A 5D Anthropomorphic Numerical Phantom for Respiratory-Gated Parametric Imaging Simulation Studies in Dynamic Emission Tomography

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Abstract— **Dynamic image acquisition protocols are increasingly used in emission tomography, for drug development and clinical research. As such, there is a need for computational phantoms accurately describing both the spatial as well as temporal distribution of the radiotracer, taking into account periodic and non-periodic physiological processes during the course of the acquisition, such as tracer kinetics and respiratory motion. To this end, we developed a new 5D anthropomorphic digital phantom for accurate parametric imaging simulation studies in emission tomography. The proposed phantom is comprised of 3 spatial and 2 temporal dimensions and is based on high spatial and temporal information derived from 4D MR data. The envisaged applications of this digital phantom include development and evaluation of motion correction and image reconstruction algorithms in PET and SPECT, development of protocols and methods for tracer and drug development and new kinetic parameter estimation algorithms amongst others. Example applications are shown in parametric [^{18}F]FDG and [^{15}O]H_2O PET imaging.**

***Index Terms*—Computational phantom, parametric imaging, respiratory motion, PET, MRI**

I. INTRODUCTION

The use of voxelized and mathematical computational phantoms has become increasingly widespread due to their ability to provide a platform where different methods and techniques in the field of medical imaging can be thoroughly evaluated [1]. Lately the introduction of hybrid phantoms has enabled the combination of flexibility and realism to be realized within a single anatomical phantom representation.

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Advanced hybrid phantoms based on non-uniform rational B-splines (NURBS) such as the NCAT and more recently the XCAT provide detailed male and female datasets using high resolution anatomical information [2-4]. In the context of emission tomography, such as PET and SPECT, most techniques rely on simulating activity distributions encountered during a static scan. However, the need for more accurate quantification both in clinical research and drug development has lead to the increasing use of dynamic imaging protocols. Consequently, the development of realistic digital phantoms for multi-compartmental tracer kinetic studies in dynamic PET and SPECT, which combine accurate anatomical information with temporally periodic and non-periodic functional processes occurring during the course of a scan, such as respiration and tracer activity distribution, is of interest. This has led to the development of the PCAT phantom, however its scope was limited to dynamic perfusion studies in cardiac PET and SPECT imaging [5]. In this work, using high resolution MR anatomical and temporal information, we develop a 5D anthropomorphic numerical phantom, incorporating temporal gating from respiratory induced body motion and compartmental modelling tracer kinetic capabilities for parametric imaging simulation studies in dynamic emission tomography. This new voxelized phantom, allows respiratory gated and non-gated datasets to be simulated along with any tracer-specific compartmental model representing the temporal distribution of the activity concentration during dynamic imaging protocols in PET and SPECT. Using top hat functions, the same platform can also be used to represent static image acquisition protocols.

II. METHODS

A. 3D anatomical phantom

High resolution anatomical information, covering the thoracic and upper abdominal area were generated using MRI-derived data from a breath-hold (end-exhale) ultra-short echo-time _(UTE) 3D MRI scan, to segment the different regions of interest (soft tissue, cortical bones, liver and lungs) as detailed in [6, 7]. The myocardium, heart ventricles and large vessels were segmented using an ECG triggered MRI scan during free breathing. Apart from these template organ structures, additional patient specific structural variants, such as tumours

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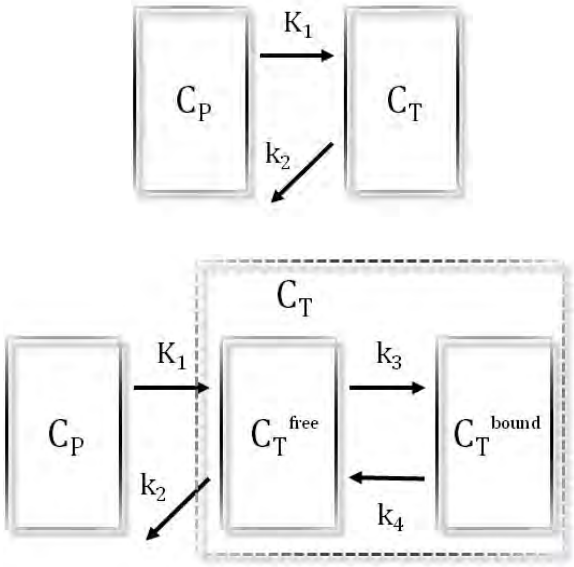

Fig. 1. Schematic diagram of a single-tissue and a two-tissue kinetic model showing the different compartments as well as the constant rate controlling the rate of change in activity concentration for each compartment.

of different size and shape, can be manually inserted in different organ regions.

