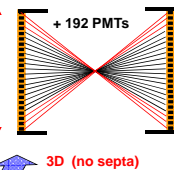
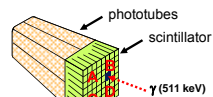
★ planar sensitivity

• extended axial FOV

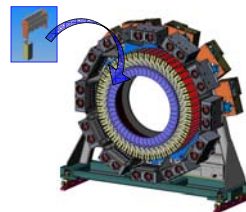
16.2 cm → 21.8 cm

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

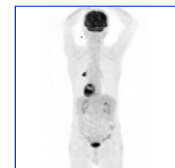
★ volume sensitivity



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

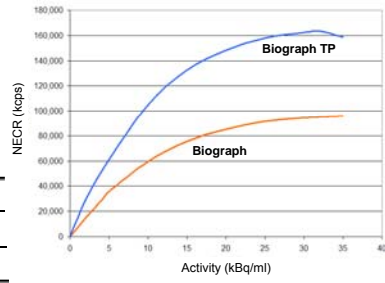
Scatter (%) (425 keV – 650 keV)

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

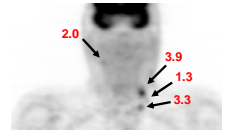
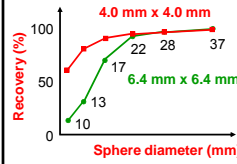


Spatial resolution (Γ)

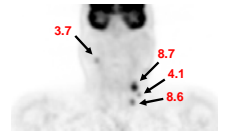
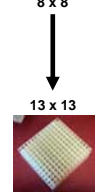
$$\Gamma = 1.25 \sqrt{\left(\frac{d}{2}\right)^2 + (0.0022D)^2 + r^2 + b^2}$$

- 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)

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

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

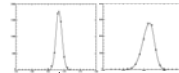
Labels: attenuation, $\{(P-R) \cdot N - S\}$

Ordinary Poisson OSEM

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

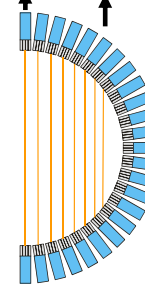
Labels: normalization, attenuation, includes geometric distortions, Prompts (P), randoms, scatter

