Evolution of Data Acquisition and Processing in Medical Imaging with Radiation

Roger Lecomte, Ph.D.
Outline

• Background

• Historical review of PET

• Preclinical PET scanner developments
  – 1st APD PET system
  – LabPET™ developments

• Current and future directions
  – Multimodality PET/CT
  – Time-of-flight PET
Medical Imaging Modalities

Using ionizing radiation:
- X-ray
  - Radiography
  - Computed Tomography (CT)
  - Spectral CT
- Nuclear medicine
  - Planar scintigraphy (gamma camera)
  - Single Photon Emission Computed Tomography (SPECT)
  - Positron Emission Tomography (PET)

Using non-ionizing radiation:
- Ultrasound (US)
- Magnetic Resonance Imaging (MRI)
- Optical
- ...
Imaging Modalities using Radiation

- Panel detectors
  - Compact arrays of pixel detectors

PET
- Radioactive tracer
- Scintillation detectors
### Information Required for Medical Imaging

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CT</th>
<th>SPECT</th>
<th>PET</th>
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</thead>
<tbody>
<tr>
<td>Position</td>
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<td>✓*</td>
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<td>Energy</td>
<td>(✓)**</td>
<td>✓✓</td>
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<tr>
<td>Time</td>
<td>Frame rate</td>
<td>-</td>
<td>✓✓ ToF***</td>
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</table>

* (x,y) + Depth-Of-Interaction (DOI)
** Spectral counting CT
*** Time-of-flight
Positron Emission Tomography (PET)

Dynamic imaging of *in vivo* processes

Tracer concentration vs Time

Unstable radiotracer

PET scanner in action

Coincidence processing unit

Sinogram or list-mode data

Image reconstruction

Radiotracer concentration

Time

Brain PET Image

Time-Activity curves

✓ Dynamic imaging of *in vivo* processes
✓ Tracer concentration vs Time
First Medical Application of Positrons - 1952

- Idea to use annihilation radiation for measuring internal structures first proposed in 1951 by Sweet\(^1\) and Wrenn\(^2\).

- First clinical positron imaging device, two coincident NaI(Tl)-PMT detectors with 2-D scanning motion, used in 1952 to obtain images of radiotracer distribution in the brain by Brownell at Massachusetts General Hospital.\(^3\)

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1973-74: “PETT II” hexagonal array, 24 NaI(Tl) detectors, Ter-Pogossian et al., Washington University, St.Louis.

1977-78: Positome II
First BGO PET scanner
64 BGO detectors
C.J. Thompson, Montreal Neurological Institute.
The Race to Higher Resolution

- **1977:** Positome II-IIIp: 64-128 BGO detectors → ~1.5 cm FWHM
- **1978:** PETT III / Ortec ECAT II (1st commercial PET scanner)
  - 96 NaI(Tl) detectors → 9.5 mm FWHM
- **1981:** Donner-280: 280 NaI(Tl) → BGO detectors
  - 8 mm NaI(Tl) / 9.5 mm BGO → ~8 mm FWHM
- **1986:** Donner-600: 600 BGO detectors
  - ✓ 3 mm BGO → 2.6 mm FWHM
  - ✗ Single detector ring

- **Semiconductor detectors**
- **Solid state photodetectors**
- ✓ **Crystal coding**

The Race to Higher Resolution

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- 1981: Donner-280: 280 NaI(Tl) → BGO detectors
  - 8 mm NaI(Tl) / 9.5 mm BGO → ~8 mm FWHM
- 1986: Donner-600: 600 BGO detectors
  - 3 mm BGO → 2.6 mm FWHM
- 1990: BGO block detectors
  - 4 mm BGO → 3.8 mm FWHM
- 1998: LSO quadrant sharing detectors
  - 4 mm LSO → 2.8 mm FWHM

Block Detectors for PET Scanners

- Up to 361 (19×19) pixels in 4 electronic channels
- Can be processed by analog or digital electronics

\[
R_x = \frac{A + B}{A + B + C + D}
\]

\[
R_y = \frac{A + C}{A + B + C + D}
\]
# Evolution of PET Image Quality

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>Image Quality</th>
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<tbody>
<tr>
<td>PET III</td>
<td>1975</td>
<td></td>
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<tr>
<td>ECAT II</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>NeuroECAT</td>
<td>1978</td>
<td></td>
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<tr>
<td>ECAT 931</td>
<td>1985</td>
<td></td>
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<tr>
<td>ECAT EXACT HR+</td>
<td>1995</td>
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</table>

