Performance Evaluation of Scatter Modeling of the GPU-based *"Tera-Tomo"* 3D PET Reconstruction

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***Abstract*—In positron emission tomography (PET), photon scattering inside the body causes significant blurring and quantification error in the reconstructed images. To solve this problem we have developed Monte Carlo (MC) based 3D PET reconstruction algorithms implemented on the Graphics Processing Unit (GPU). Our implementation takes multiple Compton scattering into account without any significant additional cost. The performance of the scatter correction is evaluated using GATE simulation as well as by comparing reconstruction results of Tera-Tomo to the reference reconstruction implementation of the Philips Gemini TOF PET which applies attenuation correction and single scatter simulation (SSS) for scatter correction. The comparative reconstruction results are based on the NEMA NU2-2007 image quality phantom.**

I. Introduction

In positron emission tomography (PET) annihilating gamma photon pairs are detected in order to calculate the spatial distribution of the positron-emitting isotope injected into the patient's body. The events detected in coincidence define a line of response (LOR), along which the originating event of positron-electron annihilation is searched. However, gamma photons may interact with the patient's body which can result in single or even multiple scattering. As a result, the LOR is not a straight line any more, but a combination of line segments. If scattering is not addressed in the reconstruction algorithm, then the result may involve significant blurring and may lead to inaccurate quantification [3]. The scattering phenomenon can be handled by many approximating methods, such as the SSS algorithm [2], which approximates the expected distribution of scattered events by an iterative scheme along with a reconstruction operation that does not involve any scatter modeling.

In the *Tera-Tomo* project, MC based 3D reconstruction approaches have been implemented [6] on the GPU. We focused on the precise yet efficient, on-the-fly calculation of system matrix (SM) elements, that is, the path of the gamma photons are calculated and the relevant physical effects are taken into account, including the detector response [7], [5], the Compton scattering, and the absorption inside the body as well as positron range modeling. One of our approaches applies quasi-Monte Carlo techniques for evaluating the related high-dimensional integral of SM. This so-called adjoint solver is capable to model multiple-scattering effects inside the body without any significant additional cost compared to the geometry-only case. This enables scatter correction to be applied in a whole-body PET examination and results in a scatter-corrected reconstructed volume in a few minutes right after the end of the acquisition.

II. Methods

The employed reconstruction scheme is the total variation (TV) regularized expectation maximization (EM) method, where the SM elements of forward and back projections are calculated on-the-fly [6].

Regarding the projectors of the adjoint solver the calculations are organized by LORs in the forward projection step and by the voxels in the back projection step [6]. This scheme fits better to the architecture of the GPU enabling the atomic GPU operations to be avoided. In this approach, multi-dimension integrals of the scatter modeling is approximated by a quasi-MC quadrature in the forward projection. The steps of multi-scatter modeling are summarized in Figure 1. The sampled paths between the scattering points are re-utilized when calculating contributions in the LORs; thus taking the scattering events into account has no significant additional cost. Further details of scatter modeling in the adjoint MC method can be found in [8]. This approach has also been verified by using a GATE [4] simulated mathematical phantom sets as well as NanoPET™/CT measurements [6].

III. Results

First, we present results based on a mathematical phantom that is simulated by using GATE. We have built the model of AnyScan® human PET scanner [1] in GATE. A voxelized NEMA Image Quality (IQ) phantom was introduced using back-to-back gamma source, the activity distribution follows the suggestion put down in the NEMA NU2-2007 standard. We have carried out the simulation using ideal detectors, i.e. forcing gamma absorption in detector crystals. In this way,

