Analytical Image Reconstruction Strategies for AX-PET Data

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AX-PET Collaboration

Abstract—Axial-PET (AX-PET) concept aims at significant reduction in parallax error and simultaneous improvement in sensitivity and spatial resolution by employing a novel geometry based on stacks of axially oriented long crystals and orthogonally placed wavelength shifter strips. Current AX-PET demonstrator has two modules. Better sampling and larger field-of-view (FOV) are achieved by rotating one of the modules up to ±60°. By using a rotating source, projections can be taken from all possible angles. In this study, we investigate analytical reconstruction strategies for the list-mode AX-PET data. This process consists of pre-processing steps such as construction of 3D sinograms (histogramming) and dedicated geometrical corrections. In histogramming, we used 1, 0.8750, and 0.4375 mm radial and axial sampling with the angular sampling of 1°. The sinograms were constructed by using span9 axial compression scheme. The constructed 3D sinogram data were corrected in order to have homogeneously sampled sinograms and also for the inter-crystal gaps by using transradial bicubic interpolation method. For image reconstruction, we used 3D reprojetcion (3DRP) with Colsher’s filter (as implemented in Software for Tomographic Image Reconstruction, STIR). The physical phantoms were scanned with the two-module AX-PET demonstrator. The quantitative evaluations were performed by calculating the Full Width at Half Maximum (FWHM) values of the fitted Gaussian curves to the manually drawn profiles across the phantom inserts. The preliminary reconstructed phantoms showed that we are able to resolve the NEMA insert down to 2 mm. Moreover, with the reduced parallax error, we are able to obtain more uniform spatial resolution in the transaxial field-of-view.

Index Terms—Radial sampling, angular sampling axial compression, histogramming, micro-Derenzo phantom, NEMA phantom, axial PET, 3D Reprojection, transradial bicubic interpolation gap-filling.

I. INTRODUCTION

Spatial resolution is one of the assessment criteria for the positron emission tomography (PET) systems. Numerous factors influence the spatial resolution of the PET systems. These factors arise from the physics behind the events generation as well as the design features of the PET systems such as size of the crystals, distance between the detectors, depth-of-interaction (DOI) information etc. The spatial resolution of the PET systems also depends on the reconstruction parameters such as number of radial, angular, and axial samples, the amount of axial sampling used in the sinogram construction and the employed reconstruction method.

The simultaneous improvement in the sensitivity and spatial resolution was shown to be possible via recently introduced novel PET geometry, Axial-PET (AX-PET1). AX-PET is based on axially oriented stack of long crystals and orthogonally placed stack of wavelength shifter (WLS) strips. This novel design allows optimization of spatial resolution (crystal and WLS strip dimensions) and sensitivity (more layers) independently. With the AX-PET concept, the improved DOI information of the coincidences reduces the parallax error resulting in more uniform spatial resolution in the field-of-view (FOV). The details of AX-PET were discussed previously in [1, 2].

Previously, the statistical reconstruction results of the AX-PET demonstrator were published in [3]. In this study, we investigate the analytical reconstruction strategies for the 3D AX-PET data. Analytical reconstruction methods are important in characterization of the PET scanners and asked in standards such as FDA and NEMA.

II. AX-PET DEMONSTRATOR SETUP

AX-PET stands for a novel detector design for PET scanners based on axially oriented elongated LYSO crystals and orthogonally placed WLS strips. It aims at a significant reduction of the parallax error combined with improved sensitivity and resolution. In Fig. 1, we show one AX-PET module consisting of a stack of LYSO crystal and WLS strips which are individually read out by Geiger-mode Avalanche Photo Diodes (G-APDs = Silicon Photo-Multipliers, SiPMs).

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and marketed as Multi Pixel Photon Counters (MPPCs). The current design was built with 48 LYSO crystals (of dimensions $3 \times 3 \times 100 \text{ mm}^3$) and 156 WLSs ($0.9 \times 40 \times 3 \text{ mm}^3$). The data are read via 204 channels. While the transaxial coordinates ($x$ and $y$) are discrete (cross section of the crystals), the axial coordinate ($z$) is of continuous nature. The hardware details of the AX-PET module were discussed previously in [1, 2].

The current design of the AX-PET demonstrator consists of two modules. While one of the modules is fixed, the other module can be rotated by up to $\pm 60^\circ$. Therefore, larger and better sampled FOV was obtained by changing the relative angle between the two modules and by rotating the source. In Fig. 2, we illustrate the coverage of two modules in the transaxial plane. It should be noted that one module can be in coincidence with the other module in face-to-face or in an off-the-face configuration ($20^\circ$ in our case). For example, in Fig. 2, the shaded area with the light red color shows the coverage as the coincidences were collected in face-to-face configuration. The extended coverage was obtained by collecting the events from off-the-face configurations when one of the modules was rotated to $\pm 20^\circ$. The shaded area with blue color shows the extension of the coverage obtained with the rotation of the module. The tomographic imaging is obtained by using a rotating source in the field-of-view (FOV). The green line in Fig. 2 illustrates the span of the angles covered as the source is rotated by $20^\circ$. Consequently, rotating the source in 18 steps for each of the two module configurations covers all possible angles within an extended FOV (indicated as blue circle in Fig. 2).