Distortions from a circular geometry

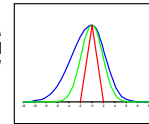


Lines-of-response become more closely spaced as distance from center increases

Point spread function for the central LORs is symmetrical

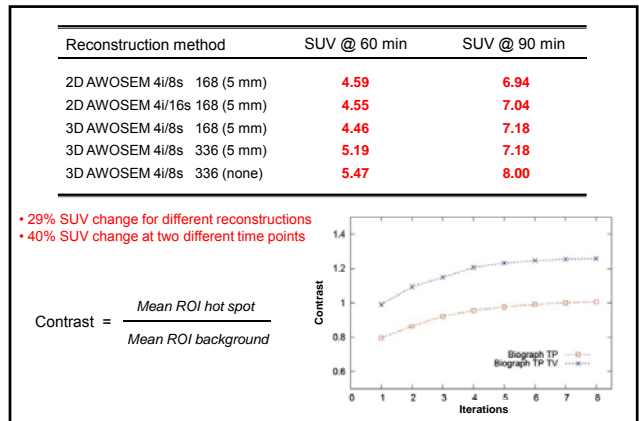
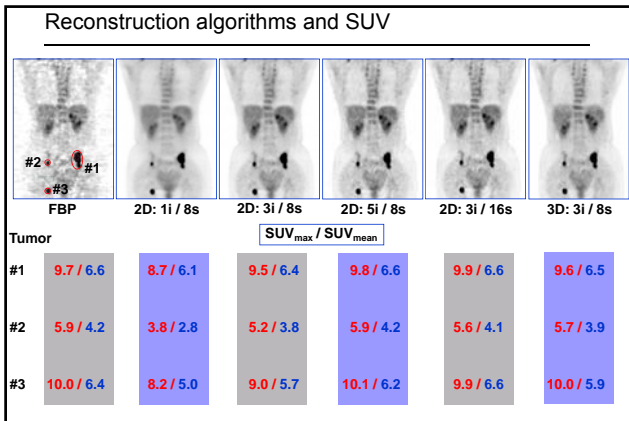
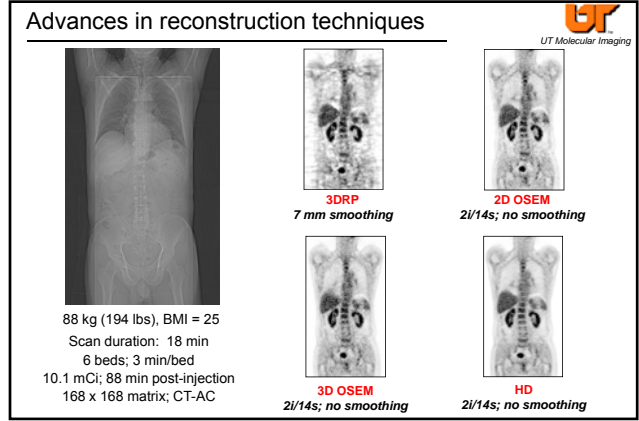
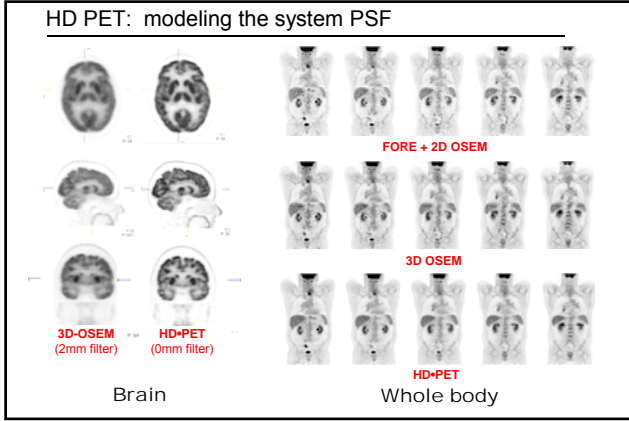


Point spread function for lines-of-response at large radius are asymmetrical and broader due to tilt of the crystal and depth of interaction

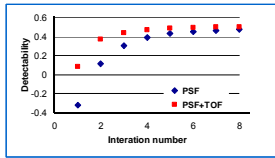
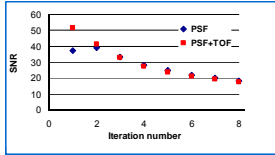
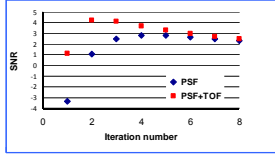


AW-OSEM linearly interpolates between sinogram bins (red line)
PSF interpolates between sinogram bins with measured spatially-variant point spread functions (green line)