**Radioisotopes:**

- $^{18}$F-FDG
- $^{18}$F-FP-β-CIT

The Race to Higher Sensitivity

2D → 3D Configuration of PET Scanners

- 5 to 7-fold gain in absolute sensitivity
- Increased scatter, randoms, deadtime
The Race to Higher Sensitivity

ECAT EXACT (1993)

HRRT (1998)

Dual-layer phoswich for DOI measurement*

Evolution of Technology

Electronic devices

PET scanners

Moore’s Law

Nutt’s Law
Evolution of Technology

UC Davis Total-body PET Scanner
Cherry & Badawi

- Total-body PET scanner (~2 m long)
- ~40-fold gain in sensitivity, 30 s scans
- 8x more detectors (~10^6 crystals)
- $15.5M
Spatial Resolution in PET*

\[
FWHM = a \sqrt{\left(\frac{d}{2}\right)^2} + b^2 + (0.0022D)^2 + r^2
\]

**Tomographic reconstruction**
1.1 < \(a\) < 1.3
\((a=1: \text{no recons.})\)

- **Geometric**
  - Detector size (triangular)
- **Coding**
- **Non-collinearity**
- **Positron range**
  - Ring diameter: \(D=10-80\) cm
  - \(\approx 0.2-2\) mm
  - \(^{18}\text{F}:\)
  - ~0.1 mm FWHM
  - ~0.5 mm rms

**Detector**

**Physical limit**
\(\approx 0.4 - 0.7\) mm

- **FWHM**: Full Width at Half Maximum
- **\(a\)**: Factor accounting for resolution degradation due to tomographic reconstruction
- **\(d\)**: Detector size
- **\(b\)**: Detector positioning accuracy
- **\(D\)**: Distance between coincident detectors (~ring diameter)
- **\(r\)**: Positron range in tissues

Spatial Resolution in PET

\[ FWHM = a \sqrt{(d/2)^2} + b^2 + (0.0022D)^2 + r^2 \]

Coding

Positioning accuracy ≠ Intrinsic (geometric) resolution!!
Coding effect in PET Scanners

Source size \{ Non-colinearity \} Subtracted

Coding vs Non-Coding

**Analog coding**
- Large area photodetectors
- Low channel nb
- Mature technology (PMT)
- High gain (>10^6), low noise
- Inexpensive

- Limited spatial resolution
- Spatial distortion
- High dead time
- Low max count rate

**Direct 1:1 coupling**
- No coding effect
- No spatial distortion
- High intrinsic spatial resolution
- Low dead time
- High max count rate

- Pixelated readout
- High channel nb
- High cost

Image courtesy of Philips Healthcare
Signals from Detectors

\[ I(t) = I_0 e^{-t/\tau_s} \]

\( \tau_s \): Scintillator decay time

\[ I(t) = \begin{cases} I_0 f(t) & t < T \\ I_0 e^{-t/R_f C_f} & t > T \end{cases} \]

\( T \): Electron collection time

\[ I(t) = I_0 \left( e^{-t/R_f C_f} - e^{-t/\tau_s} \right) \]

\( R_f C_f \): Preamplifier time constant
Technology Developments

• 1986: APD-based detector module for PET

• 1987: Dedicated preamplifier for APD

• 1989: Patent on Depth-of-Interaction (DOI)

- BGO or BGO/GSO crystals
- Commercial product
- Custom analog electronics
- Advent of “block” detector (Casey & Nutt, 1986)
- Nobody could reproduce timing results

⇒ APD detector module unnoticed...
### 1995: Sherbrooke Animal PET Scanner


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Detectors</td>
<td>512 BGO $3 \times 5 \times 20$ mm$^3$</td>
</tr>
<tr>
<td>Resolution</td>
<td>1.75 mm (intrinsic)</td>
</tr>
<tr>
<td></td>
<td>$2.1 \times 2.1 \times 3.1$ mm$^3$ or 14 µl</td>
</tr>
<tr>
<td>Efficiency</td>
<td>200 cps/µCi (0.51%)</td>
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<tr>
<td>Sensitivity</td>
<td>2 kcps/µCi/ml/cm</td>
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<tr>
<td>Timing window</td>
<td>50 ns</td>
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</table>

