RTNCAT (Real Time NCAT): Implementing Real Time physiological movement of voxellized phantoms in GATE

P.Descourt[1,2], W.P.Segars[3], F.Lamare[1], L. Ferrer[2], B.Tsui[3], Y Bizais[1], M.Bardiès[2], D.Visvikis[1]

1. U650 INSERM, Laboratoire du Traitement de l'Information Médicale (LaTIM), Université de Bretagne Occidentale, Brest, France
2. U601 INSERM, CHU Nantes, Nantes, France
3. Department of Radiology, John Hopkins University, Baltimore, USA

***Abstract* - GATE figures among existing MC simulation codes for emission tomography applications. Although it allows working with voxellized activity distributions it does not enable the incorporation of physiological motion in a real time sense for such distributions. This restriction causes substantial drawbacks where dynamic phenomena such as respiratory or radiotracer motion are of interest. A new C++ class, named "GateRTPhantom" has been introduced in GATE to enable simulation of physiological motion in Real Time within voxellized phantoms. These objects are managed by a class named "GateRTPhantomMgr". The new approach has been assessed using the 4D NCAT phantom. The real time implementation approach (RTNCAT: Real Time NCAT) was compared with the classic implementation of dynamic processes through the individual simulation of a number of static frames. A total of 20 frames throughout a respiratory cycle were produced (0.250ms each). The accuracy of the RTNCAT module was validated through a qualitative and quantitative comparison of 3D images containing the emission locations of single photons in the phantom. Parameters such as the total number, the mean value and the standard deviation of the number of emitted photons per voxel were evaluated. In all of these parameters a high level of agreement was observed supporting the developed approach for the real time modelling of physiological motion. In addition, practically identical times of execution were seen for the two approaches.**

I. INTRODUCTION

Monte Carlo simulation is an increasingly powerful tool in the study of medical imaging modalities such as PET and SPECT [1]. Its use ranges from the development of new imaging devices, image-reconstruction algorithms and correction techniques to the optimization of acquisition protocols. Among the existing simulation codes [1], GATE (Geant4 Application for Tomographic Emission) [2] stands as a particularly reliable, robust and mostly complete tool. It is designed as a dedicated Monte Carlo platform for emission computed tomography that could model both the radioactive decay processes in complex voxellized phantoms and sophisticated detector arrangements and associated signal flow chains including dead time effects [3]. The realistic description of a phantom or model of the small animal/human anatomy to be used within the simulation process represents also a crucial aspect of the accuracy with which one is able to simulate pre-clinically and clinically realistic datasets. In that sense GATE offers the ability to work not only with simple analytical objects but also with voxellized phantoms.

The four-dimensional (4D) NURBS-based CArdiac-Torso (NCAT) phantom [4] provides a realistic and flexible model of the human anatomy and physiology to be used in emission computed tomography simulations. The complex surface structure of the organs is modelled using non-uniform rational B-splines (NURBS). Realistic models of cardiac and respiratory motions are included as well as the possibility of placing lesions in organs that move with respiration. A parameter's file allows the user to define details of the phantom such as respiratory motion cycle duration and amplitude as well as activity concentration in organs/lesions. Although the phantom is based on NURBS, voxellized format output volumes can be obtained, either as an average or at particular positions throughout the respiratory cycle. Finally, another interesting feature of the NCAT phantom is the description of the time-dependent evolution of the activity inside each organ. The latter is included in NCAT through text files storing, for each organ, the time-dependent curve activity of this organ taken from measurements in the form of a list. NCAT interpolates at each time the activity deduced from the organ specific time activity curve and places it in the specific organ allowing the simulation of time-dependent evolution of an organ's activity. Similar and equivalent processes can be achieved using the mouse whole-body (MOBY) phantom in small animal imaging [5].

Although simulation codes such as GATE may allow the use of static voxellized objects, they do not enable the incorporation in a real time fashion of physiological (such as organ or activity) motion associated with the description of such voxellized volumes. This restriction may cause significant drawbacks in cases where dynamic phenomena such as respiratory motion are of interest. For example, using NCAT frames at particular time points throughout the respiratory cycle does not include the effects of motion within each gated frame, and is susceptible to be significantly depending on the duration of these frames relative to the overall respiratory cycle. An alternative approach will be to consider very small temporal sampling and perform multiple simulations using such static voxellized volumes but the processing burden with such an approach is extremely high and therefore impractical. The objectives of this work were to incorporate real time physiological motion as can be described by phantoms such as NCAT and MOBY into GATE preserving at the same time the information at the voxel level.

