Application of GPU-based Image Reconstruction for a Clinical Organ-Targeted Positron Emission Tomography (PET) Scanner

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Introduction

Clinical organ-targeted PET is a comparatively new approach to molecular imaging that has emerged to meet the demands of precision medicine and has shown clear advantages in detectability of small lesions compared to whole-body (WB) PET. However, widespread clinical adaptation of the organ-targeted technology requires advances in data acquisition and image reconstruction techniques to account for peculiarities of organ-targeted PET system architecture so that diagnostic capabilities are maximized while the radiation exposure associated with PET imaging and image acquisition time are both minimized. The latter is the key to improve patient throughput making organ-targeted PET imaging cost efficient.

Here we present our results on reformulating the Maximum Likelihood Expectation Maximization (MLEM) image reconstruction algorithm from Central Processing Unit (CPU) to Graphics Processing Unit (GPU) as applied to a clinical organ-targeted PET system with planar detector heads (called Radialis PET Camera, Figure 1). Planar geometry allows for a versatile organ-targeted PET system design extending its use beyond a single target organ (Figure 2) thus permitting higher rates of utilization and making clinical use of the PET scanner cost-efficient.

Figure 1. The Radialis Organ-Targeted PET Camera

In terms of image reconstruction speed, GPU usage has already become a "gold standard" in WB and pre-clinical PET. However, to the best of our knowledge, this is the first time a GPU-based MLEM algorithm is reported for the clinical limited-angle reconstruction for planar detector geometry of an organ-targeted PET. Our results demonstrate that reconstruction time for clinical images with GPU-based MLEM is less than 5 minutes which makes it comparable with short image acquisition time of Radialis PET Camera which is possible due to its ultra-high sensitivity.

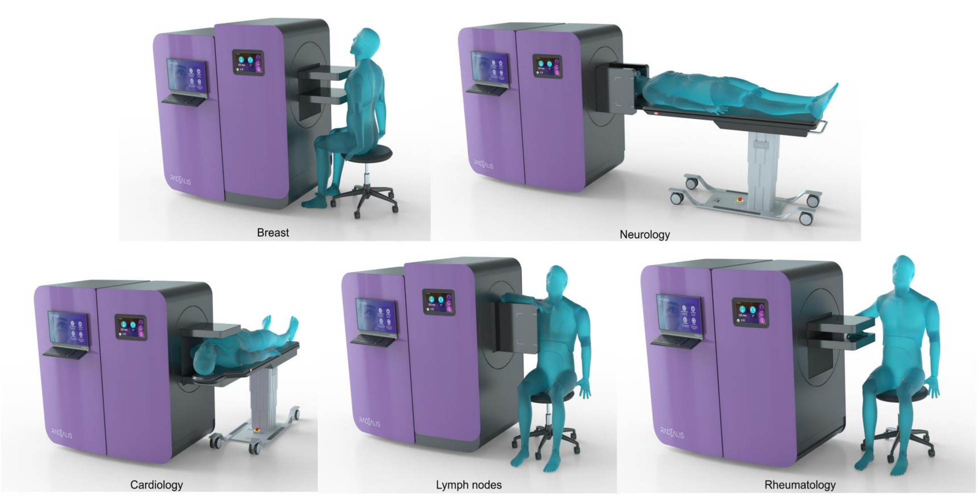

Figure 2. Versatility of Radialis PET design. Use cases for breast (top-left), neurology (top-right), cardiology (bottom left), lymph nodes (bottom-center), rheumatology (bottom-right)

The first application of the Radialis organ-targeted PET camera is in breast imaging. Radialis PET utilizes planar detector head design where 12 sensor modules are arranged in a 4x3 array (Figure 3). The modules are Cerium doped Lutetium Yttrium Orthosilicate/Silicon Photomultipliers (LYSO/SiPMs) - based. LYSO is pixilated to make a 24×24 grid with each pixel being 2.32mm×2.32mm×13mm. The total size of the field-of-view (FOV) is 232mm×174mm.