- Individual readout
- Parallel electronic channels
- Mostly analog processing
• All discrete components
• Front-end in scanner
• Data processing & acquisition in separate crates
2001: 2nd Most Active Preclinical PET Center

Cardiac PET Imaging
Normal rat (270 g)
3.8 mCi $^{18}$FDG 60 min
ECG-gated acquisition

Whole-Body PET Scan
$^{18}$F$^-$ + $^{18}$FDG, 250 g rat

PET Imaging in Oncology
EMT-6 mammary tumors treated by PhotoDynamic Therapy (PDT)
BALB/c mouse (20 g)
400 µCi $^{18}$FDG 60 sec
Next step?

• APD technology still a laboratory development
• Further dissemination of technology not possible
  ✗ Major upgrade necessary
  ✗ Cost reduction mandatory

⇒ Options:
• Redesign detectors
• Update electronics → Integrate front-end
• Marketing agreement with major medical equipment manufacturer ?
• Launch start-up ??
**APD Detector Module**

- Quad APD
- Dual LYSO/LGSO Phoswich
- 8-pixel detectors / module
- 2 mm × 2 mm pixels

<table>
<thead>
<tr>
<th></th>
<th>LYSO</th>
<th>LGSO</th>
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<tbody>
<tr>
<td>Scintillation constant (ns)</td>
<td>40</td>
<td>65</td>
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<tr>
<td>Light yield (% NaI(Tl))</td>
<td>85</td>
<td>40</td>
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<tr>
<td>Emission maximum (nm)</td>
<td>420</td>
<td>420</td>
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<tr>
<td>Refraction index</td>
<td>1.81</td>
<td>1.82</td>
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<tr>
<td>Density (g/cm³)</td>
<td>7.19</td>
<td>6.5</td>
</tr>
<tr>
<td>Effective Z</td>
<td>65</td>
<td>61-65</td>
</tr>
<tr>
<td>Probability of PE (%)</td>
<td>33</td>
<td>30</td>
</tr>
</tbody>
</table>

Pepin et al. *NSS/MIC* 2007
Preamplifier ASIC

- 16/32 channels
- 80 ns peaking time
- 650 e- rms
- 117 mW
- TSMC CMOS 0.81 µm
- Shared with RatCAP development (BNL)

Robert et al. NSS/MIC 2003
Signal Processing

4 main sub-systems

Analog Front-end and Digital Board 48X → Data Concentrator (HUB) 8X → Coincidence Detection Board 1X → Buffering and Communication → 2.0 Gbps Serial Link → Firewire Link

Analog Boards

- 16 X Crystals
- 16 X APD
- Adjustable 500V Regulator

Digital Board

- 16 X CSP
- 32-dual MAX1193 ADC
- DAQ FPGA XC2VP30
- Aurora High speed transceiver

DSP TMS320C6414

To data Concentrator 1X

References:
CF Timing Discrimination

Amplitude detector

Baseline restorer

Time at threshold: \[ t_{th} = t_1 + (y_{th} - y_1) \left( \frac{t_2 - t_1}{y_2 - y_1} \right) \]

Crystal Identification

- Several analog pulse shape discrimination techniques
- Digital implementation:
  - Auto-Regressive Moving Average with eXogenous variable (ARMAX)
  - Vector quantization

Michaud et al. NSS/MIC 2003
Michaud et al. IEEE Trans Nucl Sci 2010
LabPET Pre-commercial Prototype

Digital APD-based PET Scanner

Quad APD, 8-pixel, Phoswish detector module

APD

2 mm

11 mm

LYSO

LGSO

14 mm

Scintillation crystals: 3072 to 9216
APDs & electronic channels: 1536 to 4608
FOV: 3.75 to 11.4 cm axial ×16.2 cmØ
Timing window: 22 ns

Detectors: LYSO/LGSO phoswich
2 × 2 × 12-14 mm³ pixels
Reach-through UV-enhanced APD

Individual readout & fully parallel electronics

- Integrated 16-ch CMOS front-end
- 40 MHz sampling
- Real-time digital signal processing


R Fontaine et al. The hardware and signal processing architecture of LabPET™, a small animal APD-based digital PET scanner. *IEEE TNS* 56:3-9, 2009
**Light/Charge Sharing vs Individual Pixels**

Same resolution can be achieved with pixels twice as large!

