PET/CT Scanner Designs and Characteristics

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Have a seat Kermit. What I'm about to tell you might come as a big shock.....

Making a diagnosis from imaging

FDG brain scan

Normal CT
Normal PET

Diagnosis from anatomy.....
Diagnosis from function...


PET/CT
PET/MR
SPECT/CT

Cherry, Mandel et al
Beyer, Nutt et al
Hasegawa, Lang et al

PRT-1
PET/CT: artist's impression

PET detectors (BGO)
CT detectors (Xe)

First FDG brain study on PRT-1, May 1991

The Geneva PRT Camera Project 1990 - 1992

PET/CT PET/CT PET/CT PET/CT
PET/CT PET/CT PET/CT PET/CT
SPECT SPECT SPECT SPECT
PET PET PET PET

PET detectors (BGO)
CT detectors (Xe)
PET/CT prototype design, 1998

PET/CT imaging, 1998-2001

Early PET/CT recognition

PET/CT Project, 1995 - 1998

PET/CT prototype

Thomas Boyer
Paul Kinahan
Claude Comtat
David Brasse
Hugo Embert

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

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As always.....the skeptics

"I think fusion is overhyped 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 physiciaans would prevent development of this special system."

"I hate to say it, but radiologists and nuclear medicine doctors 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."

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skepticism: an attitude of doubt or a disposition to incredulity either in general or toward a particular object (e.g. PET/CT)

• PET/CT will be too expensive
• PET will restrict access to CT
• now costs less than PET-only
• majority perform PET/CT scans
• CT now takes 5-10 min total
• AC now used routinely
• dual certified PET/CT techs
• dual-boarded physicians
• many places generate one report
• progress resolving most issues...

Fused image accurately localizes uptake into a lymph node and thus demonstrates spread of disease. Fused images can improve staging of head and neck cancer

• 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

Gantry dimensions: 228 cm x 200 cm x 168 cm
CT rotation: 0.4 s; 16 slice

Dual-modality imaging range
PET/CT design choices

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

PET/CT patient support designs

PET/CT scanner status in 2008

**Discovery**

ST, ST, Rx

**Biograph**

GXL, TF

**Gemini**

GSX, TF

**SceptroP3**

LSO 4.4 x 4.4 x 25 mm³, 2D only, rotating 4 slice CT

**Aquiduo**

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

**updates**

- 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

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>LSO</th>
<th>GSO</th>
<th>BGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/ml)</td>
<td>7.13</td>
<td>6.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Effective Z</td>
<td>74</td>
<td>61</td>
<td>66.4</td>
</tr>
<tr>
<td>Decay (ns)</td>
<td>30-60</td>
<td>35-45</td>
<td>41</td>
</tr>
<tr>
<td>Timing (ps)</td>
<td>200</td>
<td>585</td>
<td></td>
</tr>
<tr>
<td>Light (ph/MeV)</td>
<td>8,200</td>
<td>10,000</td>
<td>30,000</td>
</tr>
<tr>
<td>% NaI</td>
<td>15</td>
<td>25</td>
<td>80</td>
</tr>
</tbody>
</table>

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

\[ \Delta t = \left\{ t_B - t_A \right\} \]

\[ \text{SNR}_{\text{TOF}} = \frac{\text{SNR}_{\text{non-TOF}}}{\frac{\Delta t}{2}} \]

TOF PET performance:
- Timing resolution: 650 ps
- 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

Non-TOF TOF
60 s scan duration

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

Non-TOF TOF
114 kg; BMI = 38.1
12 mCi; 2 hr pi 3-min bed position

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
Discovery STE

Crystal dimensions, mm: 4.7 x 6.3 x 30
- Number of blocks: 280
- Number of rings: 4
- Number of crystal rings: 560
- Number of detector rings: 24
- Ring diameter: 88.6 cm
- Total number of crystals: 13,440

Transverse resolution:
- @ 1 cm (mm): 5.1 (2D), 5.2 (3D)
- @ 10 cm (mm): 5.6 (2D), 5.6 (3D)

Axial resolution:
- @ 1 cm (mm): 4.7 (2D), 5.4 (3D)
- @ 10 cm (mm): 6.0 (2D), 6.0 (3D)

System sensitivity – 3D: 8.47 cps/kBq
- 2D: 2.2 cps/kBq
- Peak NECR – 2D: 87.9 kcps @ 44.9 kBq/cc
- Peak NECR – 3D: 75.1 kcps @ 12.8 kBq/cc

Scatter fraction – 2D: 21%
- 3D: 34%

Coincidence window: 9.6 nsec

Energy window settings:
- 2D: 375-650 keV
- 3D: 425-650 keV

System sensitivity – 2D: 8.47 cps/kBq

Effective AFOV (cm): 12.5 (3D), 13.7 (2D)

