NiftyPET: Fast Quantitative Image Reconstruction for a New Brain PET Camera CareMiBrain

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Abstract—Fast and quantitative image reconstruction for a new dedicated brain PET camera, CareMiBrain, is presented using the open-source Python package NiftyPET. The camera consists of 48 monolithic LYSO crystals arranged in 3 rings of 16 detector modules each, with an effective 240 mm transaxial FOV and 152 mm axial FOV and resolution below 2 mm. The coordinates of any photon detection at each module are encoded using $96 \times 96$ virtual pixels, which are then written to list-mode (LM) data for coincidence and single events. The image generation pipeline, from LM data processing to image reconstruction is performed on graphics processing units (GPU) using NiftyPET: First, the prompt LM data is processed producing 5184 sinograms in span-1 with 192 projection angles and 240 bins, while single events are used to estimate random event sinograms; the centre of mass of the radio-distribution in the projection space is used for motion detection with a temporal resolution of 1 second. The normalisation is performed using a scatter-free long acquisition of a dedicated ring phantom. Scatter correction is performed using a fully 3D voxel-driven scatter model (VSM); forward and back projections are calculated on the fly using the ray-driven Siddon algorithm. The above computations are performed using high-throughput GPU routines while enabling easy access for data quality checks at any point of the image generation pipeline. The quantitative performance was evaluated using the Derenzo and uniform cylindrical phantoms, demonstrating accurate corrections for photon attenuation, scatter and random events across a range of radioactivity doses.

I. INTRODUCTION

PET has become widely available in major hospitals, with increasing clinical use in Neurology. Most demand for brain scans is fulfilled using whole body PET/CT or PET/MR scanners, however, a dedicated brain PET scanner has a significantly greater sensitivity and higher resolution due to a smaller detector ring while exhibiting a smaller footprint and lower costs for hospitals [1].

II. METHODS

A. The Camera

CareMiBrain is a dedicated brain PET system developed by General Equipment for Medical Imaging – Oncovision S.A (Spain). The scanner consists of 48 monolithic Lutetium Yttrium OrthoSilicate (LYSO) crystals arranged in 3 rings of 16 modules each, with an effective 240 mm transaxial and 152 mm axial FOV [2] (Fig. 1). The crystals are coupled to a photosensor array of $12 \times 12$ silicon photo-multiplier (SiPM), $3 \times 3$ mm each. Monolithic crystals together with the proprietary readout electronics have the advantage of a high resolution determination of the depth of interaction (DOI), equivalent to 4 layers of pixelated crystals.

CareMiBrain spatial resolution at the centre of the axial FOV is approximately FWHM = 1.7 mm (which for whole-body PET it is above 4 mm), and peak sensitivity is 7% at 30% energy window. Photon impact position on the crystal is decoded applying the centre of mass method to the multiplexed signals for SiPM rows (Y coordinate) and columns (X coordinate). Measured impact position is corrected using a position correction that is previously calibrated, and converted to mm. Coincidences are formed between a detector and the nine opposite detectors on any of the three system rings, resulting in 648 different possible combination of module pairs (Fig. 1). X and Y coordinates of each detector module are covering the calibrated FOV of the monolithic crystal ($48 \times 48$ mm) and are converted to virtual pixels before writing the list mode file. Default virtual pixel size is $0.5 \times 0.5$mm ($96 \times 96$ pixels per module), but it can be adjusted to any pixel size.
**BRAIN LIST-MODE DATA PROCESSING AND IMAGE RECONSTRUCTION**

**QUANTITATIVE EVALUATION USING UNIFORM AND DERENZO PHANTOMS**

**Fig. 2.** Left: LM processing, motion detection and image reconstruction of brain scan. Right: Evaluation of the system using phantom scans.

**B. Image Generation**

The LM data is processed rapidly and concurrently across 32 CUDA streams producing 5184 prompt sinograms in span-1 with 192 projection angles and 240 bins [3]. Single rates, $S_i$ and $S_j$ at any virtual pixel $i$ and $j$ are used to estimate random event sinograms using the model for random rate between the detectors as follows: $R_{ij} = 2 \tau S_i S_j$. The temporal information in LM data together with the axial centre of mass of the radio-distribution in the projection space is used for motion detection with a temporal resolution of 1 second, calculated on the fly. A direct normalisation is performed using a scatter-free long acquisition of a dedicated ring phantom. Scatter correction is performed using a fully 3D voxel-driven scatter model (VSM) with a single scatter modelling. The probability of a photon pair emitted at $E$ with the unscattered photon detected at $i$ and the other photon scattered at $S$ and detected at $j$ is $P_{ij}(SE) = P_i(SE)P_j(S)$, where $P_i(SE)$ is the incident probability of unscattered photons detected at $i$ with the opposing photon incident at scattering point $S$, while $P_j(S)$ is the probability of scattering at $S$ and detected at $j$. Attenuation correction is performed using a CT-based or a synthesised $\mu$-map (using the available MR). Forward and back projections are calculated on the fly using the ray-driven Siddon algorithm for calculating exact line intersections through voxels in 3D. All the computations are performed using high-throughput GPU routines coded in C CUDA with Python C extensions such that all the routines are available in Python for easy user interface, enabling access for quality checks at all stages of image reconstruction. The performance of the system and image reconstruction was evaluated using the Derenzo and uniform cylindrical phantoms.

**C. Results**

The average prompt, normalisation and random sinograms, together with the map of detected single events (which are used for estimating random events) are shown in Fig. 2A using a 10-minute FDG brain scan with an injected dose of 178 MBq. Also, as part of the LM processing, the head curves of prompt and singles events per second are obtained together with the estimated axial head motion (Fig. 2B&C). Forward and back projections take 0.5 s and 0.8 s to compute, respectively. Full scatter projection using 2 mm voxels takes around 15 s depending on the size of the object. The transaxial, coronal and sagittal views of the reconstructed brain scan using ordered subsets expectation maximisation with 5 iterations and 16 subsets are shown in Fig. 2D. The quantitative performance is evaluated using a $\times 10$ cm uniform phantom at a wide range of injected doses. The quantitative corrections are assessed by a summed sinogram profile with the goodness of fit of the scatter and random models to the measured prompt data (Fig. 2E). The quantitative linearity of the system across injected doses up to 30 MBq is shown in Fig. 2F. The transaxial and sagittal views of the reconstructed uniform phantom, together with the image profile demonstrating the axial uniformity are shown in Fig. 2G. The image resolution is evaluated using the Derenzo...
phantom, for which the transaxial and sagittal views are shown in Fig. 2H.

III. CONCLUSION

CareMiBrain is a novel brain PET system and when combined with the high-throughput NiftyPET image reconstruction, it can produce high-resolution images with high quantitative accuracy.

REFERENCES