Design of a spatially-variable-focusing collimator and impact of the forward projection model in reconstruction for small-animal SPECT

*Didier Benoit*, Julien Bonte, Irène Buvat

QIM IMNC-IN2P3/CNRS, UMR 8165, Orsay

DROITE Seminar, October 25, 2012
1. **Project overview**
   - Introduction
   - Detector
   - Collimators

2. **Simulation in GATE**
   - GPU/CPU Implementations
   - Results

3. **Reconstruction**
   - OS-EM-ML
   - Projectors
   - Normalization
   - PSF Model

4. **Results**
   - Sensitivity
   - Results
   - Spatial Resolution

5. **Conclusion/Perspectives**
Introduction

- SIGAHR5 project (Système multi-modulaire préclinique d’Imagerie GAmmma Haute Résolution et Sensibilité).
- Aim : Design a multi-fonctionnal preclinic scintigraphic imaging system, appropriate for 3 types of applications:
  - Oncology.
  - Neurology.
  - Cardiology.

- Small-animal SPECT imaging.
- High performance system with semi-conductor detectors (CZT).
- Original collimation system : Spatially-Variable-Focusing Cone-Beam collimator (SVF-CB).
- First SVF-CB collimator in small-animal SPECT.
- French TecSan ANR started in 2009, coordinated by Biospace Lab.
**Project Partners**

- **Biospace Lab**, Paris, marketing, automatism, systemic, software.
- **CEA-LETI**, Grenoble, gamma detection technology, electronic.
- **IMNC**, Orsay, simulations, reconstruction.
- **INSERM U877 unit** (Daniel Fagret), Grenoble: radiotracer, cardiology applications.
- **TIRO CEA-University** (Philippe Franken), Nice: radiotracer, oncology applications.
- **INSERM U930 unit** (Denis Guilloteau), Tours: radiotracer, neurology.
IMNC Aims

- Modeling the collimator and detector with GATE [1-2].
- Implementation of an appropriate iterative reconstruction:
  - Study the feasibility to reconstruct with focal lengths inside the field-of-view (FOV).
  - Develop a PSF model for this collimator.
  - Show the impact of different forward and back projector models.
- Characterize the SVF-CB collimator (sensitivity, spatial resolution) and compare to a parallel collimator.

Detector simulated in GATE:

- CZT pixels.
- Pixels: 0.75x0.75x5.0 mm³.
- 131x131 pixels.
Parallel Collimator

Parallel collimator simulated in GATE:
- **Septa** in *tungsten*.
- 0.3x0.3 mm square holes.
- 0.15 mm septa width.
SVF-CB In Collimator

SVF-CB In collimator simulated in GATE:

- **Focals in field of view** (FOV).
- Septa in tungsten.
- 0.3x0.3 mm square holes at the surface of detector.
- 0.15 mm septa width.
SVF-CB Out Collimator simulated in GATE:

- **Focals out field of view** (FOV).
- 0.3x0.3 mm square holes at the surface of detector.
- Septa in tungsten.
- 0.15 mm septa width.
Focal Distributions

Hyperbolic focal length distributions, in the transaxial plane, proposed by CEA-LETI:

\[ f(x) = f_{\text{min}} \sqrt{\left(\frac{x}{x_{\text{max}}}\right)^2 \left[\left(\frac{f_{\text{max}}}{f_{\text{min}}}\right)^2 - 1\right] + 1} \]
SPECT simulation in GATE: Aims

Work in collaboration with Julien Bert (LaTIM) in Brest during the first two weeks of July 2012.

- GATE/GPU and GATE/Multi-core CPUs interface for SPECT imaging.
- Ray-tracing technique in the collimator.
- No interaction modeled in the collimator (work in progress in Brest).
- Parallel and convergent square-hole collimator only.
- Application: small-animal SPECT $^{99m}$Tc (140.5 keV).
Method

1. **Particles emission** (\(^{99m}\)Tc source).
2. **Storing the particle features** at the collimator entrance (until a buffer is full).
3. When the buffer is full, we **project the particles** onto the collimator exit with the ray-tracing technique on GPU or on multi-core CPUs.
4. When the buffer content is processed, we **complete** the simulation as usual in GATE creating new tracks corresponding to the exiting particles.
Results

- Factor 10 between GPU (580 GTX) and 1 CPU (Intel XEON) in collimator only (for a point source simulation, 1 GBq, 0.1 sec. acquisition duration, size of buffer 20000000 particles). 40 min simulation duration.
- GATE/GPU and GATE/Multi-core CPUs interface available.
- Ray-tracing limitation: no particle interaction within the collimator is modeled, so only appropriate for $^{99m}$Tc.
- Future work:
  - Modeling the particle interactions within the collimator (work in progress in Brest): scatter and septal penetration will be simulated.
  - Extending to other collimator geometry (only square-hole collimators are supported at the moment).
Using the OS-EM-ML[3] iterative algorithm:

- Neither scatter nor attenuation correction.

\[ \lambda_j^{(k+1)} = \frac{\lambda_j^{(k)}}{\sum_{t \in S_i} \frac{\alpha_{t,j}}{N_t}} \sum_{t \in S_i} \frac{\alpha_{t,j} p_t}{\sum_{b=0}^M \alpha_{t,b} \lambda_b^{(k)}} \]

- \( k \): iteration
- \( S_i \): subset i
- \( \lambda_j \): estimate voxel j
- \( t \): element in subset
- \( \alpha_{t,j} \): system matrix entry
- \( N_t \): normalized element t
- \( p_t \): data pixel element t
- \( M \): voxel elements