III. HISTOGRAMMING AND IMAGE RECONSTRUCTION

The data from the two-module AX-PET demonstrator with the extended FOV were organized in list-mode format. We used an in-house list-mode data format which consists of the detector coordinates forming LORs in the 3D space. The list-mode data consist of only “golden events” defined as coincidences which are associated with only one hit LYSO crystal and one cluster (set of adjacent activated strips) of WLS strips per module.

In this study, we used three list-mode datasets of the three measured phantoms filled with $^{18}$F aqueous solution (Fig. 3). The measurements were performed at the Animal Imaging Center, ETH-Z, Zurich, Switzerland and at the company Advanced Accelerator Applications, Saint Genis Pouilly, France. (a) The measurement with eight capillaries extending from the center of the FOV to the edge of the FOV. The inner diameter of the scanned capillaries was 1.4 mm and they were 30 mm long. In total 17M counts were collected. (b) The second list-mode data were obtained from the scan of micro-Derenzo$^2$ phantom. The micro-Derenzo phantom consists of four 2.5 mm rods, four 2.0 mm rods and six 1.5 mm rods filled with the radioactivity. The total number of counts was 40M. (c) The QRM-MicroPET-IQ$^3$ phantom which was constructed according to NEMA NU 4-2008 standard was also scanned. The NEMA phantom is composed of three distinct compartments. The first compartment (marked as red colored A-A in Fig. 3 (c)) has two 8 mm rods which were left as cold rods in the scan. The compartment which is shown with the blue color gives the uniformity information for the measurement. The last compartment (highlighted with the green color) has five hot inserts of 5, 4, 3, 2 and 1 mm. During the NEMA phantom scan, 30M counts were collected. The 3D list-mode data were histogrammed by using span9 axial compression scheme. The FOV of $66 \times 66 \times 80 \text{ mm}^3$ (as shown in Fig. 2) was considered for the image reconstruction. The discrete transaxial coordinates ($x$ and $y$) were used directly in the histogramming. The continuous axial coordinates ($z$)
were discretized according to the chosen radial sampling in the construction of the sinograms. In this study, we used radial samplings of 1, 0.8750, and 0.4375 mm, respectively. The pitch distance between the crystals in consecutive layers in y direction (3.5/2 mm or equivalently 1.75 mm) was considered in the choice of the radial samplings. Therefore, the axial coordinates were assumed to be read from 1, 0.8750, and 0.4375 mm long discrete crystals for the radial samplings of 1, 0.8750, and 0.4375 mm, respectively. For the angular sampling, we used 1° increments which yielded 180 angular views in the constructed sinograms. Consequently, depending on the employed sampling, the 3D sinogram dimensions, number of segments, the dimensions of the reconstructed 3D images and counts per sinogram bins differed as shown in Table I.

Even though the list-mode data had only golden events and we did not need to apply correction for randoms or scattered events, we had to apply geometrical corrections to the histogrammed data and data estimation methods for the missing sinogram bins [4]. For the geometrical correction, we calculated all possible LORs which can be recorded by the current rotating two-module AX-PET demonstrator. The obtained map which shows the probabilities of the individual detector pairs in recording the events was used to correct the constructed sinograms. The information on the missing sinogram bins was also extracted from the normalization map. In Fig. 4, we illustrate the normalization map for the sinogram belonging to the transaxial segment. The red and blue shaded regions in the map draw the bins obtained from face-to-face and off-the-face configurations, respectively. In order to perform successful analytical reconstructions, the sinograms should be compensated for the inter-crystal gaps lying in the shaded regions as well as for the relatively bigger gaps lying between the triangular regions shaded with the blue color. Depending on the employed amount of sampling in histogramming, the undetectable sinogram bins change in amount and shape. These missing parts of the data were estimated by using the transradial bicubic interpolation\(^4\) gap-filling method published previously in [5, 6]. In our previous studies, we discussed the effect of the missing sinogram bins and the gap-related artifacts in the analytically reconstructed images in [5, 6, 7, 8].