For image acquisition, two detector heads are positioned on either side of the immobilized breast. In case of the Radialis PET the detector heads can rotate and move detector plates closer and away from each other in order to ensure a perfect fit for a patient. Dedicated acquisition electronics allow coincidence data to be saved on the primary computer as a binary file for further processing by the reconstruction software.

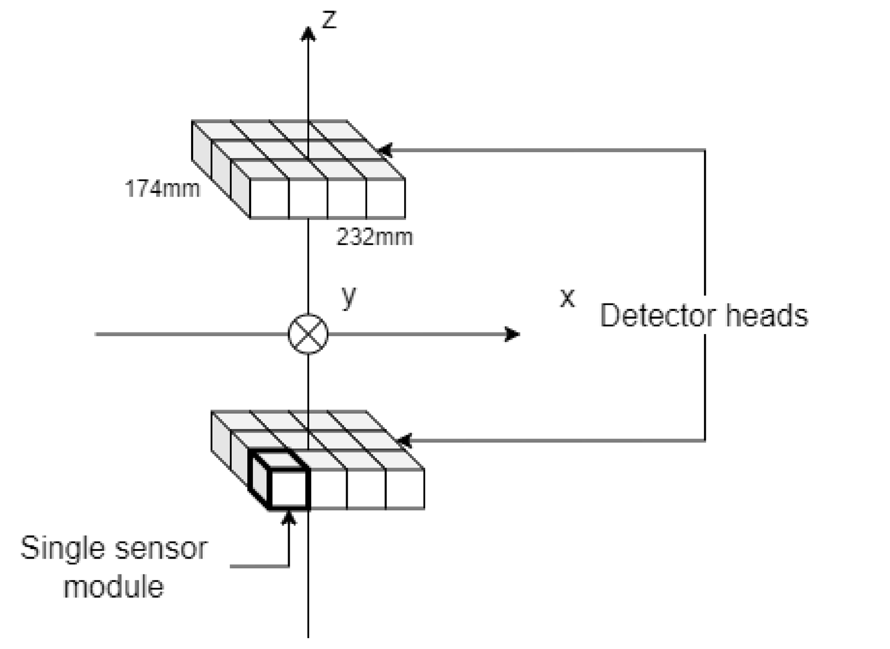

Figure 3. Planar detector heads orientation and coordinate axes

Radialis Image Reconstruction

Once data acquisition is complete, the acquired data is converted into a list-mode format which includes coordinates and energy information for each coincidence/event. List-mode format was selected for data storage because of it is advantageous for a planar detector setup where not all angles are available to construct sinogram data. Sparce nature of the event data allowing fast and efficient processing on a GPU. The reconstruction characteristics of the Radialis PET are summarized in the Table 1.

Characteristic	*Radialis PET*
Detector geometry	Two planar detector heads
Acquisition duration, min	5
Data type	List mode
FOV, mm	232 x 174
Image resolution	577 x 433 x 24
Voxel size, mm	0.4 x 0.4 x dynamic
Reconstruction algorithm	3D-MLEM
Number of iterations	15
Corrections	Attenuation, Scatter, and Decay

Table 1. Characteristics of Radialis image reconstruction

The list mode data is reconstructed using the 3D version of MLEM algorithm. The voxel size is 0.4x0.4 mm^2 and voxel's z dimension is calculated dynamically based on the number of slices (default is 24) and the distance between detector heads. The detailed breakdown of the proposed GPU-based MLEM implementation is shown in Figure 4. Most of the operations are happening in the GPU environment efficiently utilizing different GPU memory types including constant and shared memory. The data transfer between CPU and GPU was minimized.