Detector material: BGO

511 keV Stopping power: 95%

Hygroscopic: No

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: LSO

511 keV Stopping power: 80%

Hygroscopic: No

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

Low BMI

High BMI

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
  - NECmax: 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

Courtesy Osama Malawi PhD, MD Anderson Cancer Center
NEMA NU-2 2001 performance measurements

<table>
<thead>
<tr>
<th>Scatter (%) (425 keV – 655 keV)</th>
<th>Noise Equivalent Count Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biograph</td>
<td>Scatter (Biograph)</td>
</tr>
<tr>
<td>34</td>
<td>50</td>
</tr>
<tr>
<td>Biograph TP</td>
<td>Scatter (Biograph TP)</td>
</tr>
<tr>
<td>34</td>
<td>60</td>
</tr>
</tbody>
</table>

Peak NECR (kcps)

<table>
<thead>
<tr>
<th>Activity (kBq/ml)</th>
<th>Peak NECR</th>
<th>Activity (kBq/ml)</th>
<th>Peak NECR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Biograph</td>
<td>94 @ 34 kBq/ml</td>
<td>Biograph</td>
</tr>
<tr>
<td>20</td>
<td>Biograph</td>
<td>101 @ 31 kBq/ml</td>
<td>Biograph</td>
</tr>
</tbody>
</table>

Spatial resolution ($\Gamma$)

\[ \Gamma = 1.25 \sqrt{(D^2) + (0.0022D)^2 + r^2 + b^2} \]

- $d$ = 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

<table>
<thead>
<tr>
<th>Sphere diameter (mm)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0 mm x 4.0 mm</td>
<td>22</td>
</tr>
<tr>
<td>6.4 mm x 6.4 mm</td>
<td>28</td>
</tr>
<tr>
<td>13 x 13</td>
<td>37</td>
</tr>
</tbody>
</table>

Improving the imaging system model

**Attenuation-weighted OSEM**

\[ i_j^{i+1} = \frac{1}{\sum P_{i,j}} \left[ \sum P_{i,j} \cdot \left( \sum P_{j,i} \cdot i_j^i \right) \right] \]

**Ordinary Poisson OSEM**

\[ i_j^{i+1} = \frac{1}{\sum P_{i,j}} \left[ \sum P_{i,j} \cdot \left( \frac{1}{n_i} \cdot a \right) + \left( r_i + n_i + c \right) \right] \]

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

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

**Advances in reconstruction techniques**

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

<table>
<thead>
<tr>
<th>Tumor</th>
<th>SUVmax / SUVmean Tumor</th>
<th>SUV @ 60 min</th>
<th>SUV @ 90 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>8.7 / 6.6</td>
<td>4.59</td>
<td>6.94</td>
</tr>
<tr>
<td>#2</td>
<td>5.9 / 4.2</td>
<td>4.55</td>
<td>7.04</td>
</tr>
<tr>
<td>#3</td>
<td>10.0 / 6.4</td>
<td>4.46</td>
<td>7.18</td>
</tr>
</tbody>
</table>

Contrast = \[
\frac{\text{Mean ROI hot spot}}{\text{Mean ROI background}}
\]

+ 29% SUV change for different reconstructions
+ 40% SUV change at two different time points
TOF prototype: SNR and detectability

![Graph showing SNR and detectability](image)

### SNR
\[
\frac{\langle S \rangle - \langle B \rangle}{\sigma_S}
\]

### Detectability
\[
\frac{\langle S \rangle - \langle B \rangle}{\sqrt{\sigma_S^2 + \sigma_B^2}}
\]

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

![Graph showing SNR gain](image)

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
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 consistent 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)


Attenuation

Patient outline

Detector

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

CT: \( \mu(E_{70}) = p_e \left( \sigma_c(E_{70}) + \sigma_{pe}(E_{70}, Z_{eff}) \right) \)

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

\( Z_{eff} \) = effective atomic number

\( I = I_0 e^{\mu x} \)

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

CT-based attenuation correction

\( I = I_0 \left\{ \exp \left[ \int_{x_1}^{x_2} \mu(x) \, dx \right] \right\} = I \cdot ACF \)
CT-based attenuation correction

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

Scaling function

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

Scalibng function

Respiration and CT-AC

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

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

PET/CT market impact

NEMA - US Shipments ($M)
PET/CT:
- for staging disease
- for therapy planning
- for monitoring response
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: 99% vs 83% PET; 73% CT
- Thyroid
  Accuracy: 93% vs 79% 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

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

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

The Future

PET biomarkers

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

The Future
UTGSM Molecular Imaging and Tracer Development Program

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Pam Trentham

National Cancer Institute

...and now on your iPhone