Table I. Dimensions for 3D Sinograms, Reconstructed Images and Counts/Sinogram Bin Values

<table>
<thead>
<tr>
<th>Sampling (mm)</th>
<th>Constructed Sinogram Dimensions</th>
<th>Number of Segments</th>
<th>Reconstructed Image Dimensions</th>
<th>Counts / sinogram bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0000</td>
<td>67×180×1401</td>
<td>17</td>
<td>67×67×153</td>
<td>Capillaries</td>
</tr>
<tr>
<td>0.8750</td>
<td>77×180×1737</td>
<td>19</td>
<td>77×77×171</td>
<td>0.7061</td>
</tr>
<tr>
<td>0.4375</td>
<td>153×180×7077</td>
<td>39</td>
<td>153×153×351</td>
<td>0.0872</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>micro-Derenzo</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0062</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>QRM-MicroPET-IQ NEMA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7061</td>
</tr>
</tbody>
</table>

\(^4\) http://www.cs.tut.fi/~sgn/m2obsi/m2obsiWWW/demos/gapfilling/Gap-Filling.html

Fig. 3. The scanned phantoms. (a) Eight capillaries in the AX-PET demonstrator. (b) micro-Derenzo Phantom. (c) QRM-MicroPET-IQ NEMA phantom. The dimensions are in mm.

![Fig. 4. Normalization map obtained by calculating all possible LOR combinations for two-module AX-PET demonstrator.](http://stir.sourceforge.net/)

The corrected 3D sinograms were reconstructed analytically by using the 3D reprojection (3DRP) method as implemented in Software for Tomographic Image Reconstruction, STIR\(^5\). We used the 3DRP method with Colsher’s filter. The final reconstructed image dimensions are given in Table I.

\(^5\) http://stir.sourceforge.net/
IV. RESULTS

In this study, we show the preliminary 3DRP reconstruction results for the phantom data scanned with the two-module AX-PET demonstrator. The reconstructed images obtained from eight capillaries, micro-Derenzo and QRM-MicroPET-IQ NEMA phantom are shown in Fig. 5, 6, and 7, respectively. According to the results, with the employed reconstruction parameters, we are able to reconstruct the images successfully. We observed that the finest sampling (0.4375 mm) data suffered from low counts/sinogram bin and resulted in noisiest reconstructed images. NEMA inserts down to 2 mm diameter were visible for the 1 and 0.8750 mm samplings and barely visible for the 0.4375 mm sampling. Moreover, the 1.4 mm diameter capillaries were visible for all reconstruction cases.

The quantitative quality of the reconstructed images was investigated by calculating the Full Width at Half Maximum (FWHM) values. The manually drawn profiles across the inserts in the transaxial views were fitted to Gaussian curves and the FWHM values for the fitted Gaussian curves were calculated. This calculation was performed for all transaxial slices from which mean and median FWHM values were extracted. In Fig. 8, 9, and 10, the FWHM values for different sampling rates and for the measured phantoms are plotted. In the plots minimum, maximum, mean and median FWHM calculated from all transaxial slices are given for that specific insert. The median FWHM values for the capillaries were around 1.55 mm for all sampling cases. However, the variation in the FWHM values along the axial direction was higher for the 0.4375 mm sampling than the others. This is due to the low statistics (counts/sinogram bin) in the histogrammed data.

Fig. 5. Reconstructed images of the eight capillaries shown from transaxial (top row) and sagittal (bottom row) views for different sampling rates for 1, 0.875 and 0.4375 mm from left to right.

Fig. 6. Reconstructed images of the micro-Derenzo phantom for different sampling rates for 1, 0.875 and 0.4375 mm and the labels for the inserts from left to right.

Fig. 7. QRM-MicroPET-IQ NEMA phantom images for different compartments from top row to bottom row and for different sampling rates for 1, 0.875 and 0.4375 mm from left to right.

Fig. 8. FWHM calculated from eight-capillary images.
Fig. 9. FWHM calculated from micro-Derenzo phantom images.

Fig. 10. FWHM calculated from QRM-MicroPET-IQ NEMA phantom images.

V. CONCLUSION

In this work, we investigated the analytical reconstruction strategies for the data acquired from the two-module AX-PET demonstrator with the extended FOV setup. The process from list-mode data to the reconstructed images consisted of dedicated histogramming (number of radial, angular and axial samples, amount of axial compression) and sinogram correction (normalization and gap-filling) steps in order to exploit novel properties of the AX-PET concept. We observed the effect of different amount of radial and axial samplings (1, 0.8750, and 0.4375 mm) while keeping the angular sampling (1°) and axial compression (span9) fixed. The analytical reconstruction results presented in this study are preliminary and the work is still in progress. The FWHM measure of the capillaries showed that AX-PET reduces the parallax-error and provides near uniform spatial resolution in the FOV. However, for the finer sampling rates (such as 0.4375 mm) resulted in noisy images from which the FWHM calculations became harder. The low statistics (counts/sinogram bin) in the histogrammed data also affected the performance of gap-filling method and consequently resulted in degradation in the reconstructed images. The studies will be continued further in order to find the optimum sampling (radial, angular and axial directions) and sinogram corrections (normalization and gap-filling) which best exploits the novel properties of the AX-PET concept.

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REFERENCES