**microPET II prototype**
(Tai et al, PMB 2003)
- 0.975 mm LSO
- 64-ch PMT + F.O.
- X-Y Analog decoding

**LabPET**
- 2 mm pixels
- APD readout
- Parallel digital signal processing

(FWHM = 1.22 mm)

(Tai et al, IEEE TNS 2008)

(FWHM = 1.21 mm)
**LabPET™ (2005)**

1st commercial APD-based PET scanner

- **Detector**: LYSO/LGSO $2 \times 2 \times 12-14$ mm$^3$
- **Resolution**: 1.22 mm (intrinsic)  
  1.35 mm isotropic *or* 2.4 µl
- **Efficiency***: 200 cps/µCi (2.5%)
- **Peak NEC***: 252 kcps (mouse phantom)
  
  * LabPET8: 7.5 cm axial FOV

---

Transaxial  
RV

Sagittal

Coronal

LV

20 g mouse, 24 MBq $^{18}$FDG,  
30 min acquisition @ 30 min post-injection

---

200 g rat brain  
77 MBq FDG

---

Lecomte et al,  
IEEE MIC 2004 2006  
SNM 2006  
Fontaine et al,  
IEEE MIC 2004 2005 2006  
Bergeron et al,  
IEEE MIC 2007 2008 2009  
SNM 2008  
IEEE TNS 2009
Scanner Triumph™/LabPET™ (2009)

Resolution 1.2 mm / 1.8 μl
Reconstruction 3D + Physics modeling

Rat 185 g, 31 MBq Na^{18}F (Bone tracer), 60 min acq @ 68 min p.i.

Image Definition in PET

Na$^{18}$F Bone Scans

75 kg human
Clinical PET scanner
(5-6 mm or ~1 cc)

$\times 1/300$

185 g rat
LabPET$^\text{TM}$ (2009)
(1.2 mm or 1.8 µl)

$\times 1/10$

20 g mouse
LabPET$^\text{TM}$
(1.2 mm or 1.8 µl)

~1 µl?
**Spatial Resolution in PET**

\[
\text{FWHM} = a \sqrt{\left(\frac{d}{2}\right)^2 + b^2 + (0.0022D)^2 + r^2}
\]

Tomographic reconstruction

1.1 \textless a \textless 1.3

(a=1: no recons.)

**Geometric**

Detector size

(triangular)

**Coding**

Individual: \( \approx 0 \) mm

Charge: \( \approx 1 \) mm

Light: \( \approx 2 \) mm

**Non-colinearity**

Ring diameter

Source size

**Physical limit**

\( \approx 0.4 - 0.7 \) mm

\( b \approx 0 \)

\( d \approx 1.2 \) mm

\( b \approx 0.5 \) (scaled)

\( d \leq 0.5 \) mm

\( \leq 1.0 \) mm \( \Rightarrow \)

\( \approx 0.7 \) mm

Challenges

• Channel density x10
• Photodetector & front-end electronics packaging
• Power management (digital processing)
• Digital electronics prohibitively costly for large scale applications
  ✗ Power consumption/channel must be decreased
  ✗ Cost reduction mandatory

⇒ Solutions:
• Redesign detectors
• Update electronics → Integrate analog front-end
  → Simplify signal processing to integrate
LabPET II Detector Development

- 4 × 8 APD/LYSO array
- 1.12 × 1.12 mm² pixels
- One-to-one coupling
- FWHM/FWTM = 0.82/1.54 mm
- FWTM < 2×FWHM (∆ shape)
- Detector resolution: 0.73 mm
- Sub-mm image resolution expected!


✓ Counting CT imaging capability
✓ Can be made MR-compatible
Information in Signal from Detectors

Characteristics:
- Polarity
- Rise/Fall time
- Amplitude
- Area
- Baseline
- Noise
- Rate

Amplitude → peak detector + ADC ⇒ Energy
Pulse start → LE/CF discriminator ⇒ Time
Pulse shape (e.g. rise time) ⇒ Positioning

Complex, hi-power, costly electronics!
**Time over Threshold (ToT)**

- Dual thresholds to achieve better precision

![Graph showing detector signal and noise analysis of signal with thresholds T1, T2, T3, and T4.]