II. MATERIALS AND METHODS

A Introduction of the concepts of GateRTPhantom and GateRTPhantomMgr

The strategy designed to incorporate NCAT into the GATE code has been kept general in order to allow the utilization of any phantom including physiological motion. In addition, more than one such "moving" phantom can be handled during a given simulation.

GATE consists of different layers with a number of C++ classes in each of these layers defining available tools [2]. For the purpose of incorporating real time physiological motion in association with voxellized phantoms, a new C++ class named "GateRTPhantom" (where RT stands for Real Time) has been introduced. These objects are managed by a new class named "GateRTPhantomMgr" which is instantiated only once during a simulation. In this general scheme, each Real Time phantom which is to be integrated into the GATE code is constructed from a C++ class which derives from the base class "GateRTPhantom".

B Application to the NCAT case

Considering the specific NCAT case, as the GATE simulation progresses in time, the attenuation and activity maps are recalculated from the NCAT library subroutines. This is achieved by a C++ class named "GateRTNCAT" derived from the "GateRTPhantom" class, which monitors the dynamical computation of the NCAT phantom as the simulation progresses in time. The frequency at which the phantom is "re-evaluated" is specified by a time sampling parameter which represents the minimal time interval separating two computations of the whole NCAT phantom.

This new C++ class manipulates the pointer objects which control the C++ map containers, one for the 3D voxellized attenuation volume and the other for the corresponding 3D voxellized activity volume. These objects are used to associate an activity or an attenuation value to a triplet of integers which determines the position of the voxel under construction. Additional modules have been developed to take into account activity temporal evolution in regions of interest or specific organs within voxellised phantoms.

The "GateRTNCAT" module is controlled by the user through the GATE scripting language in order to allow easy access to inexperienced users, based on the general philosophy behind GATE. In a similar fashion, a specific parameter ("SetTimeSampling") can be used by the user to define the temporal sampling to be employed in the readout of the externally specified time activity curves.

C Validation of RTNCAT

In order to quantitatively validate the implemented real time physiological motion method, we compared the developed Real Time NCAT module to the standard methodology used to combine GATE and static NCAT frames for both respiratory and activity movements.

In the case of respiratory motion twenty individual frames (emission and attenuation voxellized volumes) corresponding to a length of 250ms each were generated using the NCAT parameters file. A 5 second respiratory cycle with a 2cm maximum diaphragm motion was used. Cardiac motion was also included (1s period), while moving lesions were also added in the lung and the heart. In order to compare the two approaches the time sampling parameter in the "GateRTNCAT" module was set up to 're-evaluate" the two phantom volumes (emission and attenuation) each 250ms. For both approaches the detector volume was provided by the Phillips GEMINI PET scanner model experimentally validated by Lamare et al [3].

In addition, a couple of time activity curves were generated to characterise the accuracy of the real time simulation of activity distribution in specific regions/organs of interest in the NCAT phantom. Different time activity curves were assigned to the liver and a lung lesion, with these two structures been the only one's to be assigned any activity levels in the emission frames. Data was generated using an 1s simulation with these 4D NCAT emission frames.

The ROOT file outputs [6] have been used in the analysis of the simulated datasets. 3D images of the emission locations of single photons in the phantom corresponding to the detected coincidences were formed by counting the number of photons that were emitted in each voxel. In the case of the 20 static simulations all of the individual ROOT file outputs were read in turn in order to produce the corresponding 3D images of the emission locations to be compared with those of the real-time moving phantom.

III. RESULTS + DISCUSSION

The coronal images presented in Figure 1 give a slice of the 3D emission location maps for the two approaches considered. For both approaches a lower number of emissions detected can be seen on the lower and the upper part of the images since these areas correspond to the detection of out of field of view activity, considering that the system used in the simulation has a total sensitive axial field-of-view of 18cm. Similar levels of movement can be observed at the level of the heart and liver. Table 1 contains the results from a quantitative analysis including various parameters such as the total number of single photons emitted in the phantom and detected in the sensitive volume as well as the mean value and the standard deviation of the number of emitted photons in each voxel. In all of these parameters a high level of agreement can be observed, supporting the developed approach for the implementation of the real time motion of voxellized sources within GATE. In addition, no extra time burden was observed in the real time motion implementation as manifested by comparing the time of simulations for the two approaches (i.e. real time motion and multiple static frames), which were practically identical.

