Monte Carlo-based Reconstruction for Positron Emission Tomography

The poor spatial resolution of positron emission tomography (PET) images has limited the application of this imaging modality into some expanding fields, e.g. treatment planning, therapeutic evaluation and cardiac imaging. The spatial resolution degradation is attributed to the non-perfect data acquisition. In this thesis we investigated accurate modeling of the data acquisition process for improvement of the spatial resolution.

We investigated a Monte Carlo-based method to model these effects for a clinical whole body PET scanner. The calculation and storage of the system model are challenging for the slow Monte Carlo simulation due to the huge dimension of the system matrix. To address this issue, we developed a framework of techniques. The first component is a set of simple variance reduction techniques for resolution modeling based on egs_pet (a light weight PET simulator using the EGSnrc code package). These variance reduction techniques improved the simulation efficiency by a factor of about 15. The second component is symmetry handling for a cylindrical PET scanner, which improves both the simulation efficiency and the storage requirement by a factor up to 406. The last component is a rotator-based reconstruction algorithm, which enables reconstruction with the pre-computed partial system matrix. Our system matrix simulation needs five days on 50 cores of Xeon 2.66 GHz CPU. The resulting system matrix has a size of 1.8 GB of memory when we limited the maximum ring difference to 14. The contrast noise trade-offs were significantly improved compared to a line-length system model with a Siddon projector pair.

Monte Carlo based models are not very accurate for modeling effects due to readout. Therefore experiment-based point spread function (PSF) modeling was also investigated. The PSFs were measured on a sparse grid covering a small portion of the entire field of view (FOV). The rest part was obtained by symmetry properties. A parameterization technique was employed to estimate the PSFs at the unmeasured locations. The system model was further downsized by employing a factorized matrix approach, where the full system model is expressed as a product of a projection space blurring component and a geometrical component. The obtained system model is about 250 MB. The contrast noise trade-off was significantly improved compared to a line-length system model with a Siddon projector pair. The PSF model was also found to be superior to the Monte Carlo model in both contrast recovery and noise reduction.

In addition, we also investigated the ringing artifacts, which were detected in image reconstruction with both the Monte Carlo model and the PSF model. We evaluated the ringing artifacts with three different system models: an under-compensated model, an over-compensated model and a matched model. These models characterized the impact of “taper artifacts” on the ringing artifacts. We used “taper artifacts” to represent the artifacts caused by the partial volume effect. Data at different noise levels were produced to evaluate the impact of noise artifacts on the ringing artifacts. The ringing artifacts were found to be sensitive to the width of the system model and nearly independent of the data noise. The ringing artifacts were demonstrated to be a secondary effect compared to the noise artifacts and taper artifacts, however, the ringing artifacts were inherent in PET imaging with resolution compensation. We also noticed that moderately overcompensation of resolution loss may yield slightly over-estimated resolution and contrast, particularly for small hot lesions. These characteristics could be beneficial in diagnosis or treatment planning.

Finally, we have demonstrated that resolution compensation is an efficient way in improving image quality of PET. The improvements are twofold: (i) improved resolution, which yields sharper images and uniform resolution across the FOV; (ii) improved contrast, which improves the quantification of both hot and cold lesions. Our studies also indicate that the PSF model is resulting in better image reconstructions than the Monte Carlo model.

Reference

Long Zhang, Steven Staelens, Roel Van Holen, Jan De Beenhouwer, Iwan Kawrakow and Stefaan Vandenberghe, Fast and memory-efficient Monte Carlo-based image reconstruction for whole-body PET, Med. Phys. **37**, 3667 (2010)

Long Zhang, Steven Staelens, Roel Van Holen, Jeroen Verhaeghe, and Stefaan Vandenberghe, Characterization of the ringing artifacts in rotator-based reconstruction with Monte Carlo-based resolution compensation for PET, Med. Phys. **37**, 4648 (2010)

Long Zhang, Roel Van Holen, Steven Staelens, and Stefaan Vandenberghe, Experimental PSF Modeling for Fully 3D PET Reconstruction, accepted 11th International Meeting on Fully 3-D Image Reconstruction in Radiology and Nuclear Medicine, 2011