Compton Scattering in Positron Emission Tomography: If you can't beat it, reconstruct it

Monte Carlo Simulations in Positron Emission Tomography and Image Reconstruction using Scattered Coincidences

***M. Schaar, M. Rafecas**, Institute of Medical Engineering, Universität zu Lübeck*

In Short

- Positron Emission Tomography (PET) allows for identification of those regions with pathologically altered metabolism in patients by detecting gamma radiation in scintillation detectors.
- Accurate simulations of PET based on Monte Carlo (MC) methods help to understand the role and intertwining of physical processes in PET.
- PET image quality is negatively affected by scattered photons as the original photon trajectory is not on the volume seen by involved detectors.
- Scattered photons do contain potentially useful information which can be extracted in the reconstruction accurate models of physical interactions.

Positron Emission Tomography is a well-established tomographic imaging tool mainly employed to diagnose certain types of cancer, as well as inflammatory diseases or neurological disorders. PET is based on the administration of a radipharmaceutical that participates in the patient's metabolism and decays by emitting positrons. These positrons annihilate with the electrons of the tissue. As a result, two annihilation photons of equal energy (511 keV) are emitted in opposite directions. The annihilation radiation is detected by the scintillation detectors which compose a PET scanner. Coincidence detection electronics allow the pairs of photons originating from the same annihilation to be identified as a coincidence event. To create tomographic images from the coincidence events measured by a PET scanner, image reconstruction methods are applied. The reconstructed PET image displays the spatial distribution of the administered radiopharmaceutical in the patient. Regions with pathologically altered metabolism are identifiable in the PET image due to their abnormal radiopharmaceutical uptake.

Ideally, annihilation photons reach the detectors without undergoing any interaction in the patient (true coincidence). In that case, it is assumed that emission of the two photons occurred somewhere along the line connecting the two involved detectors (line-of-response, LOR). The measured LORs constitute the input information of the image reconstruction. Unfortunately, a non-negligible fraction of photons scatters within the patient through Compton effect but is still detected. In that case, the LOR assigned to the event (scattered coincidence) does not correspond to the original emission trajectory.

As the LORs assigned to scattered coincidences is wrong, scattered coincidences contribute to introduce background noise and degrade image resolution. Scattered coincidences can be partly rejected using narrow energy windows, as the energy deposited by the scattered photon is smaller than 511 keV. However, a narrow energy window also results in a loss of true coincidences due to the limited energy resolution of the scanner. This fact translates into higher levels of statistical noise. Additionally, even a narrow energy window does not completely excludes the presence of scatter. Therefore, methods to compensate for scatter effects have been developed. However, existing methods consider scatter as a source of noise and ignore that scatter events still contain some useful information.

In the project at hand, we aim to exploit the information content of scatter coincidences to increase the scanner sensitivity in software. Among other advantages, an increase in sensitivity should allow for reducing the injected dose. Our goal is to include scatter events in the reconstruction by considering that such events cannot be characterized by a simple LOR. One challenge we face is that the amount and distribution of scatter depends on the patient. Given the large number of possible LORs, it is currently impossible to pre-calculate and store on disk a complete model which accounts for the scatter contribution of each image voxel in each possible LOR. Therefore, common image reconstruction approaches rely on estimates of the scatter contribution for each LOR. Conventional iterative reconstruction algorithms use this contribution as an additional noise term. On the contrary, the project presented here aims to include patient scatter within the system matrix required in iterative reconstruction. This matrix models the probability that radiation assigned to a certain LOR originated from a certain voxel.

To develop and validate novel reconstruction approaches, synthetic data are commonly employed. For PET, as radiation emission, transport and detection are stochastic processes, MC simulations can provide realistic data. Currently, the toolkit GATE [1] is a well-established MC simulation package able