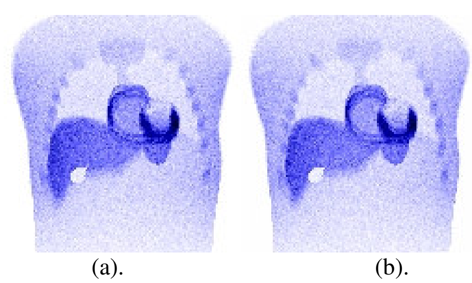


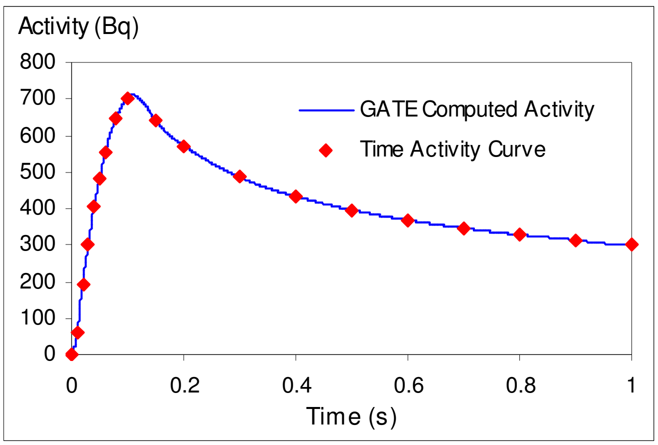
Fig. 1: Coronal slices through the 3D volumes containing the single event emission locations for the detected coincidences considering (a). the multiple static NCAT simulations approach, and (b). the Real Time NCAT approach

Table I: Quantitative comparison on the 3D volumes of emission locations for the multiple static and real time motion implementations of NCAT with GATE

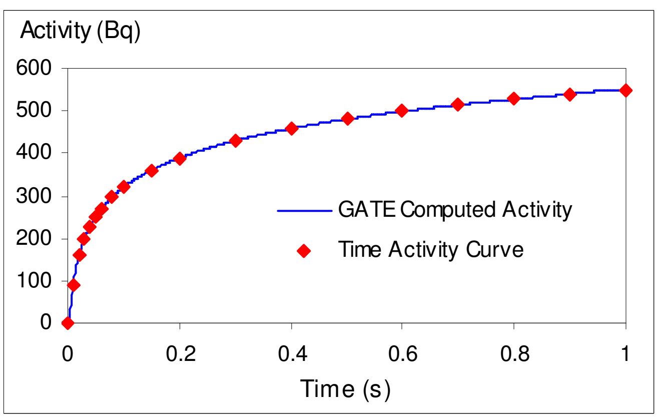
	Mean voxel Value	Standard deviation	Total numbers of singles
NCAT	11.1916	15.2171	23470419
RTNCAT	11.1876	15.2159	23461520

addition, no extra time burden was observed in the real time motion implementation as manifested by comparing the time of simulations for the two approaches (i.e. real time motion and multiple static frames), which were practically identical.

Figures 2 and 3 demonstrate the good agreement obtained between the time activity curves generated for the liver and the lung lesion and those obtained by the region of interest analysis of the generated singles emission images at particular time points during the 1s simulations.



(a).



(b).

Fig. 1: Simulated and GATE computed time activity curves for (a). the liver and (b). the lung lesion

IV. CONCLUSIONS AND FUTURE WORK

A new class has been added to the emission computed tomography dedicated Monte Carlo simulation code, GATE, in order to enable real time physiological motion of voxellized sources in terms of both tracer and organ movements. Although a general approach has been developed allowing the incorporation of any moving phantom in voxellized format, the implemented approach has been tested with the 4D NCAT phantom. Future work will concentrate on the validation of the implementation for radiotracer motion in combination with organ movement as well as on a study of the impact of the implemented real time 4D NCAT phantom in the evaluation of respiratory gated emission imaging.

REFERENCES

[1]. I Buvat, I Castiglioni. *Monte Carlo simulation in PET and SPET*, Q J Nucl Med, 46(1), 48-61, 2002

[2]. S Jan, G Santin, D Strul, S Staelens et al *GATE: a simulation toolkit for PET and SPECT*, Phys Med Biol, 49, 4543-4561, 2004

[3]. F Lamare, A Turzo, Y Bizais, D Visvikis *Validation of a Monte Carlo simulation of the Philips Allegro/GEMINI PET systems using GATE,* Phys Med Biol, 51, 943-962, 2006

[4]. WP Segars, DS Lalush, BMW Tsui *Modelling respiratory mechanics in the MCAT and spline-based MCAT phantoms*, IEEE Trans Nuc Sc, 48(1), 89-97, 2001

[5]. Segars WP, Tsui BM, Frey EC, Johnson GA, Berr SS. *Development of a 4D digital mouse phantom for molecular imaging research.* Mol Imag Biol, 6(3),149-159, 2004

[6]. R Brun, F Rademakers *ROOT – an object oriented data analysis framework,* Nucl Instrum Methods A389, 81-86, 1997