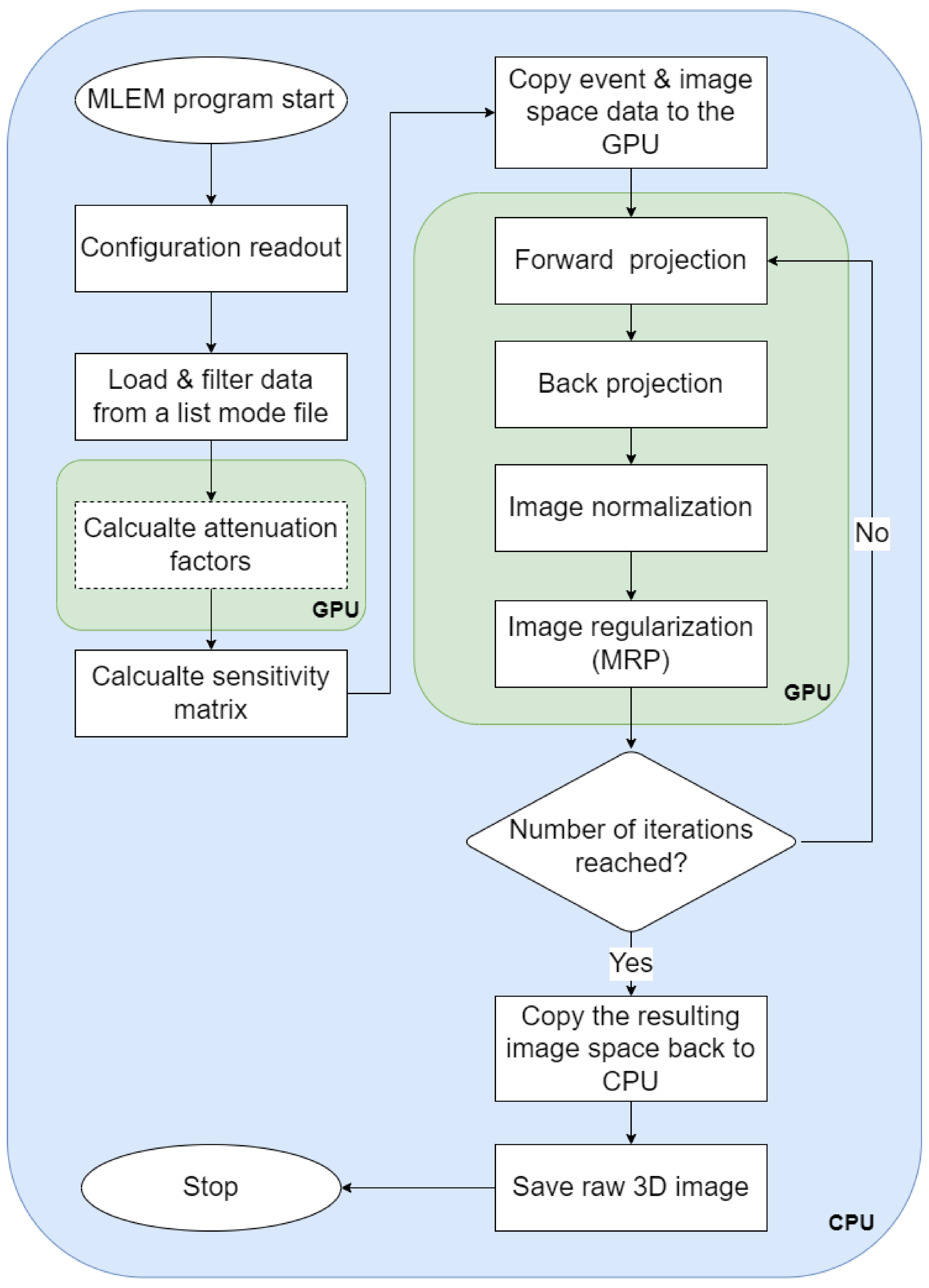

Figure 4. Detailed Radialis MLEM algorithm breakdown

For each MLEM iteration, forward and back projections are performed, and the resulting image is normalized. Finally, image regularization is performed using a Median Root Prior (MRP) method for noise reduction. Pseudocode for the forward projection operation is shown in Algorithm 1.

```
Initialize shared memory to hold intersected voxels
for each slice along Z axis do
    for each line assigned to the thread do
        Read coordinates and weight from global memory
        Find the intersected voxels between the line and the current slice.
    Save into shared memory
        for every intersected voxel do
            Calculate and add contribution of current voxel to the current
    slice for the current line
        end for
        Atomically add slice contribution to the current line in the global
    memory
    end for
end for
```

