Composite System Modelling for High Accuracy Brain PET Image Reconstruction using GATE

Martin A. Belzunce and Andrew J. Reader

***Abstract*—High resolution and good quantification is needed in specific regions of the brain in a number of PET brain imaging applications. An improvement in the spatial resolution and in the quantification of the tracer uptake can be achieved by using statistical reconstruction methods with an accurate model of the scanner acquisition process. This model is represented by a system response matrix and needs to include all the factors that contribute to the degradation of the reconstructed images. Monte Carlo simulations are the best method to model the complex physical processes involved in PET, but they have an extremely high computational cost and the system matrix needs to be recomputed for every new scan. Furthermore, for 3D PET the system matrix can have billions of elements, therefore at present it is impossible to store in memory during the iterative reconstruction. Consequently, on-the-fly Monte Carlo modelling of the system matrix has been previously proposed by other authors, where a Monte Carlo simulation is used in the forward projector and a simpler analytic model in the backprojector. In this work, we propose a different approach, where a composite system matrix is used, with a complete Monte Carlo model computed with GATE for a small subregion of the field of view and a simpler analytic model for the voxels outside that region. We evaluated the feasibility of the method using 2D simulations of a striatum phantom and a brain phantom. For each case, a Monte Carlo system matrix was generated with GATE for a subregion centred in the striatum. The brain simulations were reconstructed using the proposed method and compared with the standard reconstruction used clinically, with and without resolution modelling. For the striatum phantom, the use of a GATE system matrix showed an improvement of the reconstructed image, where a better definition of the structures in the striatum region was observed. For the case of the brain phantom, where the composite system matrix is used, an improvement was also observed but more limited compared with the pure GATE system matrix.**

I. Introduction

In a number of applications of PET brain imaging, high resolution and good quantification is needed in specific regions of the brain. For example, the striatal uptake of [^{18}F]FDOPA is used to study Parkinson's disease, where a fall in the uptake has been observed in Parkinson's patients undergoing PET scans [1], [2]. An improvement in the spatial resolution and in the quantification of the tracer uptake in the striatum can be achieved by using statistical reconstruction methods with an accurate model of the acquisition process in the scanner [3].

This model is represented by a system response matrix (SRM) and needs to include all the factors that contribute to the degradation of the reconstructed images [3]: the geometrical properties of the scanner, the positron physics (i.e. the positron range and the non-collinearity of the two photons emitted in the annihilation), the attenuation of the photons before arriving to the detector, the scattered photons not rejected with the energy window, the random coincidences, the detector's response (including the crystal size, the crystal penetration, the inter-crystal scatter) and the efficiency variations for each line-of-response (LOR).

The system matrix can be generated from analytical models [4], from measurements [5] or from Monte Carlo simulations [6]–[9]. The latter permits the modelling of the complex physical processes involved in PET (e.g: positron range, photon acollinearity, etc.), albeit at a very high computational cost. Furthermore, in order to be able to model the positron physics and the scatter in the patient, the system matrix needs to be computed for every new scan; additionally, the system matrix for 3D PET can have more than 1×10^{12} elements, therefore impossible to store in memory during the iterative reconstruction. Consequently, on-the-fly Monte Carlo modelling of the system matrix for SPECT image reconstruction has been previously proposed by other authors [10], [11] as a possible solution, where a SPECT Monte Carlo simulation is used in the forward projector and a simpler analytic model in the backprojector.

In this work, we propose using a composite system matrix, where a scan-dependent Monte Carlo model is used only for a small subregion of the image and a simpler analytic model with an on-the-fly projector for the voxels external to the subregion. This enables the storage in memory of the smaller Monte Carlo system matrix. For example, it can be used to obtain better image quality in the striatum than with the analytical system matrix. We evaluated the feasibility of the method using 2D brain simulations. A pure Monte Carlo system matrix was evaluated with the simulation of a striatum phantom, while the composite system matrix with a brain phantom. Both system matrices were generated with GATE [12] and used to reconstruct a subregion of the brain phantom centred in the striatum. The method was compared with the standard reconstruction used clinically, with and without resolution modelling.