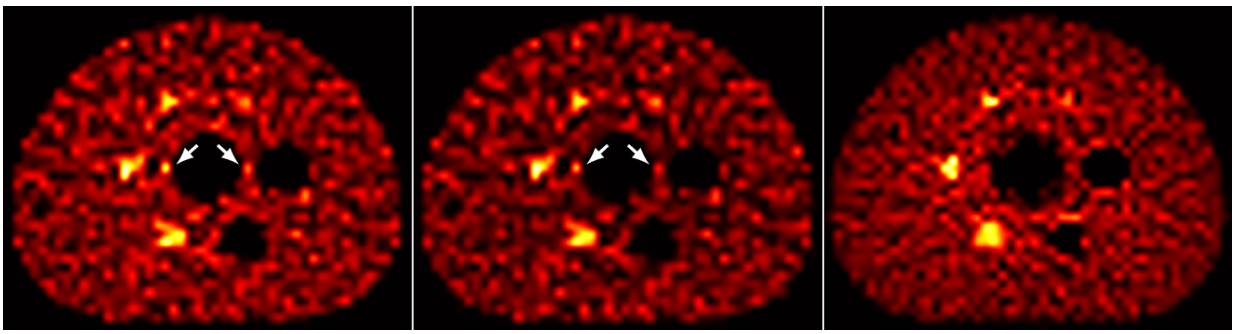

Figure 1: *Reconstructed images, left to right: Maximum Likelihood Expectation Maximization (MLEM), MLEM with conventional scatter correction, MLEM with scatter model in system matrix. Arrows mark artifacts not present when using our system model.*

to reproduce a large variety of imaging scenarios. We rely on GATE data to develop the scatter models and test the algorithms. To this aim, a virtual PET scanner and several phantoms have been simulated, among others the 3D NEMA body phantom (see Fig. 1). A drawback of MC simulations are the long computing times required to generate statistically solid data, as the processes involved are described by probability distributions which are sampled using random numbers. To simulate a realistic PET scan, many millions of photons are generated and tracked, from the emission source through the body until detection in the scanner. This fact is a severe obstacle if single desktop computers are used. Image reconstruction is also a computationally demanding process, in particular when accurate models of the physics are included into iterative algorithms. Additionally, to reconstruct scatter events, coincidences are handled individually, slowing down the reconstruction. Thanks to increased performance of workstations and the availability of high performance computing environments such as the HLRN, it is feasible to obtain simulated data describing realistic PET measurements, accurate objects and scanners, and complex activity distributions. Furthermore, on-the-fly calculations of a system matrix which accounts for scatter become feasible.

The usability of scatter events is illustrated in Fig. 2. Only scatter events were reconstructed to validate the model which was used in combination with different algorithms. Even if no true coincidences are used, three of the four simulated rods are visible, and noise between rods is more efficiently reduced by our proposed reconstruction algorithm, see Fig. 2b and 2d. Recently, our system model has been extended to three dimensional image reconstruction and evaluated using the National Electrical Manufacturers Association (NEMA) NU 2-2007 protocol. The results obtained by this procedure have been published in [2]. Exemplary slices of the reconstructed volumes are shown in Fig. 1. Using our approach, noise in terms of background variability is reduced and contrast recovery coefficients of larger sources are improved. Further steps include the optimization and acceleration of the reconstruction as well as additional evaluations using different kinds of data statistics, phantoms and scanning parameters.

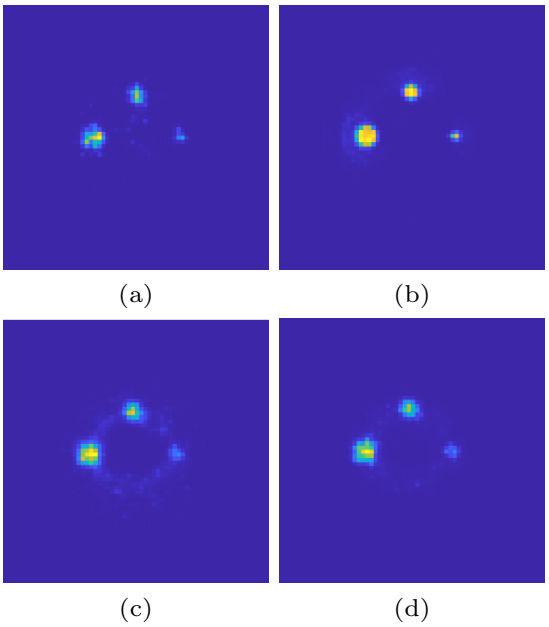

Figure 2: *Reconstruction of only scatter events for a phantom consisting of four rods of different diameters filled with radioactivity and placed in a water-filled cylinder. Conventional method, (a) and (c), and our proposed method, (b) and (d). Two selected slices are shown: slice located close to the edges of the field of view, (a) and (b); slice at the center, (c) and (d).*

WWW

https://www.imt.uni-luebeck.de/research/nuclear-imaging.html

More Information

[1] S. Jan et al., *Phys. Med. Biol.* **49**, 19 (2004), doi:10.1088/0031-9155/49/19/007.

[2] M. Schaar and M. Rafecas, *Proc. IEEE NSS-MIC Conf. Rec.*, 2019, in press.