Algorithm 1. Forward projection operation pseudocode

All standard elements of image reconstruction (attenuation, scatter, and decay corrections) are incorporated in reconstruction of clinical images.

The resulting GPU-based algorithm was compared to the CPU counterpart and evaluated in terms of speed, clinical image quality and system performance indicators obtained with standardized tests conducted using NEMA NU-4 Image Quality (IQ) phantom.

Results

Reconstruction speed effects CPU vs GPU

With the proposed GPU-based MLEM we were able to achieve:

- More than 200 times reduction in a single iteration time of MLEM in comparison with clinical CPU reconstruction (executing on 8 CPU threads)
- 25 times reduction in overall reconstruction time on average in comparison with clinical CPU-based algorithm
- The speedup increases with file size increase. The image reconstruction time is reduced from 43 minutes to less than 5 minutes on average. Comparison of acquisition and reconstruction time is shown in Figure 5

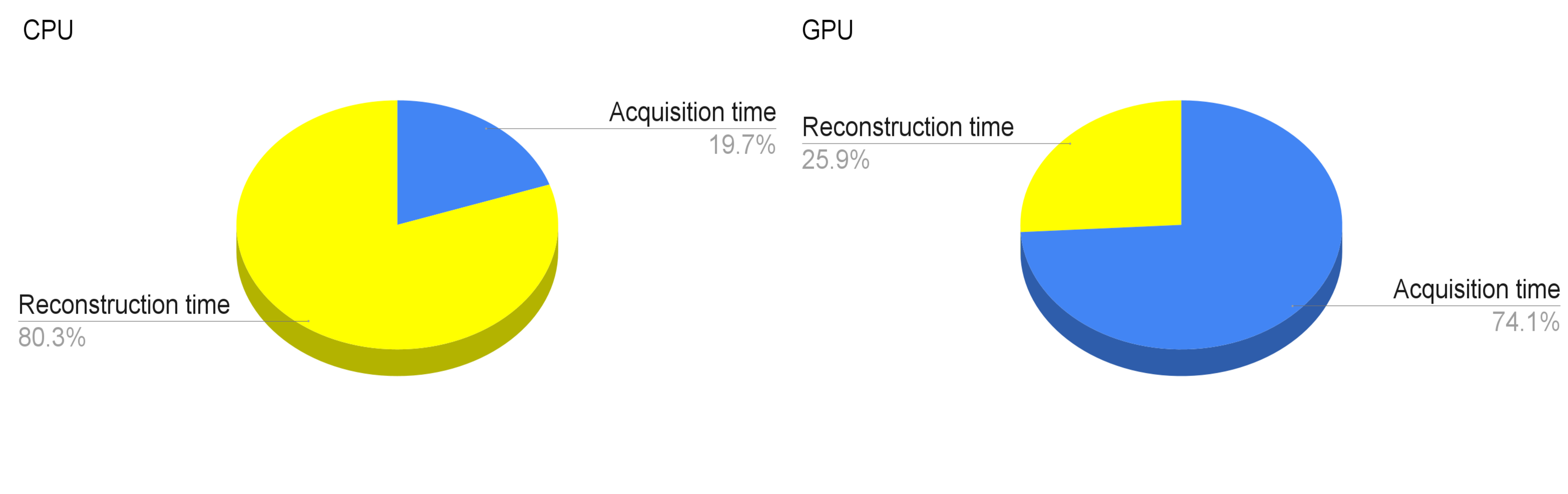

Figure 5. Proportion of time spent on image acquisition vs image reconstruction. Comparison between CPU (left) and GPU-based (right) reconstruction on a sample clinical case with 5 minutes acquisition.