- Relative voltage for different energy pulses (V) vs. Time (ns)
- Noise analysis of signal with On and Off times indicated at T1 and T3.
LabPETII 64-channel Front-End ASIC

- HV regulator
  - 0 to -450 V
  - 0.5 V increment

- Temperature sensor
  - 0 to 100°C
  - 1°C accuracy

- DLL (312.5 ps)

- Programmable charge injector:
  - ASIC functionality test before assembly
  - Automated channel gain calibration

- Digital data processing

- Analog channel (×64)

- TSMC 0.18 µm
  - 5.9 mm × 4.6 mm
  - ~ 480 mW

Arpin et al, IEEE NSS/MIC 2011
64-channel Mixed Signal ASIC

- 64-channel analog/digital processing
- Time-over-Threshold (ToT) scheme
- Dual threshold, 64 on-chip counters
- 100 MHz clock rate
- 2 Mevents/s LVDS data transfer rate
- 400 mW
- TSMC 0.18 µm CMOS technology
- Prototypes made through CMC Microsystems

Arpin et al, IEEE NSS/MIC 2011
ToT Results

Measured ToT Spectra

Corrected Energy Spectra

Non-linear energy calibration

E Gaudin et al. Performance characteristics of a dual-threshold Time-over-Threshold APD-based detector front-end module for PET imaging. *IEEE TNS/MIC 2015, N2AP-102*
LabPETII Detector Front-End

- 4x8 crystal arrays
- 4x8 APD arrays
- Ceramic carrier
- Daughter board
- 64-channel ASIC
- Std connector

Modular design

128-ch module

Crystal arrays

ASIC

CMC Microsystems
Agile Technologies
Excelitas Technologies

LabPETII DAQ System

LabPET II Generic Detector Technology

- **Mouse Scanner**: 6,144 channels
- **Rat Scanner**: 24,576 channels
- **Rabbit Scanner**: 49,152 channels
- **Human Brain Scanner**: 129,024 channels
LabPETII Mouse Scanner

Analytical System Matrix Computation
(J-D Leroux, personal communication)

✓ ~0.8 mm resolution achieved
✓ DOI desirable

79 mm ID
30/45/60 mm FOV
51 mm axial

6144 channels
4×8 crystal arrays
4 crystal arrays / module
128-ch modules
12 modules/ring → 192 pixels/ring
4 rings of modules → 32 pixel rings
48 detector modules
LabPET II (Mouse) First Image

Prototype Mouse Scanner

- Rod source 1.52 mmØ
- 10 MLEM iteration
- Analytical system matrix
- ~1.6 mm FWHM
- No efficiency normalisation
- Still detector misalignment
Current and Future Developments

- Combined dual modality PET/CT
- Time-of-Flight PET
Dual Modality PET/CT

NEMA - US Shipments ($M)

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<tr>
<th>FY</th>
<th>Q2</th>
<th>Q3</th>
<th>Q1</th>
<th>Q2</th>
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<td>$14</td>
<td>$14</td>
<td>$16</td>
<td>$16</td>
<td>$11</td>
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</table>

CT  PET  Fusion
Using PET Detectors for CT?

Motivation

✓ Common detection system
✓ Reduced cost
✓ Concurrent (simultaneous?) imaging of anatomy and molecular processes
✓ Perfect co-registration of PET and CT images in *space* and *time*
  ⇒ Co-registered dynamic image series
  ⇒ Correction of motion in CT image

Challenges

❓ Compromises on PET, CT, or both

Opportunity

✓ PET detectors are photon counting

Hardware fusion of PET & CT
**Spatial Resolution in μCT**

\[
F_{\text{WHM}}_{\text{total}} \approx \sqrt{F_{\text{WHM}}_{d}^2 + F_{\text{WHM}}_{x}^2}
\]

\[
F_{\text{WHM}}_{d} \approx 2.35 \left( \frac{1}{M} \right) \frac{\Delta x}{2}
\]

\[
F_{\text{WHM}}_{x} \approx M \times X_f
\]