B. 4D dynamic phantom for 1-tissue and 2-tissue models.

To describe the temporal distribution of a given tracer, custom-made software capable of providing multi-compartmental modeling for 1-tissue and 2-tissue models (Fig. 1), including a blood volume component is used. Given the input function, a temporal sampling protocol and known tracer specific kinetic parameters (constant rates) for each organ structure in the anatomical phantom, time-activity curves (TACs) are generated. Simple or complex models can be realized in different organs, including dual blood supply and differential delay and dispersion. TACs are assigned at the voxel level, generating a time series of voxelized phantoms with a temporal sampling dictated by the dynamic acquisition protocol selected during the TAC generation.

C. 5D gated phantom using MR-derived motion fields

To simulate different types of realistic motion during a dynamic scan, the fast analytic simulation toolkit (FAST) is used [6]. Acquired 4D MR data providing a uniform temporal sampling of a few complete respiratory cycles are sorted in gates and then the most representative MR gates are registered to a reference frame at the end-exhale position to derive the motion fields. These are subsequently used to warp the dynamic emission data and generate a number of respiratory gates for each time frame in the dynamic image sequence. Deep and shallow breathing can be simulated along with other non-periodic types of motion. A similar procedure is followed to generate the corresponding gated attenuation maps segmenting the data into air, soft tissue, lungs and bone.

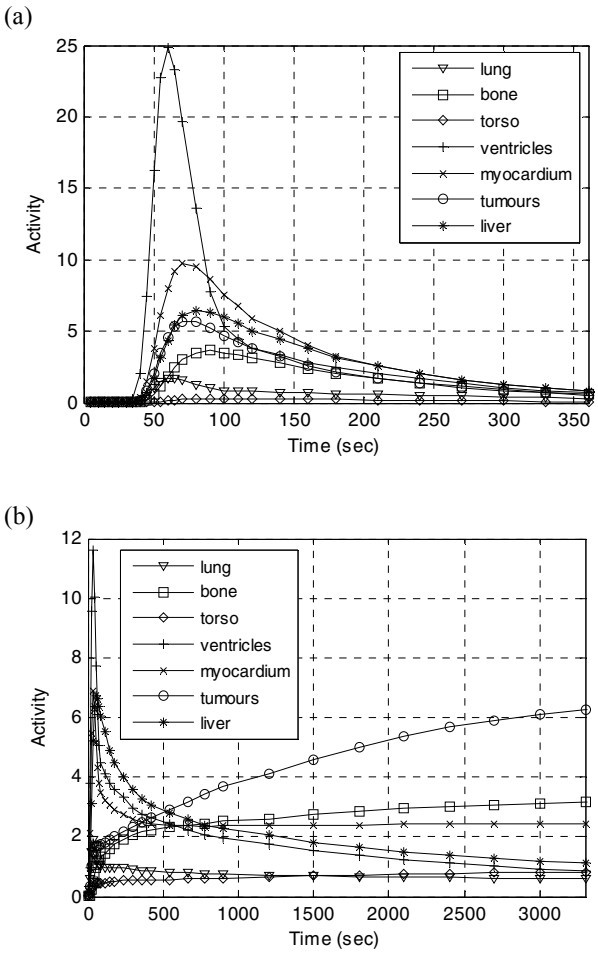

Fig. 2 Simulated TACs corresponding to typical (a) [^{15}O]H_2O and (b) [^{18}F]FDG kinetics which were used for the different regions of interest in the 3D anatomical phantom.

D. 5D projection data

The simulated gated dynamic images can then be forward projected to generate projection datasets for investigation of numerous techniques for motion correction, image reconstruction, and kinetic parameter estimation.

III. RESULTS

To demonstrate the capabilities of this new simulation platform in respiratory gated dynamic PET imaging, kinetics typically encountered in metabolic imaging using [^{18}F]FDG and perfusion imaging using [^{15}O]H_2O were simulated in the phantom. Using kinetic parameters for the different organs and tissues obtained from the literature and along with input functions derived from real dynamic scans, TACs were generated using a single-tissue 3 parameter model (K_1, k_2 and blood volume) with 28 time frames [1×130sec, 14×5sec, 5×10sec, 3×20sec, 6×30sec] and a two-tissue 4 parameter model (K_1, k_2, k_3 and blood volume) with 29 frames [9×10sec, 3×30sec, 4×60sec, 4×120, 8×300sec], respectively. Using the