II. Materials and Methods

Iterative reconstruction methods utilize a SRM that describes the acquisition process in the scanner as:

$$y = P \cdot f + r \tag{1}$$

where P is the SRM, f is a vector describing a voxelized image with the distribution of the radiotracer in the field of view (FOV), r is a vector representing the background noise due to the random coincidences and y is the measured data arranged into sinograms. Each element P_{ij} of the SRM models the probability that the annihilation photons from a positron emission from voxel j are detected in sinogram bin i.

In practice, the system matrix is usually defined using a factorized model with the following components:

$$y = A \cdot N \cdot X \cdot H \cdot f + s + r \tag{2}$$

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where A and N are diagonal matrices with the attenuation and normalization factors, X is the x-ray transform that projects image f into sinograms, H is a matrix that models the resolution of the system; and s and r are the scatter and randoms estimates respectively. The x-ray transform is usually computed using an on-the-fly projector. In this case the resolution modelling is done in image space [13], but it can be also modelled in sinogram space or not modelled at all. The benefits and drawbacks of resolution modelling have been discussed in [14], [15].

A more accurate model for the system matrix could be obtained with Monte Carlo simulations, for example using GATE. This is a scan-dependent and non-factorized system matrix that accounts for all the physical effects, including the scatter, and most of the detector components:

$$y = P_{gate} \cdot f + r \tag{3}$$

where P_{gate} is the unified system matrix computed with GATE and r is an additive vector that accounts for the randoms, which is the only component not taken into account by the system matrix.

A. Composite System Matrix

In practice, using a Monte Carlo model is not feasible because it is not possible to store in memory and the computational cost is too high. In addition, for the case of a scan-dependent system matrix it is not possible to apply symmetries to reduce the data size because the model depends on the attenuation map. For this reason, we propose the use of a composite system matrix that uses a Monte Carlo model computed with GATE for a selected subregion of the image and the standard model of equation (2) for the pixels external to the subregion:

$$y = k_{gate} \cdot P_{gate} \cdot f_{int} + k_{fact} \cdot A \cdot N \cdot X \cdot f_{ext} + s_{ext} + r \tag{4}$$

where P_{gate} is the system matrix computed with GATE for all the pixels in the subregion f_{int}, while the second term is the factorized analytical model of equation (2) for the pixels external to the subregion (f_{ext}); s_{ext} is the estimate of the scatter coming only from f_{ext}; k_{gate} and k_{fact} are calibration factors for the GATE and the factorized system matrices respectively. Finally, r is the randoms estimate.

B. Striatum and Brain Simulations

GATE simulations of a striatum phantom and a brain phantom were used to evaluate the reconstruction with a pure GATE system matrix and with the composite system matrix respectively. In the simulations, only one ring of the Biograph mMR was modelled [16], [17], since we were interested in evaluating the proposed method for 2D reconstructions, in the first instance. Voxelized phantoms were used for the activity and attenuation maps. The phantoms were based on the Brainweb phantom [18], the pixel size was 0.5×0.5 mm^2 and the head had a realistic size of 20 cm length (Fig. 1). The striatum phantom consisted of a small activity map of 34×28 pixels centred in the striatum of the brain phantom with hot and cold lesions of 4 mm diameter and the respective attenuation map for that subregion of the brain phantom as it is hilighted with a red line in Fig. 1. A total of 3.5×10^6 coincidence events were simulated for the striatum phantom and 1.5×10^7 coincidences for the full brain phantom.

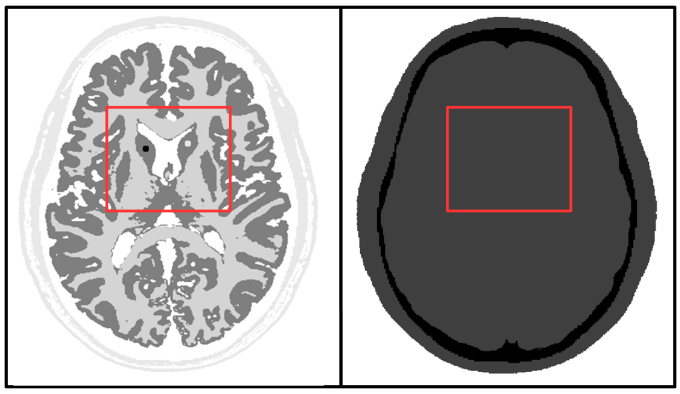

Fig. 1. Voxelized brain phantom simulated with GATE, with the striatum phantom subregion highlighted with a red border. Left: activity map of the phantom. Right: μ-map of the brain phantom.

