Exploitation of Realistic Computational Anthropomorphic Phantoms for the Optimization of Nuclear Imaging Acquisition and Processing Protocols

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Abstract— **Monte Carlo (MC) simulations play a crucial role in nuclear medical imaging since they can provide the ground truth for clinical acquisitions, by integrating and quantifing all physical parameters that affect image quality. The last decade a number of realistic computational anthropomorphic models have been developed to serve imaging, as well as other biomedical engineering applications. The combination of MC techniques with realistic computational phantoms can provide a powerful tool for pre and post processing in imaging, data analysis and dosimetry. This work aims to create a global database for simulated Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET) exams and the methodology, as well as the first elements are presented. Simulations are performed using the well validated GATE opensource toolkit, standard anthropomorphic phantoms and activity distribution of various radiopharmaceuticals, derived from literature. The resulting images, projections and sinograms of each study are provided in the database and can be further exploited to evaluate processing and reconstruction algorithms. Patient studies using different characteristics are included in the database and different computational phantoms were tested for the same acquisitions. These include the XCAT, Zubal and the Virtual Family, which some of which are used for the first time in nuclear imaging. The created database will be freely available and our current work is towards its extension by simulating additional clinical pathologies.**

I. Introduction

Over the last two decades the integration of advanced computational methods in the field of medical imaging is rapidly evolving. Among those tools, MC simulations, which are widely used in Nuclear Medicine, are now reaching a mature state that allows their exploitation into the clinical practice. They provide well validated tools for accurate physics modelling, simulate radiation-matter interactions and particle transportation within medium [1]. The use of anthropomorphic computational phantoms is rapidly gaining interest for the optimization of the acquisition and processing protocols that are used in clinical practice. Thus, these models are suitable in applications such as imaging, dosimetry and radiotherapy [2]. However, they are rather computer intensive and published results cannot be easily duplicated by many groups. In addition, the reproduction of realistic-like data requires a number of parameters to be taken into account, to ensure the accuracy of simulated data.

Medical databases are used for many years in daily research for studying specific patient's populations of multimodal data, such as PET/CT, SPECT/CT, PET/MRI. Most of them provide clinical data, based and categorized according to the acquisition protocol or studied disease. Taking into account the recent progress in MC simulations and computational phantoms, it becomes possible to reproduce clinical data, with realistic statistics as well as integrate patient's specific characteristics in terms of total and organs size, sex and abnormalities. This combination can lead to tools, which provide the ground truth for each processing step of the obtained images. For example, image reconstruction has moved from standard analytical Filtered Backprojection (FBP), to statistical algorithms such as Maximum Likelihood Expectation Maximization (MLEM), which includes the geometry of the detector system, patient anatomy and a number of statistical phenomena in the reconstruction process. Another example is radionuclide dosimetry, where dose calculation needs to incorporate not only patient size, but also variations in organs size, radionuclides kinetics, patient motion etc. Image quantification, which is necessary both in diagnostic and therapeutic applications, cannot rely on simulated data that have qualitative but not quantitative accuracy.

Realistic MC simulations can be performed by optimizing 4 basic levels: i) system design, ii) physical processes modelling and particle transportation, iii) realistic anatomical phantoms for attenuation and activity maps and iv) high statistics with realistic number of simulated particles. The prevalent accessibility of high-performance computing platforms stimulated the development of computational anthropomorphic anatomy models. More than 30 voxel-based tomographic models have been developed in the recent years based on anatomical images. [2]. Recent advances aimed at 4D (dynamic) models that are flexible while providing the accurate modeling of patient populations [3] developed a 4D

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NURBS-based Cardiac-Torso (NCAT) model, which combines the accurate anatomical description with respiratory and cardiac motion of the organs and this phantom was a turning point especially in the field of nuclear imaging.

Recently a number of groups have started to present simulated data and a number of attempts for the creation of open databases are reported. Reihlac et al [4] proposed a cerebral PET database while Tomei at al. [5] created an FDG-PET database for lymphoma based on the PET-SORTEO MC code. In 2005 a large database of emission tomography simulated brain and whole body images was presented [6].