Siddon[4] Ray-Tracer (S-RT)

A projection line links the center of a detector pixel to the corresponding focal line.
Voxel: $37 \times 750 \times 37 \, \mu m^3$

A projection line links a point randomly selected at the detector pixel surface to the corresponding focal line. 
Voxel: 37x750x37 $\mu m^3$, 1024 rays

Parallel collimator

SVF-CB In collimator
Siddon Ray-Tracer with Solid Angle (S-RT-SA)

A projection line links a point randomly selected at the detector pixel surface and a point randomly selected at the entrance of the collimator hole.
Voxel : 37x750x37 $\mu m^3$, 1024 rays

Parallel collimator

SVF-CB In collimator
Normalization (1)

Data are normalized in order to get the same efficiency for each pixel detector elements. The normalization map was obtained by:

- Simulating a planar $^{99m}$Tc source in GATE (10 mm width) close to the collimator (15 MBq, 5120 seconds acquisition duration).

GATE SVF-CB In simulation

GATE SVF-CB Out simulation
Normalization (2)

- Projecting an analytic planar source (as in GATE) with the different projectors. Storing in an array the ratio between our model (A) and the Monte Carlo (MC) model.

\[ EFF_t = \frac{MC_t}{A_t} \]

- Computing the mean value of these ratios.

\[ \overline{EFF} = \frac{\sum_{t=0}^{N-1} EFF_t}{N} \]

- Normalization:

\[ Norm_t = \frac{EFF}{EFF_t} \]
Examples of normalization maps:

SVF-CB In normalization
To improve the spatial resolution in the reconstructed images, we developed a PSF model for the SVF-CB collimator (non-stationary and anisotropic). For the parallel hole collimator we used an empiric stationary and isotropic PSF.

Example of few simulated points (0 mm in axial plane) reconstructed with S-RT-SA projector and SVF-CB In collimator:

0 mm radial
8 mm
24 mm
30 mm
As in [5], we defined a kernel PSF for each voxel in the image space, and we expressed the PSF as a 1D axial function and 2D transaxial functions. The reconstructed point sources were fitted with a skew distribution:

$$G(x) = Ae^{-\frac{(x-\xi)^2}{2\sigma^2}} \left[ 1 + \text{erf}\left(\frac{x-\xi}{\sigma\sqrt{2}}\right)\right]$$

- $\xi$: location
- $\sigma$: scale
- $\alpha$: shape

PSF Plotting example (1)

Point source: 0.0 mm in axial position and 0.0 mm in radial position
PSF Plotting example (2)

Point source: 0.0 mm in axial position and 28.0 mm in radial position
PSF evolution: S-RT-SA (voxel 500 µm, 4096 rays)
PSF evolution: S-RT-IV (voxel 500 μm, 4096 rays)
We simulated a $^{99m}$Tc cylindrical source (12.5 mm radius, 90 mm height), at the center of the FOV. 60 projections (over $360^\circ$), 117 MBq and 48 seconds per projection.
Results: Parallel-hole collimator

- Mean
  - S-RT
  - S-RT + PSF 1.17 mm
  - S-RT-IV
  - S-RT-IV + PSF 1.17 mm
  - S-RT-SA
  - S-RT-SA + PSF 0.8 mm

- Noise [%]
  - S-RT
  - S-RT + PSF 1.17 mm
  - S-RT-IV
  - S-RT-IV + PSF 1.17 mm
  - S-RT-SA
  - S-RT-SA + PSF 0.8 mm
Results: SVF-CB In collimator

![Graph 1: Mean vs Iteration]

![Graph 2: Noise vs Iteration]

![Graph 3: Mean vs Noise]
Spatial Resolution (1)

Simulations of line sources filled with $^{99m}$Tc and 47,36 MBq (diameter 0.28 mm, length 90 mm) in air at 2.25 mm from the FOV center. We simulated three different ROR: 25, 30 and 35 mm, with 60 projections, 32 sec per projection.
Spatial Resolution (2)

FWHM variation as a function of the number of rays for the line source with 35 mm ROR and the S-RT-SA projector.
Derenzo simulations with hot inserts (2.4 mm, 2.0, 1.7, 1.35, 1.0 and 0.75). Each insert is filled with 15.9 MBq/mL $^{99m}$Tc. No background activity. Derenzo at the center of the FOV, 120 projections, and 30 seconds per projection.
Spatial Resolution (4)

S-RT, parallel + PSF

S-RT-IV

S-RT-SA

0 10 20 30 40 50 60 70
Distance [mm]
0
2
4
6
8
10
12
14
S-RT
S-RT-IV
S-RT-SA
S-RT + 1.17 mm PSF
S-RT-IV + 1.17 mm PSF
S-RT-SA + 0.8 mm PSF
Spatial Resolution (5)

- S-RT, SVF-CB In no PSF
- S-RT-IV
- S-RT-SA
- S-RT, SVF-CB In + PSF
- S-RT-IV
- S-RT-SA
Spatial Resolution (6)
Reconstruction for an SVF-CB collimator with focal lengths within the FOV is feasible.

First SVF-CB collimator design for small-animal SPECT.

Higher sensitivity of the SVF-CB collimator compared to the parallel collimator.

S-RT-SA more accurate than S-RT because all geometric effects are included.

The PSF model improves the spatial resolution.

An original PSF model for an SVF-CB collimator has been developed.

Future work:
- Adapt the PSF model to the whole image space and improve it.
- Compute the system matrix by Monte-Carlo simulation and compare to our PSF model for SVF-CB collimator.