Phantom image quality comparison CPU vs GPU

Table 2 presents NEMA NU-4 IQ phantom analysis comparison between CPU and GPU. Schematics of the IQ phantom as well as different slices reconstructed with both CPU and GPU-based algorithm are illustrated in Figure 6.

Architecture	*Uniformity, %*	*Contrast recovery coefficients (5, 4, 3, 2, 1-mm) hot rods, %*	*Spill over ratio: air-filled, water-filled*
CPU	6.66	82, 68, 46, 24, 14	0.12, 0.2
GPU	7.69	84, 69, 47, 26, 15	0.12, 0.2

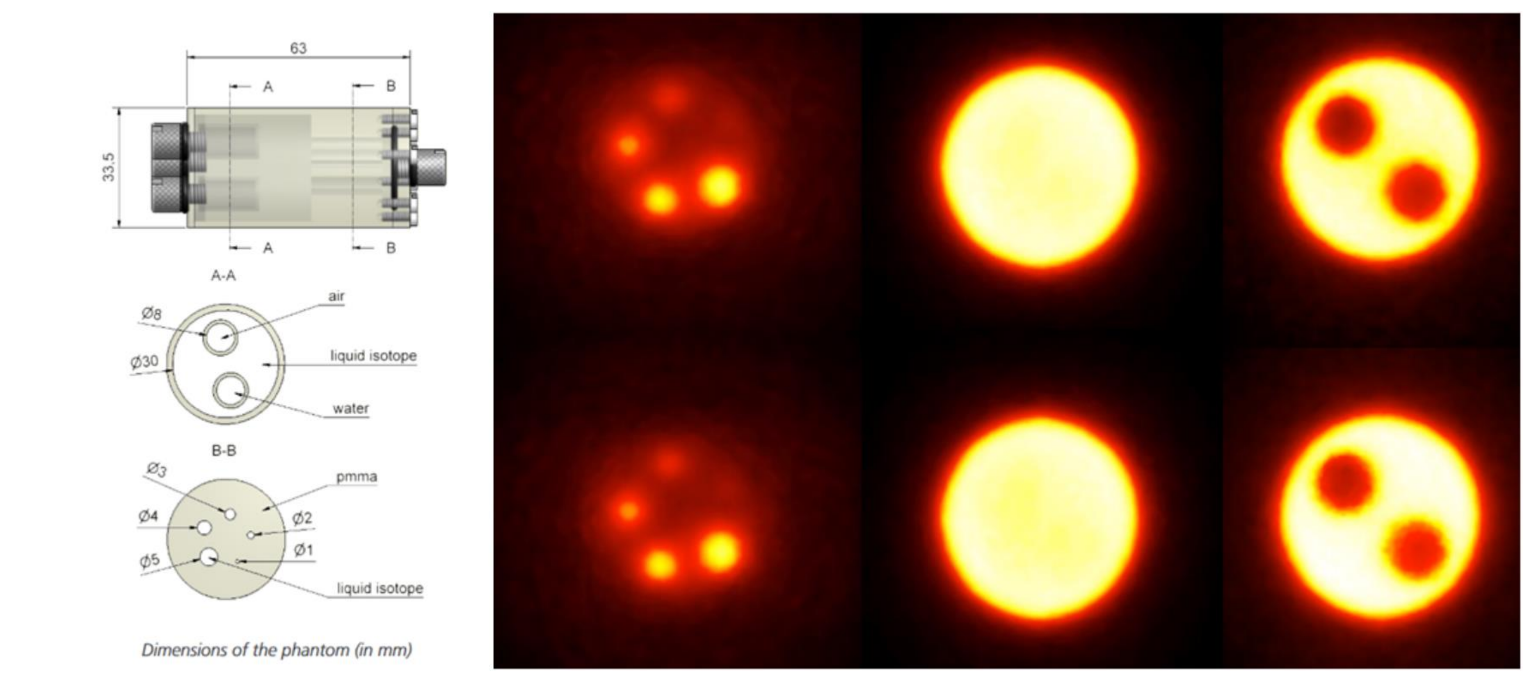

Figure 6. NEMA NU-4 IQ phantom (left) reconstructed using the latest CPU-based (right - top) and GPU-based reconstruction (right - bottom). Slices displaying the hot rods for recovery coefficient (left), uniform region (center) and air and water reservoirs (right). Visual evaluation reveals no significant difference between two phantom images reconstructed with CPU and GPU.

Clinical image quality comparison CPU vs GPU

Visual analysis of selected clinical images reconstructed with both algorithms was performed. The selected results are shown in Figure 7.