In this work we have used GATE [7] MC toolkit, which is highly accepted in the nuclear imaging community. We combined GATE with XCAT, Zubal and the Virtual Family phantoms, in order to establish the simulation methodology and provide a validated, open database of simulated PET/SPECT exams with their corresponding clinical data, which can be exploited in order to optimize acquisition and processing protocols.

II. Methods

A. Simulation and Reconstruction Tools

The GATE MC simulation toolkit, which is based on the Geant4 code was used in this study [7,8]. Over the past decade, GATE has been extensively validated and provides additional precision considering the physics modeling. This study is based on GATE v6.1 where all the appropriate physical processes needed for each acquisition were modelled using the "Standard Model". No cuts or variance reduction techniques (VRTs) were used in the particle transportation. All simulations included in the presented database offer realistic statistical accuracy and were executed in the GateLab Grid, using parallel computers in the European Grid Infrastructure (EGI) [9]. The presented database includes simulated data for both SPECT and PET imaging acquisitions. The reconstruction method used for each one of the two modalities was the iterative MLEM and the OSEM algorithms respectively. More specifically the QSPECT open-source software for tomographic reconstruction [10] was used for the production of SPECT data while the open-source software of STIR (Software for Tomography Image Reconstruction) [11] was used for the PET data. The reason for using two different variations of Expectation Maximization algorithm have to do with the already existing reconstruction packages. Comparing different reconstructions was beyond the scope of this work.

B. Computational phantoms

The anatomy of the patients in both PET and SPECT simulations was modelled using the non-uniform rational basis splines (NURBS) XCAT [12], the CT-based head Zubal phantom [13] and the Virtual Family models [14], which are based on high resolution magnetic resonance (MR) images of healthy volunteers. For the attenuation map, the various organs in each phantom were simulated using the materials provided by the GATE Materials Database (Materials.db) namely Air, Lung, Body, RibBone, SpineBone, Intestine, Breast, Spleen, Blood, Heart, Liver, Kidney, Water, SoftTissue, Adipose, Brain, Skull and Muscle. The tumors in the simulations were considered as SoftTissue media. The same phantoms were also imported in the simulations in order to define the activity map, according to each radiopharmaceutical bio-distribution. The radiotracer concentration was based on standard published data for standard tracers.

C. Simulated systems

The database includes data from different clinical systems, which have already been modeled and validated in the GATE platform. More specifically the PET acquisitions have been carried out using the Siemens Biograph-6 scanner [15] and the Philips PET Allegro system [16]. Additionally, for the SPECT and planar (scintigraphic) simulations the Siemens ECAM Dual head gamma camera was used.

D. Nuclear Medical Imaging Database (NMI_D)

The created database includes indicative data from both PET and SPECT modalities. All the data that have already been added to the database are presented in Table 1.

TABLE I. Nuclear medical imaging database contents

Acquisition tracer	Scanner model	Organ of interest	Phantom name	Scan time (min)	Activity (MBq)
Planar / Scintigraphy (Anterior – Posterior)					
^{99m}Tc-MDP	ECAM	Bones	XCAT	6.67	411.6
^{99m}Tc-MDP	ECAM	Bones	DUKE	6.67	411.6
SPECT (36 projections per 10^{o})					
^{99m}Tc-N-DBODC	ECAM	Cardiac	XCAT	15	64.8
^{99m}Tc-N-DBODC	ECAM	Cardiac	DUKE	15	64.1
^{99m}Tc-N-DBODC	ECAM	Cardiac	ELLA	15	64.1
PET (one bed position)					
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient1	XCAT	2	34.5
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient2	XCAT	2	57.4
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient3	XCAT	2	82.9
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient4	Zubal	2	25.6
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient5	Zubal	2	29.0
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient6	Zubal	2	25.9
^{18}F-FDG	Biograph-6 Allegro	Tumor Patient7	Zubal	2	26.0

The phantoms imported in GATE had a voxel scaling of 4 x 4 x 4 mm^3, equal to the crystal size of the modeled scanner. Although GATE does not have a limitation in the number of voxels in which a phantom can be descretized, smaller voxels increase computational cost; taking into account that the minimum pixel is determined by the resolution of the imaging system, small pixels are possible, but will not add much to the accuracy of the study, while significantly increasing simulation time. At the moment, the reproduction

of a typical clinical scan on fast Grid requires ~1 week of simulation time.