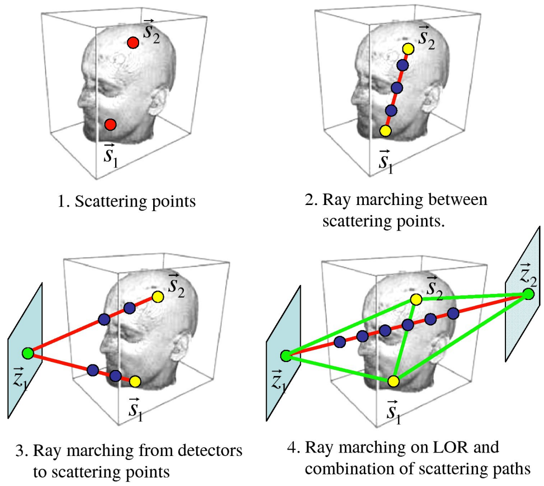
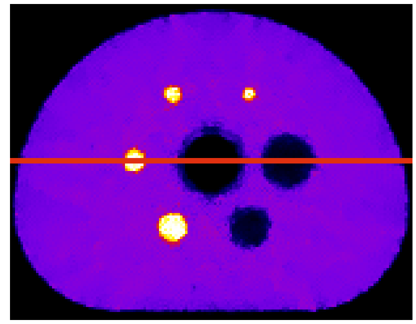


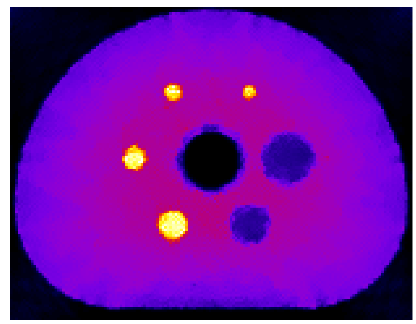
Fig. 1. Sampling steps of adjoint MC method.

we could focus on the effects of modeling attenuation and scattering inside the body, and all the other disturbing effects were switched off. We have sorted unscattered and only once scattered events for reconstruction. The reconstructed transaxial slices are depicted in Figure 2. We have reconstructed this simulation using two different levels of modeling physics in Tera-Tomo engine, i.e. using attenuation model only (red dotted profile in Figure 3) and switching scatter modeling on (green dashed profile). In order to compare them we have also plotted the profiles of the original mathematical phantom and the one we got sorting scattered events out of the simulation completely and using attenuation-only model for the reconstruction (dot-dashed cyan profile in Figure 3). We have to note that the scatter compensated profile can not reach precisely this latter one due to the loss of information during the scattering process. The higher the sampling density is in the forward projector, the more precisely the profile of the original phantom can be recovered. This result clearly shows that our adjoint method can efficiently handle scattering effect inside the body.

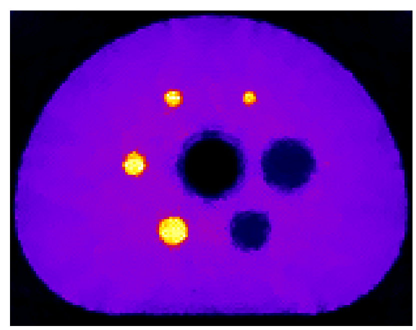
On the other hand, the performance of these implementations is also evaluated by reconstructing measured data acquired on a Philips Gemini time-of-flight (TOF) PET/CT scanner [9]. A NEMA IQ phantom is acquired and reconstructed by the in-built reconstruction software of the scanner. We took this implementation as a reference algorithm that incorporates TOF modeling, attenuation and SSS scatter correction. Then, we have reconstructed the acquired data with our adjoint MC implementation as well. Comparative transaxial slices are depicted in Figure 4. The reconstructed phantom images are evaluated by using the protocol according to the NEMA NU2-2007 standard. The hot and cold contrast, variability values are shown in Figure 5. The residual error for the lung insert was 14% using the in-built reconstruction software of Gemini scanner and 6.8% for the Tera-Tomo reconstruction software. This latter error metric reports the efficiency of the attenuation and scatter correction of the two compared



(a) attenuation only simulation, attenuation only reconstruction; location of the profiles of Fig. 3 is marked with red line



(b) attenuation + one scatter simulation, attenuation only reconstruction



(c) attenuation + one scatter simulation, attenuation + one scatter reconstruction

Fig. 2. Reconstructed transaxial slices of GATE simulated IQ phantom applying different level of modeling in Tera-Tomo reconstruction engine

