PET Performance Evaluation of MADPET4: A Small Animal PET Insert for a 7-T MRI Scanner

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* Now with KETEK GmbH, Munich, Germany.
MADPET4
(Munich Avalanche Diode PET 4)

- Small animal PET insert for 7T MRI (Agilent-Bruker)
- Inner diameter: 88 mm
- Outer diameter: 150 mm
- Axial field of view (FOV): 19.7 mm

- The first small animal PET insert with dual layer crystals individually read out by silicon photomultipliers (SiPMs)
- No active electronic components inside MRI and no shielding
MADPET4 Geometry and Detector Modules

- 2640 Ce:LYSO* scintillation crystals in 8 axial rings
- Dual layer configuration for partial depth of interaction (DOI) correction
  - Inner layer crystals: 1.5×1.5×6 mm³
  - Outer layer crystals: 1.5×1.5×14 mm³
- 3D printed low density plastic structure for holding the crystals and optical isolation between them
- All crystals facing the center with minimum gap between the crystals
- Highly symmetric
- Individually read out by SiPMs

* Hilger Crystals, Kent, England.
MADPET4 Geometry and Detector Modules

- **KETEK* PM1150NT SiPMs**
  - 1.2×1.2 mm² active area size
  - High gain (7.6×10⁶)
  - 500 kHz/mm² dark count rate (DCR) at 20°C
  - Breakdown voltage stability with temperature (15 mV/K)

- Performance when coupled to 6 mm Ce:LYSO
  - 14% energy resolution (FWHM)
  - 310 ps coincidence time resolution (CTR)

- With 1.5 m cables and ToT ASIC
  - 24% energy resolution (FWHM)
  - 570 ps coincidence time resolution (CTR)

* KETEK GmbH, Munich, Germany.
MADPET4 Components

• **Inside the MRI scanner:**
  - **Detector Modules**
    - Silicon photomultipliers (SiPMs) mounted on PCBs with USLS connectors
    - Scintillation crystals placed in a 3D printed plastic structure
  - **USLS cables (1.5 m)**
    providing the bias voltage for SiPMs and taking out the SiPM signal
  - **3D printed light-tight plastic cover**
MADPET4 Components

• **Outside the MRI scanner:**

  • Readout electronics(*)
    - PETsys TOFPET ASIC1 for reading the SiPM signal
    - ToT signal digitization on FPGAs
    - Bias voltage supply for the SiPMs

• **Data acquisition (DAQ) computer**
  - Collecting and saving the data from all channels in parallel in list mode format
  - Image reconstruction

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* PETsys Electronics, Oeiras, Portugal. http://www.petsyselectronics.com/
MADPET4 Image Reconstruction and Corrections

- **OS-EM** algorithm using **Monte Carlo** simulated system matrix

- **Polar voxels** used with 264 cylindrical symmetries of the scanner employed in the image reconstruction to reduce the simulation time and system matrix size

- Voxel size of 0.375×0.375×0.375 mm³ used

- Energy calibration and timing alignment were performed
  - 3ns coincidence window used
  - Energy thresholds of 250 keV and 350 keV studied

- Normalization correction applied

- Attenuation, scatter, and random corrections NOT applied

- Images smoothed using a Gaussian filter with 1 mm FWHM

- Slice thickness increased to 1.125 mm (unless otherwise stated)
Outline

• **NEMA NU 4 Performance Measurements**
  • Intrinsitc spatial resolution
  • Scatter fraction and count losses
  • Sensitivity
  • Image Quality

• **Hot-Rod Spatial Resolution Phantom**

• **Simultaneous *in-vivo* PET/MRI Scans of Mouse Heart and Brain**
NEMA Standards Publication NU 4-2008
Performance Measurements of Small Animal Positron Emission Tomographs

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SCOPE

The scope of this document is to propose a standardized methodology for evaluating the performance of positron emission tomographs (PET) designed for animal imaging. The objective is to establish a baseline of system performance in typical imaging conditions, and a concerted effort has been made to develop a procedure that is independent of camera design and applicable to a wide range of camera models and geometries. Camera designs such as circular ring geometry of discrete crystal or continuous block detectors, planar detector (rotating or stationary), continuous crystals, gas avalanche detectors, time-of-flight or non time-of-flight, single slice or multi-slice dedicated PET tomographs and other coincidence-capable imaging systems are covered by this procedure. It is understood that every system to be tested under this standard is able to create transverse sinograms and transverse slice images with a standard, filtered backprojection, image reconstruction algorithm. The software provided or recommended by the manufacturer should be able to accomplish basic functions such as defining and manipulating two-
NEMA NU 4 Performance Measurements