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



TOF prototype: SNR and detectability



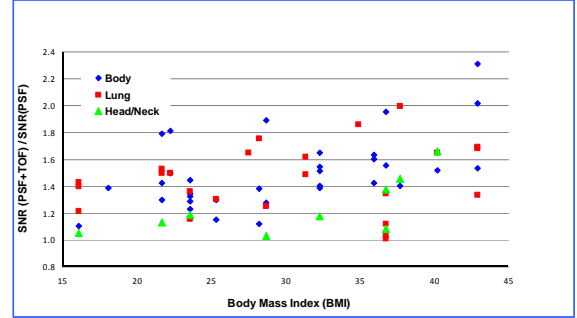
SNR

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

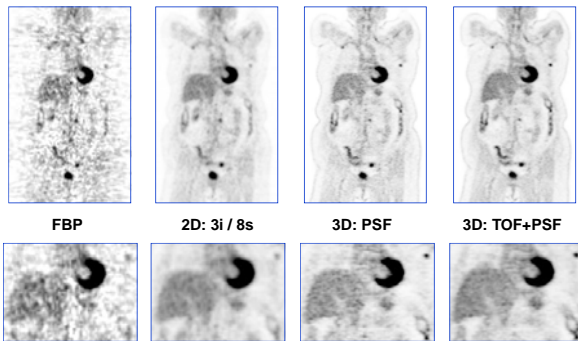
Detectability

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

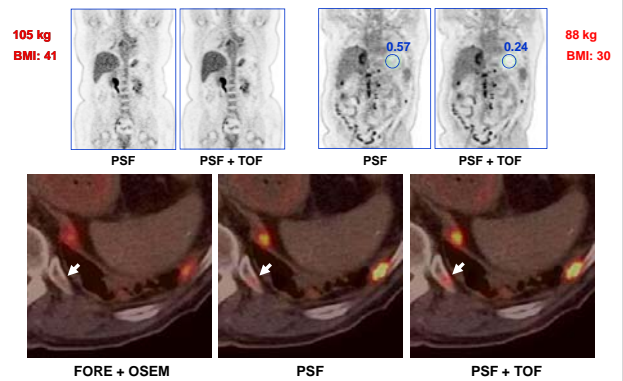
SNR gain as a function of BMI ($SNR_{TOF} / SNR_{non-TOF}$)