Specifically 7 oncological patients were simulated using the clinical PET systems and the simulated data incorporate patient specific variability [17]. Initially the PET/CT clinical data were obtained from 7 patients. The NCAT phantom was adapted to the clinical CT images and the anatomy of the NCAT was modified to match the patient's anatomy. Furthermore, the PET clinical data were used to provide the activity distribution of each patient, which was imported into the simulation. The NCAT phantom was used for the three first patients for thoracic imaging, while the Zubal phantom was used for the other four cases, in order to simulate the head/brain tumors. Each tumor was delineated and segmented from the PET images and was imported in each respective phantom. The resulting PET simulated data provided the ^{18}F-FDG bio-distribution of these 7 oncology patients. The heterogeneous activity distribution within the tumors was taken into account [17]. These simulations were repeated using 2 different clinical PET scanners (Biograph6 and Allegro).

The ECAM dual head system was used for five SPECT simulations. Two scintigraphic bone acquisitions were performed using the biodistribution of ^{99m}Tc-MDP as it was taken from the literature. The XCAT and the DUKE model from the "Virtual Family series" were used for these acquisitions. This is the first time that the "Virtual Family series" is used in nuclear imaging according to our knowledge. In both phantoms the same activity distribution was imported in various organs and the same acquisition protocol was used in both cases. The anterior and posterior whole body images of these two models was the output of the simulations. Three SPECT acquisitions were also simulated using the same system and the activity bioditribution of ^{99m}Tc-N-DBODC taken from the study of [18] for cardiac imaging. 36 projections from 0^{o} to 360^{o} with a 10^{o} step were acquired from the XCAT, the Duke and Ella (from Virtual Family) phantoms.

III. RESULTS

Apart from the resulted images the sinograms of each acquisition are provided to make possible image reconstruction by different reconstruction algorithms. Furthermore, each simulation is categorized based on the isotope and the computational phantom that was used. In the following sections we provide some indicative examples of the database that investigate several parameters.

A. PET (clinical system)

The 7 oncological patients presented in the database were simulated using both Biograph6 and Allegro systems. The original PET clinical images are provided in order to compare the different reconstructed data. In Figure 1 the central slice of patient2 is shown in three cases; the clinical image the image simulated with Biograph6 and the image simulated with Allegro scanner. Three line profiles are also compared.

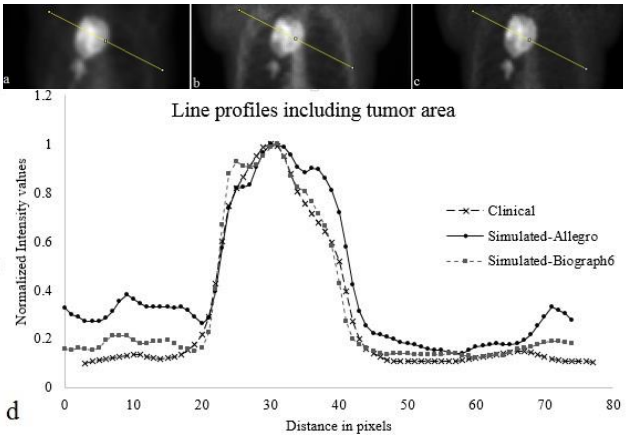

Figure 1. First line: Planar anterior projections of patient3; a) clinical image, b) image simulated with Allegro system and c) image simulated with Biograph6 system. Second line: Corresponding line profiles.

