Realistic Pathological Simulations of the NCAT and Zubal Anthropomorphic Models, Based on Clinical PET/CT Data

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Introduction

Over the past years the introduction of computer science in the field of medical physics is rapidly growing. Monte Carlo simulations are more and more widely used in Nuclear Medicine as a tool that could be used in the clinical practice. GATE Monte Carlo toolkit provides high accuracy in physics modeling.

Positron Emission Tomography (PET) imaging is still considered as the state of the art for oncology diagnosis.¹⁻⁴ FDG is the most widely used radiotracer in such applications. Optimization of the quantitative use of PET in clinical practice data and imaging processing methods is also a field of intense interest and research.

GATE is a Monte Carlo simulation toolkit based on the precise modeling of the physical processes of the Geant4 code. It is dedicated for Nuclear Imaging applications (SPECT and PET) with large flexibility in using voxelized phantoms and complex geometries with movement incorporation. GATE is extensively validated, although realistic simulations are highly demanding in computational resources.

Using MC simulated datasets in PET is the most reliable approach to validate and assess the performance of image processing algorithms such as: Partial volume effects correction, denoising, segmentation, reconstruction and automated detection.

Objectives

The major aim of the current study is to standardize a method for realistic patient-specific oncology simulations. A dataset of realistic PET simulations for different type of tumors is presented, taking into account the heterogeneity activity distribution of the clinical data. Therefore:

- Patient-specific characteristics were inserted in simulations
- Simulated tumors variability was tested
- Partial Volume Correction method was applied in the simulations
- Quantitative comparison between simulated and clinical PET/CT data was made
- Validation / Evaluation of the procedure was performed
- Finally, a PET simulated database with different clinical oncology pathologies (using computational anthropomorphic models) was created

Materials / Methods

Clinical PET/CT data of oncology patients were used as the basis of the simulated variability, inserting patient-specific characteristics in the NCAT and Zubal anthropomorphic phantoms.

i. GATE Monte Carlo toolkit was used (version 6.1)
ii. The Siemens Biograph-6 PET clinical scanner was simulated
iii. The standard computational anthropomorphic models NCAT & Zubal were used for the 2 pathological cases
iv. The models were adapted to the CT data (organ shapes/sizes), using the NURBS algorithm
v. The activity distribution was derived from the PET images
vi. The tumors of both patients were segmented and inserted in the phantom, using:
   - Homogeneous activity distribution
   - Heterogeneous activity distribution in voxel-by-voxel level
   - Heterogeneous activity distribution in voxel-by-voxel level with contrast enhancement for PVC.

vi. The STIR open-source software was used for the reconstruction of the simulated data, with the MLEM iterative algorithm

Technical Features

- The simulations were carried out in the GateLab GRID
- 500 CPUs were used in parallel mode for each simulation
- An average of ~5,000 CPU hours are needed for 1 simulation with realistic characteristics
- The "Standard Model" of the Geant4 physics was selected
- No cuts - No Variance Reduction Techniques (VRTs) were applied in the physical processes
- 1 iteration was performed in the MLEM reconstruction algorithm in the STIR software
- The clinical data were taken by a Philips GEMINI system and the RAMLA software was used for the reconstruction
- Gaussian filter was used in the clinical images
- Post filtering was applied to the reconstructed images for the comparison of the profiles within the tumor (patient1) and of the profiles within the brain phantom (patient2). Gaussian blur filter (image) was set equal to 0.7.
- Mean values of ROIs for the organs of interest are presented in Table I. The difference between the simulated output and the clinical organs mean values are also calculated. In the homogeneous activity distribution central ROIs of the organs were chosen.

Results I

\[ \text{Comparison of Clinical and Simulated Profiles} \]

- Patient 1: Lung tumor
- Clinical Image - NCAT Phantom - Simulated Image
- Profiles of different Activity Distributions

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<th>Profiles</th>
<th>Clinical</th>
<th>PVC</th>
<th>Heterogeneous</th>
<th>Homogeneous</th>
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<td>Patient 1</td>
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| Patient 2: Brain tumor |

\[ \text{Tumor Profiles of different Activity Distributions} \]

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<td>Patient 2</td>
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Discussion

- Realistic Monte Carlo simulations play a crucial role in the evaluation of new image processing algorithms. Monte Carlo data are reproducible and the overall process can be accurately modeled. The results of the simulations show very good agreement with the clinical data, where the mean organ values show differences < 10%. PVC with contrast enhancement improve the accuracy of the tumor activity variability modeling.
- Different PET systems were used, as well as different reconstruction algorithms were applied in the clinical and the simulated data.
- Next steps of this study are the creation of a realistic database with the optimum parameters for the most accurate realistic patient-specific Monte Carlo simulations.

References

2. A. Le Maitre et al., "Incorporating patient specific variability in the simulation of realistic whole body ¹⁸F-FDG distributions for oncology applications," Proceedings of the IEEE, 2009

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