- **\(F_{\text{WHM}}_{d}\)**: detector resolution
- **\(F_{\text{WHM}}_{x}\)**: projection blurring due to X-ray focal spot size
- **\(\Delta x\)**: pixel size
- **\(X_f\)**: focal spot size (FWHM)
- **\(M\)**: Magnification
  \[
  M = \frac{d_{xs} + d_{sd}}{d_{xs}}
  \]

Spatial Resolution in μCT

- Microfocus X-ray source and magnification required for best performance
- Range of allowed magnification with X-ray source inside PET ring

- Rat: ~500 μm @ M=3.0
- Mouse: ~400 μm @ M=3.7
Proof of Concept

- LabPET detectors & digital DAQ
- X-ray tube: 65 kVp, 20 μA, 50 μm focal spot
- Magnification M=2
- 16 2×2 mm² LYSO pixel detectors
- Parallel FBP (Nyquist cutoff)

✓ Biological tissue-like materials can be discriminated with sufficient accuracy

<table>
<thead>
<tr>
<th>Material</th>
<th>Average (HU)</th>
<th>Standard deviation (HU)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Air hole</td>
<td>-967.0</td>
<td>17.5</td>
<td>1.2 x 10⁻³</td>
</tr>
<tr>
<td>2. Polystyrene</td>
<td>-89.5</td>
<td>17.6</td>
<td>1.06</td>
</tr>
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<td>3. Polyethylene</td>
<td>-123.6</td>
<td>18.4</td>
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<td>4. Teflon</td>
<td>306.4</td>
<td>37.1</td>
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<td>5. Nylon</td>
<td>58.0</td>
<td>15.8</td>
<td>1.15</td>
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<td>6. Polycarbonate</td>
<td>35.5</td>
<td>16.0</td>
<td>1.2</td>
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<tr>
<td>Plexiglas</td>
<td>107.6</td>
<td>18.1</td>
<td>1.19</td>
</tr>
</tbody>
</table>

~ Lung
~ Fat
~ Fat
~ Bone
~ Soft tissue
~ Soft tissue
~ Porous bone

Counting CT Imaging

✓ Counting CT imaging with LabPET detectors and electronics

3D rendering of bone and tissues with corresponding axial slices obtained with CT WB scan (75 slices)

20 g mouse
Resolution: ~1.18 mm (M=2)
Acquisition Time: 500 ms (<3 min/slice)

2009 NPSS-MIC Poster Student Paper Award
Counting CT Imaging

- Counting CT imaging with LabPET detectors and electronics


2009 NPSS-MIC Poster Student Paper Award
**PET/Counting CT Image Fusion**

1st PET/CT images with PET detectors

**CT**

**PET**

**PET/CT**

Na$^{18}$F (2 mCi) PET/CT image fusion of slice through lungs of mouse (CT: 1 s; PET: 10 min)

$^{18}$FDG (2 mCi) PET/CT image fusion of slice through heart of mouse (CT: 1 s; PET: 10 min)


2009 NPSS-MIC Poster Student Paper Award
Counting CT Imaging with LabPET II

- cCT imaging with LabPET II detectors and electronics

LabPET II detector modules (8×8 LYSO arrays) (1.2×1.2 mm² pixels)

µfocus 90 kV X-ray tube (65 kV, 200 µA)

Motorized rotating/translating stages

180 projections over 360°
500 ms time frame
Magnification of 2
OSEM reconstruction (10 iterations)

LabPET/CT

Under construction at CIMS

16.6 cm diam
10.3 mm axial FOV
48 modules / ring
Single ring of LabPET II modules
8 rings of detectors
384 detectors / ring
3072 detector channels

LabPET I ASICs on custom PCB
LabPET I Digital processing
μfocus X-ray tube inside PET detector ring
Count rate capabilities

\[ I = c(E) \times (e^{-t/\tau_p} - e^{-t/\tau_s}) \]

\( \tau_p = 100 \text{ ns} \)

\( \tau_s = 45 \text{ ns (LYSO + APD)} \)

\(~25\% \text{ dead time @ ~} 2.8 \text{ Mcps}~\)

Time-of-Flight PET Systems

Annihilation

\[ t_2 - t_1 \]

LOR

\[ \Delta x = \frac{\Delta t \times c}{2} \]

\[ \Delta t \approx 100 \text{ ps} \]

\[ \Delta d \approx 1.5 \text{ cm} \]

\[ c = 30 \text{ cm/ns} \]