B. SPECT (clinical system)

Using the ECAM dual head scanner, a number of 99mTc based radiopharmaceuticals were tested. In Figure 2 the ^{99m}Tc-MDP bio-distribution is presented using the Duke phantom. More specifically the scintigraphic anterior and posterior projections are shown and a compressed image of them for each phantom.

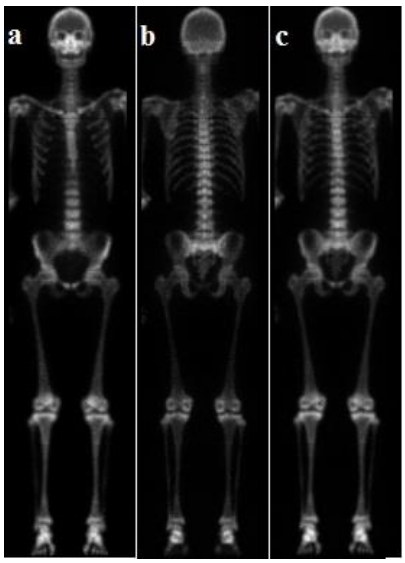

Figure 2. Projections of MDP activity distribution in Duke model a) anterior, b) posterior, c) planar

In Figure 3 a typical SPECT image (a) is shown, on which the XCAT phantom is adopted (b). Then the distribution of ^{99m}Tc-N-DBODC, which is clinically used for cardiac imaging, is assigned to the XCAT organs and the simulated image is derived (c).

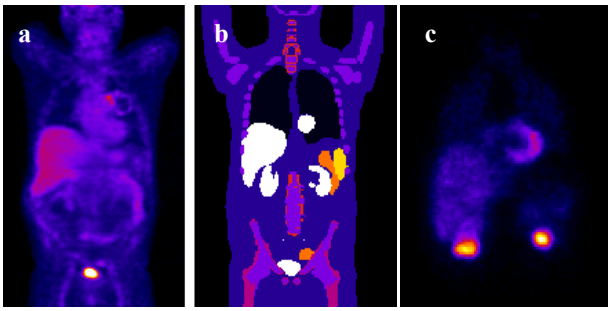

Figure 3. a) Typical cinical SPECT exam; b) XCAT phantom adopted to the clinical exam; c) Simulated ^{99m}Tc-N-DBODC cardiac study.

IV. Discussion

An open database can play a significant role in biomedical engineering research, since it can provide reference data, methods and tools to compare results of different groups, as well as overcome resources limitations. In the field of nuclear medical imaging (PET and SPECT) the existence of simulated datasets is very limited in number, accuracy and variability.MC calculations can provide the ground truth in order to validate and evaluate different acquisition protocols, processing tools and reconstruction algorithms. By combining the advantages of MC techniques with the reliability of several computational models and the evolution of computer science, medical imaging protocols can be optimized in order to reduce the absorbed dose in patients and incorporate their personalized characteristics.

In this study we have shown indicative examples of a generalized database, which is open and will be continuously upgraded by the authors. Additional simulated imaging systems will be added for comparing the results of identical acquisition protocols. Using the initial images that already exist in the database, reconstruction algorithms and processing/analysis techniques can be tested, such as partial volume correction (PVC), de-noising, segmentation, filtering and automated detection. An additional step which is now being added is the incorporation of phantoms movement (respiration and cardiac motion). On the one hand, this will provide even more realistic results and on the other hand those data can be used for the evaluation of motion correction techniques. Another direction is the extension of the database by adding more isotopes and more computational phantoms, such as the "Virtual Classrom" (by ITIS foundation - www.itis.ethz.ch) for paediatric imaging applications.

At the moment our work is focused on calculating the dosimetric data of the presented simulations. This provides additional info to the imaging applications and the dose per organ is provided according to the activity distribution and the respective computational model. In order to achieve this goal, all the sinograms of the simulations are available since this is a necessary tool for further investigation of the data. In conclusion, the nuclear medical imaging "NMI_Base", has been developed incorporating realistic simulations of several scanners using computational models. Corresponding clinical data are provided, while dosimetric data will be included as a next step.

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