C. 2D Gate System Matrix

A GATE system matrix for the PET-MR scanner Biograph mMR was computed for each of the simulations to be reconstructed. For the reconstruction of the striatum simulation data, the system matrix was computed using a simulation with a uniform activity distribution in the striatum subregion and the respective subregion in the attenuation map (both highlighted with a red rectangle in Fig. 1). For the reconstruction of the full brain simulation, the same uniform activity distribution in the striatum subregion was used, but now with the full attenuation map of the brain phantom. The simulations account for all the physical factors, therefore the scatter is included in both system matrices.

Each simulation was processed by sorting the detected events by their emission position. For each voxel of the phantom, a sinogram was generated and stored in the respective column of the system matrix. The system matrix for the reconstruction of the striatum simulation had 8.2×10^7 counts, while for the full brain simulation had 4.6×10^7 counts.

D. Image Reconstruction and Evaluation

The striatum simulation was reconstructed using MLEM with the standard model of equation (2) and with the GATE system matrix proposed in this work. For the standard model, a Siddon projector was used and the reconstructions were performed without and with resolution modelling. We call them Siddon and Siddon-PSF respectively. For the resolution modelling, a shift-invariant Gaussian kernel was applied in image space [13]. To obtain the parameters of the gaussian kernel, we used a simulation of a point source in air in the scanner. A full width at half maximum (FWHM) of 4 mm was obtained. For the simulation with the full activity map, the reconstruction with the GATE model was carried out using the composite system matrix described previously.

III. Results

Fig. 2 shows the reconstructed images for the striatum simulation at the iteration 100 for the three analysed methods: Siddon, Siddon-PSF and GATE; and they are compared with the maximum likelihood estimate for the complete data (X_{ML_c}) that can be extracted from the simulation. The image reconstructed with the GATE system matrix have a better definition of the hot and cold spots, as well as

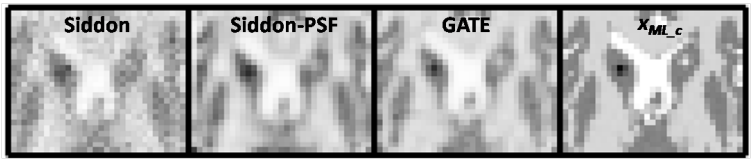

Fig. 2. Reconstructed images of the striatum simulation in the iteration number 100 using the Siddon (left), the Siddon-PSF (middle-left) and the GATE (middle-right) system matrices. On the right, the ML of the complete data is found.

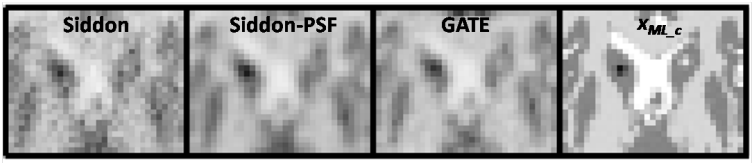

Fig. 3. Reconstructed images of the brain simulation in the iteration number 100 using the Siddon (left), Sidon-PSF (middle-left) and composite GATE (middle-right) system matrices. On the right, the ML of the complete data is found.

of the lateral ventricles and the putamen, showing the benefit of the GATE model. As expected, both methods that model the resolution in the scanner achieved higher contrast.

Fig.5 contains the striatum subregion of the reconstructed images for the full brain simulation, where the image reconstructed with the composite system matrix shows better definition of some of the structures of the brain, but the analytical system matrix with resolution modelling obtained higher contrast for the hot lesion.

IV. Conclusion

In this work we have presented a composite system matrix that uses GATE to define the system matrix for an application-specific subregion and the standard analytical system matrix for the voxels external to that subregion. This way, a system matrix computed with GATE, that was not feasible in practice, is now possible. The benefits of a pure GATE system matrix were shown for the reconstruction of a 2D simulation of a striatum phantom. The composite system matrix was evaluated with a 2D brain simulation, where some improvements were observed with respect to the analytical system matrix with or without resolution modelling. However, the benefits were limited compared to the pure GATE system matrix.

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