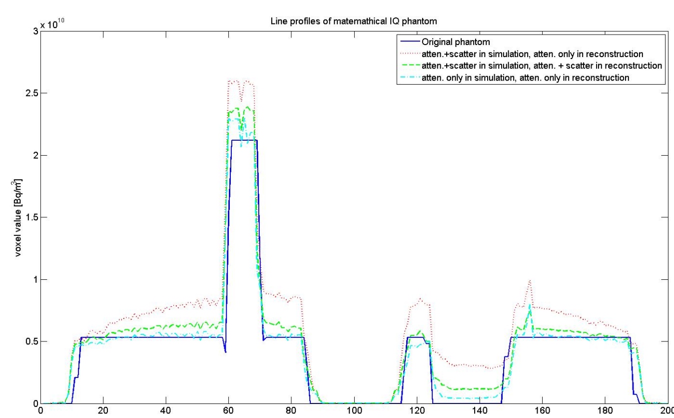
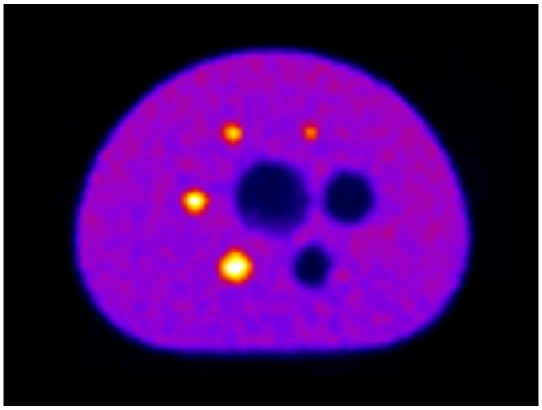
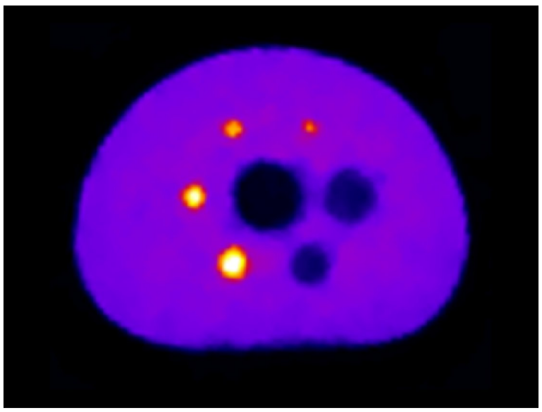


Fig. 3. Profiles of reconstructed GATE simulated IQ phantom using different level of modeling.



(a) The in-built reconstruction of the scanner.



(b) Tera-Tomo adjoint reconstruction method.

Fig. 4. Transaxial slices of NEMA IQ phantom acquired on a Philips Gemini TOF PET/CT scanner. The reconstruction was performed by using the in-built reconstruction of the scanner incorporating AC and SSS and by using the adjoint MC approach with attenuation and scatter modeling.

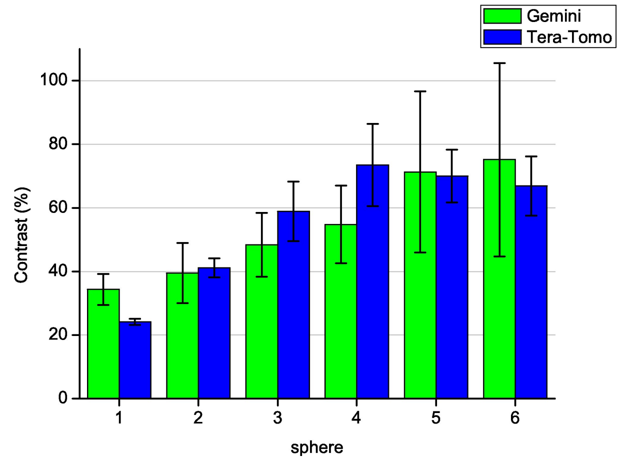


Fig. 5. The calculated contrast and variability values of hot (1..4) and cold (5, 6) spheres of human IQ phantom evaluated according to NEMA standard. The diameters of the spheres are 10, 13, 17, 22, 26 and 37 mm, respectively.

reconstruction approaches. Since in case of the NEMA IQ phantom TOF information does not have any significant effect on this metric [9], we find this comparison relevant to show the scatter-modeling performance of our reconstruction models.

The Tera-Tomo reconstruction took less than 4 min per FOV (using 3 full iterations with 14 subsets, and (2 mm)^3 voxels) employing two Nvidia GeForce GTX 480 cards.

IV. Acknowledgment

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