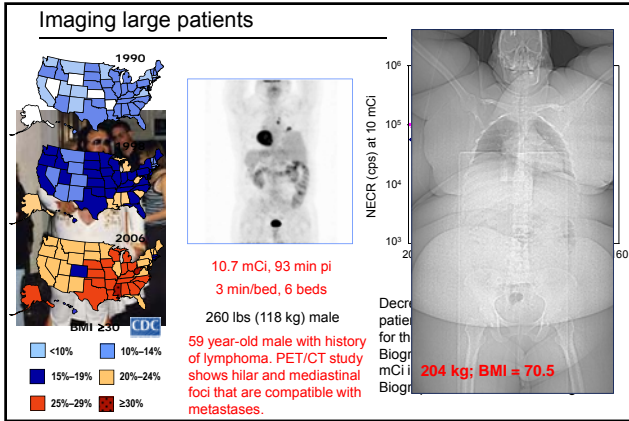


Reconstruction algorithms with TOF



Patient studies





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

Detector

511 keV

511 keV

< 511 keV

Patient outline

Detector

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

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

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

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

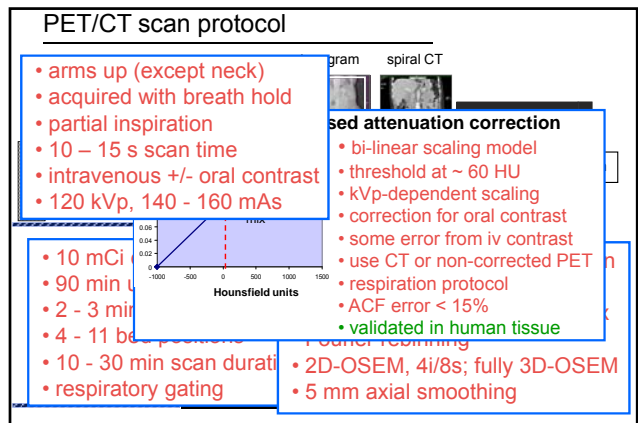
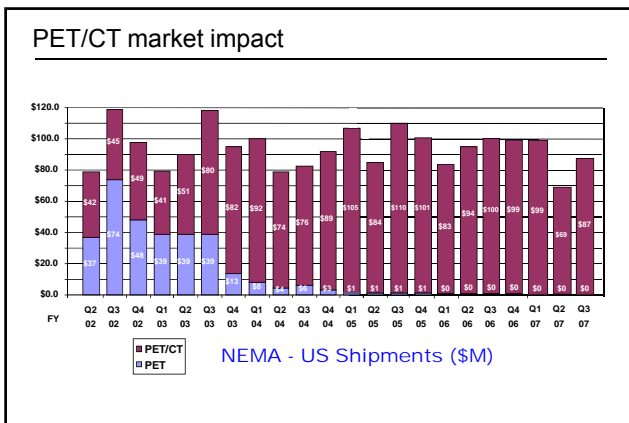
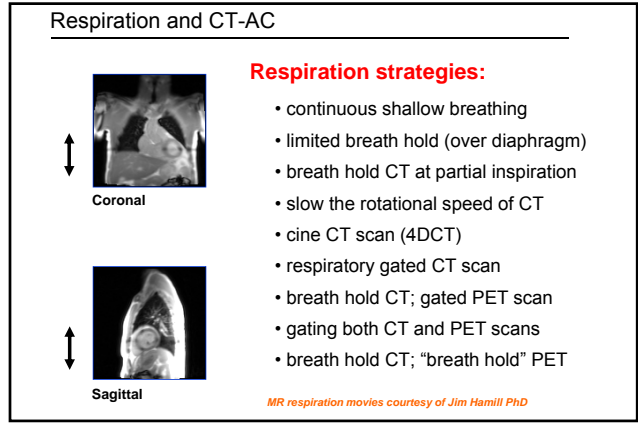
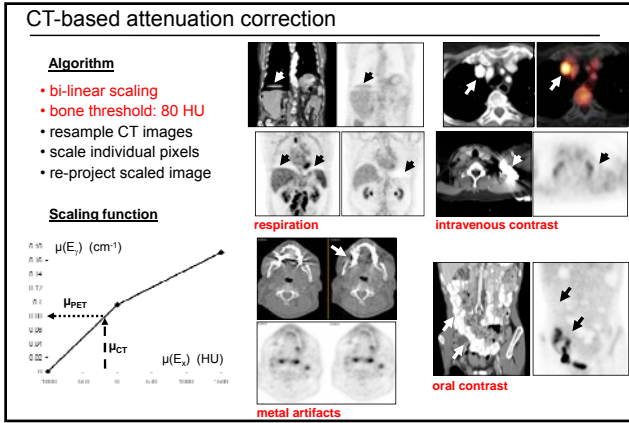
$I_0 = I \left\{ \exp\left[+\int_{x_1}^{x_2} \mu(x) dx\right] \right\} = I \cdot \text{ACF}$

CT-based attenuation correction

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

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

ρ_e = electron density; $\sigma_c(E)$ = Compton; $\sigma_{pe}(E)$ = photoelectric
 Z_{eff} = effective atomic number



PET/CT:

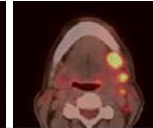
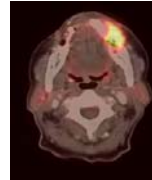
- for staging disease
- for therapy planning
- for monitoring response

Mandibular cancer

biograph 16

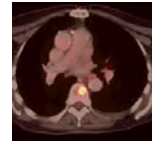


Molecular Imaging and Translational Research

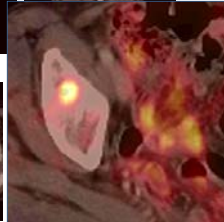


83 year-old female with mandibular cancer. PET/CT scan acquired pre-surgery identified 3 left-side positive nodes 5-12 mm in size with increased FDG uptake. Post surgery, pathology identified 35 nodes positive for cancer.

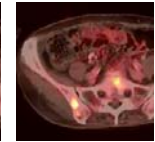
Primary (1.5 x 3.8 cm)



5 mm lytic spine lesion



Bone lesions, 6-7 mm in diameter

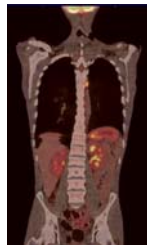


Lung cancer

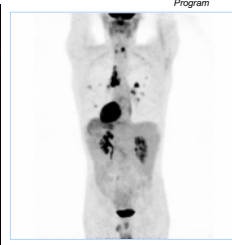
Biograph 6 TrueV



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



PET/CT

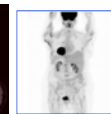
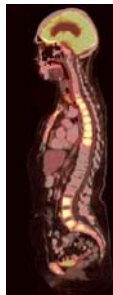