Courtesy Matthias Egger, Philips Medical Systems
Rectal carcinoma  metastases in mesentery and bilateral iliac chains

114 kg; BMI = 38.1
12 mCi; 2 hr post-inj

Data courtesy of J. Karp, University of Pennsylvania
Effective Sensitivity Gain with ToF-PET

\[ \frac{SNR_{ToF}}{SNR_{PET}} = \left( \frac{\Delta x^2}{D^2} \right)^{-1/4} = \sqrt{\frac{D}{\Delta x}} \]

But: \( SNR \propto \sqrt{\text{Nb Events}} \sim \sqrt{\text{Sensitivity}} \)

\[ G = \frac{D}{\Delta x} = \frac{2D}{c\Delta t} \approx \frac{\text{Object Dimension}}{\text{ToF Precision}} \]

40 cm Object
\( \Delta t = 600 \text{ ps} \)
\[ \frac{SNR_{ToF}}{SNR_{PET}} = \sqrt{\frac{40 \text{ cm}}{9 \text{ cm}}} = 2.1 \implies G = 4.4 \]

4 cm Object
\( \Delta t = 60 \text{ ps} \)
\[ \frac{SNR_{ToF}}{SNR_{PET}} = \sqrt{\frac{4 \text{ cm}}{0.9 \text{ cm}}} = 2.1 \implies G = 4.4 \]

Why faster timing in PET?

Sensitivity Gain in ToF-PET

\[ G = \frac{D}{\Delta x} = \frac{2D}{c\Delta t} \approx \frac{\text{Object Dimension}}{\text{ToF Precision}} \]

- **< 300 ps ToF resolution**
  - Rejecting background & scatter events (event collimation)
  - Restoring image quality for limited angle tomography

- **~100 ps ToF resolution**
  - \( \times 10 \) sensitivity gain (or equivalent dose reduction) for brain studies
  - ToF PET of small animals (rat) becomes possible

- **~30 ps ToF resolution**
  - Mouse ToF-PET imaging becomes possible
  - ~5 mm resolution along LOR
  - Direct 3D information in whole-body PET (no more reconstruction!)
No more reconstruction?
Scatter Recovery in ToF-PET

\[ E = \frac{E_0}{2 - \cos \theta} \]
\[ \Delta T = \frac{BS + SO - AO}{c/2} \]

- Backprojection along circular arc
- Iterative reconstruction of both unscattered and scattered events
- Image of trues (unscattered) can be used as a priori information

Scatter Reconstruction from Compton Kinematics

- ~80% single Compton interactions
- \[ \cos \theta = 2 - \frac{0.511}{E'} \quad \theta < 90^\circ \]

\[
\langle P_{AB}(\theta) \rangle = \tau \int_{TCA} \left( \int_S f \, dx \right) \cdot \rho_e(S) \cdot \frac{d\sigma^K_{CN}}{d\Omega} \cdot e^{-\left(\int_A \mu_A \, dl + \int_B \mu_B' \, dl\right)} \cdot \epsilon_{AB} \epsilon'_{BS} \left( \frac{\sigma_{AS} \sigma_{SB}}{4\pi R^2_{AS} R^2_{SB}} \right) dV_S
\]

- Backprojection along circular arc
- Object boundaries allows rejection of one arc
- LE threshold ~250 keV
- Very high energy resolution required

High-energy physics detector

22 m∅ × 40 m
7,000 tons
4,088 Si detectors
50,000 straw detectors
400,000 scintillation detectors

Future PET/MRI scanners

< 80 cm∅ × 25 cm
< 100 kg
~500,000 detectors
1 mm² pixels
Conclusion

✔ PET imaging in small animals nearing equivalent spatial definition as clinical PET imaging in humans (~$10^3$ gain in spatial resolution)

✔ Convergence of imaging modalities (PET/CT, PET/MRI…) appears inevitable for obtaining all potential benefits from PET

✔ ToF-PET in small animals is within reach with recent technological breakthroughs
  ⇒ Conventional tomographic image reconstruction might be avoided
  ⇒ Potential for scatter recovery and higher sensitivity

✔ Still substantial progress to be made in detectors, electronics and system integration
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