- **Intrinsic spatial resolution**
  - Measured with a $^{22}$Na point source and FBP image reconstruction
  - At two axial positions, at different radial offsets from the center

- **Scatter fraction and count losses**
  - Measured with mouse-like scatter phantom filled with $^{18}$F
  - Performed with activities of 118 MBq to 0.3 MBq

- **Sensitivity**
  - Measured with a $^{22}$Na point source at the center of different axial slices

- **Image Quality**
NEMA NU 4 – Intrinsic Spatial Resolution

- Uniform transaxial resolution up to 15 mm radial offset
- Average radial and tangential resolutions (FWHM) of 1.38 mm and 1.39 mm at the central slice
NEMA NU 4 – Scatter Fraction and Count Losses

<table>
<thead>
<tr>
<th>Energy Thr. (keV)</th>
<th>Peak Noise Equivalent Count Rate (kcps)</th>
<th>Activity of Peak Noise Equivalent Count Rate (MBq)</th>
<th>Scatter Fraction at 1.1 MBq (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>29.0</td>
<td>102.8</td>
<td>18.7</td>
</tr>
<tr>
<td>350</td>
<td>15.5</td>
<td>65.1</td>
<td>7.3</td>
</tr>
</tbody>
</table>
NEMA NU 4 – Sensitivity

![Graph showing sensitivity at 250 keV and 350 keV](image)
NEMA NU 4 – Image Quality

250 keV

350 keV
## NEMA NU 4 – Image Quality

<table>
<thead>
<tr>
<th>Energy threshold</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>%STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 keV</td>
<td>284.3</td>
<td>375.1</td>
<td>203.9</td>
<td>8.3</td>
</tr>
<tr>
<td>350 keV</td>
<td>149.0</td>
<td>232.7</td>
<td>95.8</td>
<td>10.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy threshold</th>
<th>Water-filled</th>
<th>Air-filled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOR</td>
<td>%STD</td>
</tr>
<tr>
<td>250 keV</td>
<td>24.2</td>
<td>0.1</td>
</tr>
<tr>
<td>350 keV</td>
<td>19.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>
NEMA NU 4 – Image Quality

![Graph showing recovery coefficient vs. rod diameter (mm) for 250 keV and 350 keV energies.](image-url)
Hot-Rod Spatial Resolution Phantom

- Phantom contained 13.16 MBq of $^{18}$F and was scanned for 30 minutes
- Energy threshold = 350 keV, Slice thickness = 1.125 mm
- Reconstructed with 3D OS-EM algorithm (20 iterations and 8 subsets)
Simultaneous PET/MRI of Mouse Heart

- Healthy female mouse, anesthetized with 2-3% isoflurane
- 11.5 MBq of $^{18}$F-FDG injected
- Scanned at **45 minutes post-injection** for **5 minutes**
- 350 keV energy threshold
- 3D OS-EM algorithm (3 iterations, 8 subsets, and slice thickness of 0.375 mm).

- **MRI FLASH** sequence (flip angle: $10^\circ$, TE: 2.75 ms, TR: 15 ms)
- Tx: Volume coil  Rx: Two-channel flexible array proton receive surface coil
- MR resolution: 0.3 mm (in all 3 directions)
- Neither PET, nor MR scans were ECG gated
Simultaneous PET/MRI of Mouse Brain

- Healthy male mouse, anesthetized with 2-3% isoflurane
- 6.7 MBq of $^{18}$F-FDG injected
- Scanned at **40 minutes post-injection** for **20 minutes**
- 350 keV energy threshold
- 3D OS-EM algorithm (3 iterations, 8 subsets, and slice thickness of 0.375 mm).
- post filtered with a Gaussian smoothing function with FWHM of 2 mm

- MRI **FLASH** sequence (flip angle: $30^\circ$, TE:0.15 ms, TR: 500 ms)
- Tx: Volume coil  Rx: Two-channel array rigid-housing proton RF mouse brain receive surface coil
- MR resolution: 0.15 mm (in transverse slices), 1 mm slice thickness
Conclusions

- MADPET4 has demonstrated a good overall performance especially in terms of spatial resolution and count rate
  - Considering the short axial FOV of the insert (less than 2 cm) and the low packing fraction of crystals in axial direction
- The insert can be used for small animal multi-modal research applications.

Future Work

- Full study of the MR-compatibility of the system
- Including attenuation, scatter, and randoms correction
- Optimizing the parameters of the Monte Carlo system matrix according to measurement parameters
Acknowledgment

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