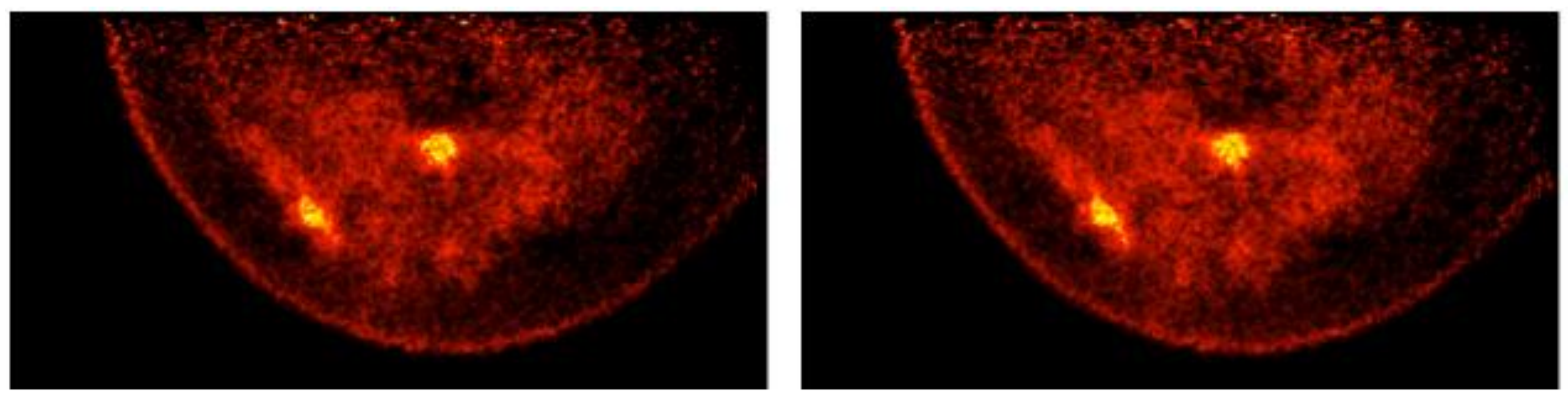

Figure 7. - A 56-years old female with invasive ductal carcinoma. Selected two slices of breast images reconstructed with CPU (left) and GPU-based (right) reconstruction algorithms. Acquisition time: 5 m. Total reconstruction time for the CPU version is ~25m 41s compared to ~3m 38s for GPU reconstruction

Summary

- We were able to develop a novel implementation for a GPU-based MLEM image reconstruction algorithm for clinical organ-targeted PET with planar detectors
- Significant reconstruction speed improvements with no changes in image quality were confirmed with standardized phantom tests and clinical data acquisition
- For clinical images, GPU-based MLEM algorithm reduces image reconstruction time by more than an order of magnitude making it less than image acquisition time thus improving patient throughput of the Radialis PET system
- Visual inspection of selected clinical images confirms no visible changes in the image quality
- Based on the overall assessment, the proposed solution was deemed ready for deployment in the clinical system