Scan duration: 10 min

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



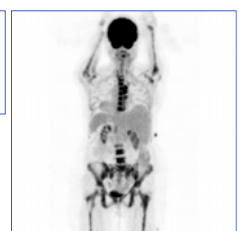
Feb 2007



CT



PET/CT

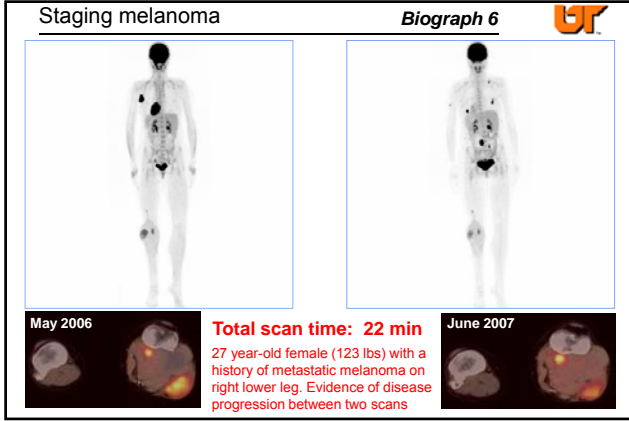


July 2007

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.

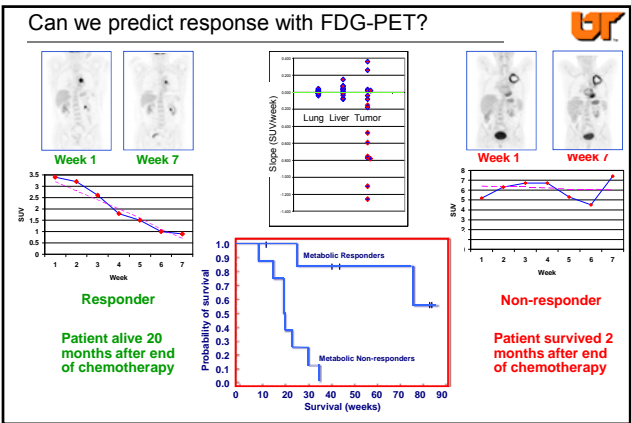
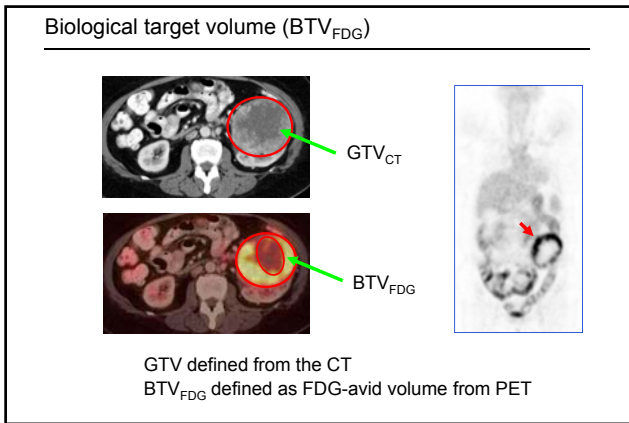


Has PET/CT made a real difference?

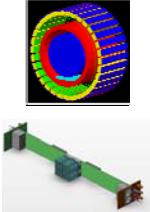
PET/CT compared to PET and CT: average over all cancers is 10-15% improvement

- **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




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

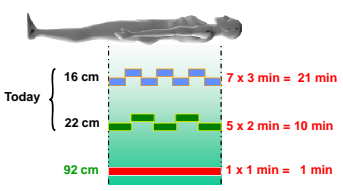
Challenges for MR/PET

- ✓ 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



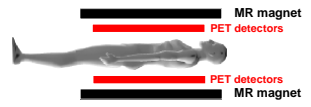
Into the future....

PET/CT




16 cm	7 x 3 min = 21 min
22 cm	5 x 2 min = 10 min
92 cm	1 x 1 min = 1 min

PET/MR S. Cherry (UCD)



MR magnet	PET detectors
MR magnet	PET detectors

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

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Pam Trentham



...and now on your iPhone

National Cancer Institute