Imaging Performance of the Tachyon Time-of-Flight PET Camera


Abstract—Tachyon, a single-ring “demonstration” Time-of-Flight (TOF) PET scanner has been developed to measure the improvement in image quality as a function of the timing resolution. The design of the detector module is optimized for timing by coupling the 6.1x25 mm$^2$ of 6.1x6.1x25 mm$^3$ LSO scintillator crystals onto a 1-inch diameter Hamamatsu R-9800 PMT with super-bialkali photocathode. We characterized the imaging performance of the system. The results show that Tachyon achieved a coincidence timing resolution of 314ps +/- 20ps fwhm over all crystal-crystal combinations, better than any PET camera that has been reported on. Phantom experiments based on the NEMA NU 2-2007 standard were performed to evaluate the basic imaging performance of the scanner including noise equivalent count rates and image resolution.

I. SYSTEM DESCRIPTIONS

Tachyon, a single-ring “demonstration” Time-of-Flight (TOF) PET scanner (Fig. 1) has been developed to measure the improvement in image quality as a function of the timing resolution. The ring diameter of the scanner is 76.6 cm. The complete scanner consists of 192 detector modules with 384 scintillator crystals.

CFD and TDC were developed to measure time and energy of events. A Siemens Cardinal coincidence controller unit with custom-designed FPGA firmware was used to detect coincidence events and upload list mode data to a host PC.

Fig. 2 Pictures of (a) the detector modules and (b) the detector module assembly.

II. SYSTEM CHARACTERIZATIONS

A. Energy resolution and time resolution

The energy resolution of the system is 19.6%±2.3% (mean±SD). (Fig. 3 a). Time jitter in electronics are 79ps±20ps. Time resolution of the detector modules are 230 ps±34ps. Time resolution of the system (defined as of each crystal-crystal combination) is 314ps ±20ps (Fig. 3 b).

NEMA NU-2007 phantom (shown in Fig. 4 a, b) was built to measure the spatial resolution of the scanner. 319 μCi of F$^{18}$ were injected into the phantom in the experiment.

Reconstruction by filtered back projection with no smoothing or apodization was employed. (Fig. 4 c). The spatial resolutions of the system are: At 1 cm radius (P0), transverse FWHM is 5.34 mm; Transverse FWTM is 8.81mm. At 10 cm radius (P1, P2), transverse radial FWHM is 5.40 mm, transverse tangential FWHM is 5.87mm; Transverse...
radial FWTM is 9.58mm; transverse tangential FWTM is 10.52mm.

Fig. 4  (a) The schematic drawing and (b) the picture of the custom-designed NEMA NU-2007 phantom used in spatial resolution measurement. (c) The reconstructed image of the phantom.

C. Noise Equivalent Count Rates (NECR):
  Another NEMA NU-2007 phantom (shown in Fig. 5 a) was built to measure the noise equivalent count rates of the scanner. 42.72 mCi of C\textsuperscript{11} was injected into the phantom in the NECR experiment.

Fig. 5 (a) The picture of the cylinder phantom used in NECR characterization. (b) Count rates and (c) scatter fractions of the system. Because of the small number of scintillator crystals in the system and in each module, it is effectively impossible to saturate the camera. Thus, the maximum NECR is 900 cps, which was obtained at 0.07 MBq/mL, the maximum radiotracer we were allowed to put in the phantom.

III. PERFORMANCE GAIN FROM TOF

A. Image reconstruction algorithm
  An iterative regularized maximum likelihood algorithm is used in the image reconstruction. The system matrix was developed using a theoretical model of event detection based on multiple ray tracing between pairs of detectors coupled with a Gaussian TOF kernel. Time delay correction, TDC nonlinearity correction, detector efficiency normalization, and attenuation correction are incorporated into the system matrix.

B. Cylinder phantom experiment
  FDG with 110\textmu Ci activity were injected in the center cylinder (320cc), and 427\textmu Ci were injected in the outer cylinder (5180cc). The ratio of activities in the center to the outside was 4:1.

  We reconstructed the images of the phantom with and without TOF information (Fig. 6 b–e). The local Contrast Recovery Coefficients (CRC) of all four images were calculated. Table 1 shows that TOF images have higher CRC than non-TOF images.

<table>
<thead>
<tr>
<th>Local CRC</th>
<th>Non-TOF (25 iteration)</th>
<th>TOF (25 iteration)</th>
<th>Non-TOF (50 iteration)</th>
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<td>0.35</td>
<td>0.50</td>
<td>0.65</td>
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</table>

C. NEMA torso phantom experiment
  Fig. 7 shows images of the NEMA torso phantom (3 mCi total activity, 4:1 contrast ratio) reconstructed with and without the TOF information (at matched spatial resolution). The visual improvement provided by TOF is stunning, and the SNR improves by a factor of 2.3.
IV. DISCUSSIONS AND CONCLUSIONS

We constructed a “demonstration” Tachyon TOF PET cameras that achieved 314ps time resolution. Quantitatively experiments show that Tachyon achieved an improved SNR, which matched well with the theoretic estimation.

We are preparing human study using Tachyon to investigate the clinical benefits of TOF PET cameras. We are building a second generation of Tachyon TOF PET camera of the same design but with LaBr3. The expected time resolution is 150ps~200ps (Fig. 8).

![Fig. 8 Preliminary results with LaBr3. (a) 7.0% Energy resolution; (b) 165ps timing resolution.](image)

V. ACKNOWLEDGMENT

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