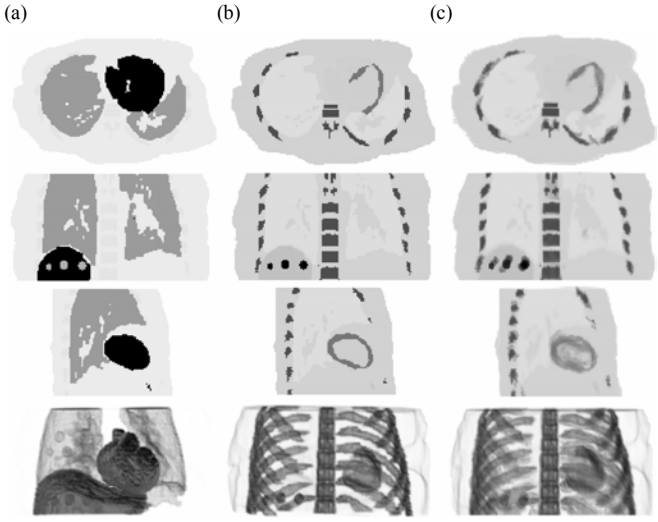

Fig. 3 Transverse, coronal, sagittal and volume rendered images of the phantom at the reference gate for 2 different time points during the simulated dynamic [^{18}F]FDG image sequence corresponding to an early time frame (a) ($t = t_0 + 40$ sec) and a late time frame (b) ($t = t_0 + 3400$ sec) where t_0 is the reference start time. The same late frame is shown in (c) for all 8 gates superimposed.

FAST toolkit, 8 respiratory gates where generated for each time frame in the dynamic image sequence [6].

The simulated time-activity curves applied on the different phantom regions are shown in Fig. 2 for [^{15}O]H_2O (a) and [^{18}F]FDG (b) kinetics. Looking at the tumor TACs in the [^{18}F]FDG dataset, the trapping of the tracer is evident due to the irreversible kinetics, attributed to a high k_3 parameter and $k_4 = 0$, which is a valid assumption for the typical duration of an [^{18}F]FDG scan. Example images from the phantom can be seen in Fig. 3. The images corresponding to an [^{18}F]FDG dynamic scan are from an early (a) and a late (b) frame at the reference respiratory gate while in (c) all 8 gated images corresponding to different phases in the respiratory cycle, are shown superimposed for the same late frame. Finally in Fig. 4, using the geometry configuration of the Siemens HiRez PET-CT and an in house data generation and reconstruction simulator, example projection data are shown at a late time frame from the reference gate (a) and after combining all the gates, creating the motion affected dataset (b). The blurring effect from all gates compared to the single gate is visible.

IV. DISCUSSION - CONCLUSION

As dynamic imaging protocols are adopted more frequently for clinical research and drug development, simulation solutions for more efficient development, evaluation and validation of novel tracers, protocols, methods and techniques in parametric imaging studies are of interest. In this work, a new 5D computational phantom for generating realistic datasets for parametric imaging studies in emission tomography, including different sources of motion and incorporating kinetic models of variable complexity was presented. The proposed phantom

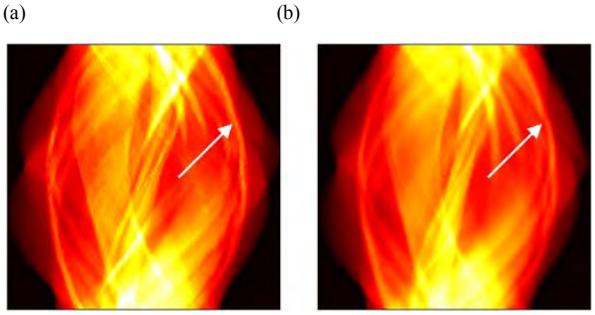

Fig. 4 Sinograms for a late frame from the reference gate, simulating a motion free dataset (a) and from all gates, simulating a motion affected dataset (b). When all gates are combined the projection data become blurred (white arrow).

can be used for a number of applications both in PET and SPECT, including motion tracking and correction, conventional and direct image reconstruction algorithm development, dynamic imaging protocols design, simulations for tracer and drug development and kinetic parameter estimation algorithm development. As such, the phantom and software platform will be a valuable tool for the molecular imaging community and is envisaged to become available for simulation studies in dynamic emission tomography.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation under grant SNSF 31003A-135176 and the EU COST Action TD1007. C Tsoumpas and I. Polycarpou acknowledge financial contribution of the SUBLIMA EU FP7 grant.

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