Evaluation of a long axial field-of-view PET scanner for non-human primates


eberg@ucdavis.edu
mini-EXPLORER: a long axial field-of-view PET scanner for monkey imaging

- Support PET imaging studies at the California National Primate Research Center (CNPRC)
  - Stem cells
  - Viral sanctuaries

- Investigate changes in scanner performance and image quality with a wide acceptance angle
Constructed from the components of a prototype clinical scanner (Siemens mCT)

- **mCT**
- **Mini-EXPLORER**
- 2x axial FOV
- 0.5x ring diameter
Scanner details

- 192 PMT block detectors
  - 13 x 13 array of LSO crystals (4 x 4 x 20 mm³)
- Timing resolution = 609 +/- 3 ps
- No depth-of-interaction encoding
Detector rings
Coincidence processor
Detector front-end electronics
# Experiment aims

1. Benchmark the scanner performance for monkey imaging.
2. What are the benefits / trade-offs of a wide acceptance angle?

<table>
<thead>
<tr>
<th>Physical performance</th>
<th>Phantom imaging studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Sensitivity</td>
<td>- Image uniformity</td>
</tr>
<tr>
<td>- Noise equivalent count rate (NECR)</td>
<td>- Transaxial spatial resolution</td>
</tr>
<tr>
<td>- Scatter fraction (SF)</td>
<td>- Axial spatial resolution</td>
</tr>
</tbody>
</table>
Physical performance: methods

Measure physical performance over a range of acceptance angles

- Range of acceptance angles applied to listmode data in post-processing

- Coincidence time window determined for each event based on ring difference:

\[ \tau = \frac{\sqrt{(FOV_{trans})^2 + (\Delta z)^2}}{c} + 3\Delta t \] (2.8 ns – 3.6 ns)
Sensitivity

NEMA NU-2 sensitivity:
- 70 cm line source inside 1 – 5 aluminum sleeves
- 8 MBq $^{18}$F-FDG
- Histogram listmode data into single slice re-binned (SSRB) sinograms for each acceptance angle
- Extrapolate sensitivity to zero aluminum thickness to compute scanner sensitivity
Sensitivity

Axial sensitivity (46 deg.)

Total sensitivity vs. acceptance angle

Expected = 5.2x (change in solid angle)

5.1x gain

Center

10 cm offset

Axial position (cm)

Sensitivity (%)

0 5 10 15 20 25 30 35

Acceptance angle (deg.)

Sensitivity (%)

0 1 2 3 4 5 6

mCT

MO6-4  Eric Berg, et al
Noise equivalent count rate and scatter fraction

Monkey NU-4 scatter phantom
- 10 cm diameter
- 40 cm length
- 350 MBq $^{18}$F-FDG
- Count rates (trues, scatters, randoms) extracted from SSRB sinograms for each acceptance angle (NEMA NU-4 2008 methods)
**Noise equivalent count rate (NECR)**

\[
NECR = T \frac{T}{T + S + R}
\]

<table>
<thead>
<tr>
<th>Acceptance angle (deg.)</th>
<th>15</th>
<th>28</th>
<th>38</th>
<th>46</th>
</tr>
</thead>
<tbody>
<tr>
<td>NECR (kcps)</td>
<td>895</td>
<td>1466</td>
<td>1707</td>
<td>1741</td>
</tr>
</tbody>
</table>

![Graph showing NECR vs Activity for different angles](chart)
Scatter fraction

\[ SF = \frac{S}{T + S} \]

### Average SF up to peak NECR

<table>
<thead>
<tr>
<th>Acceptance angle (deg.)</th>
<th>15</th>
<th>28</th>
<th>38</th>
<th>46</th>
</tr>
</thead>
<tbody>
<tr>
<td>NECR (kcps)</td>
<td>15.6</td>
<td>16.1</td>
<td>16.4</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Graph showing scatter fraction (%) against activity (MBq) for different acceptance angles (15, 28, 38, 46 degrees).
Phantom imaging

1) Uniform cylinder

2) Derenzo hot-rod

3) Axial bars

Image uniformity
10 cm diameter, 50 cm length

Transaxial spatial resolution
Rod diameter: 2 mm – 7 mm

Axial spatial resolution
Bar widths: 2 mm – 9 mm
Image reconstruction

- List-mode ordered subsets expectation maximization (LM-OSEM).
- Accurate resolution model in the system matrix (PSF modeling).
- Image voxel size: 0.5 x 0.5 x 2.0 mm$^3$.
- Time-of-flight (TOF) with 609 ps kernel FWHM.
- Corrections: Normalization and attenuation.
  - Analytically derived $\mu$-map for phantom images.
  - Currently no random and scatter correction.
Normalization

Concentric cylinder normalization phantom

- 4 mm OD (3 mm ID) tubing coiled around 30 cm diameter hollow acrylic cylinder.
- Iterative model-based algorithm to compute normalization factors\(^1\).

Image uniformity: Uniform cylinder images

- 46 degree acceptance angle
- 500 million events
Transaxial and axial uniformity

**Transaxial variation:** Radial line profile through average slice

**Axial variation:** Average pixel value for each axial slice

RMS error from the mean = 0.8%
Derenzo hot-rod phantom

- 46 degree acceptance angle
- 400M events (10 min acquisition, 8 MBq $^{18}$F-FDG)
- 3 iterations, 20 subsets
Axial spatial resolution: effect of acceptance angle

- 400M events for all acceptance angles
- 3 iterations, 20 subsets for all acceptance angles
- Quantify effect of acceptance angle by computing peak-to-valley ratio from line profiles

Average of 20 sagittal slices

15 deg. 28 deg.

19 MO6-4 Eric Berg, et al
Axial peak-to-valley ratio

- **Small bar width**: p/v limited by partial volume and voxel width
- **Large bar width**: p/v converges to ~ 6 – 7
- **4 mm bar width**: maximum relative difference between 15 – 46 deg. acceptance angles (16%)
Conclusions

- **Sensitivity**: 5% total NU-2 sensitivity (5-fold higher than mCT), 15% peak
- **Count rate performance**: up to 1741 kcps peak NECR, 16.5% SF
- **Spatial resolution**: Resolve 3 mm structures transaxially and axially
- **Image quality**: Highly uniform image quality achieved with 46 deg.

Long axial FOV + wide acceptance angle provides high sensitivity with acceptable trade-offs for monkey imaging.
Future work

Mini-EXPLORER is built and ready for imaging studies.
- Upcoming first animal study: canine imaging at UC Davis Vet. Med. before scanner is deployed at the Primate Center
- Investigate impact of wide acceptance angle, long axial FOV on image quality
- Implement all corrections for quantitative imaging
Acknowledgements

**Funding:** NIH R01 CA170874, UC Davis RISE, NSERC Postgraduate scholarship

**EXPLORER team (explorer.ucdavis.edu)**

Ramsey Badawi  
Simon Cherry  
Jinyi Qi  
Terry Jones  
Julien Bec  
Eric Berg  
Martin Judenhofer  
Edwin Leung  
Emilie Roncali  
Xuezhu Zhang  
Bill Moses  
Qiyu Peng  
Joel Karp  
Suleman Surti  
Srilalan Krishnamoorthy

eberg@ucdavis.edu