Monte Carlo Simulation For Nuclear Imaging

-

GATE : Geant4 Applications for Tomographic Emissions

Sébastien Jan

Outline

- How to define a Monte Carlo simulation ?
- GATE : A platform for Monte Carlo Simulation
- Pre-clinical imaging applications
- Clinical imaging applications

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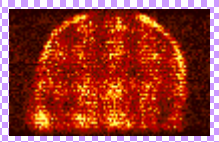
Example : Monte Carlo Simulation for PET

Isotope production
^{18}F – ^{11}C – ^{15}O …

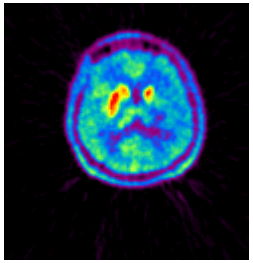
Radio-Pharmaceutics synthesis

MC Simulation

Injection



Acquisition



Quantification
&
Reconstruction

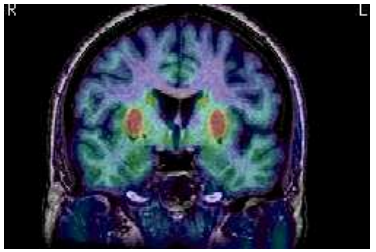
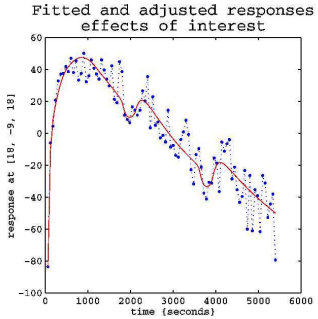
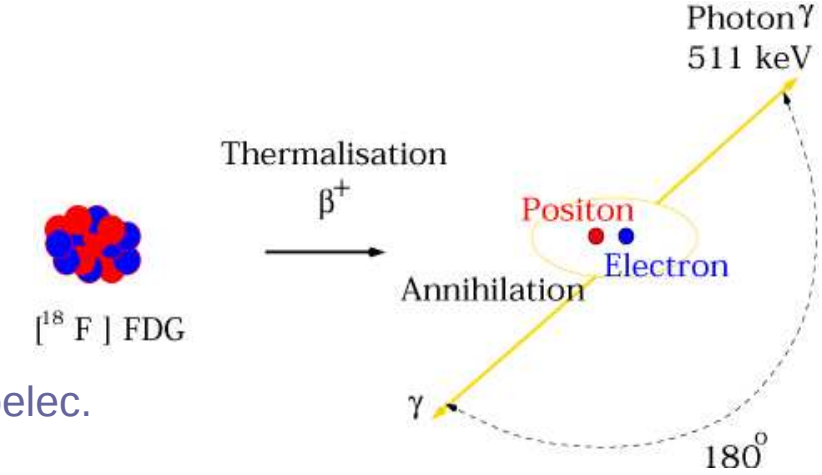


Image treatments

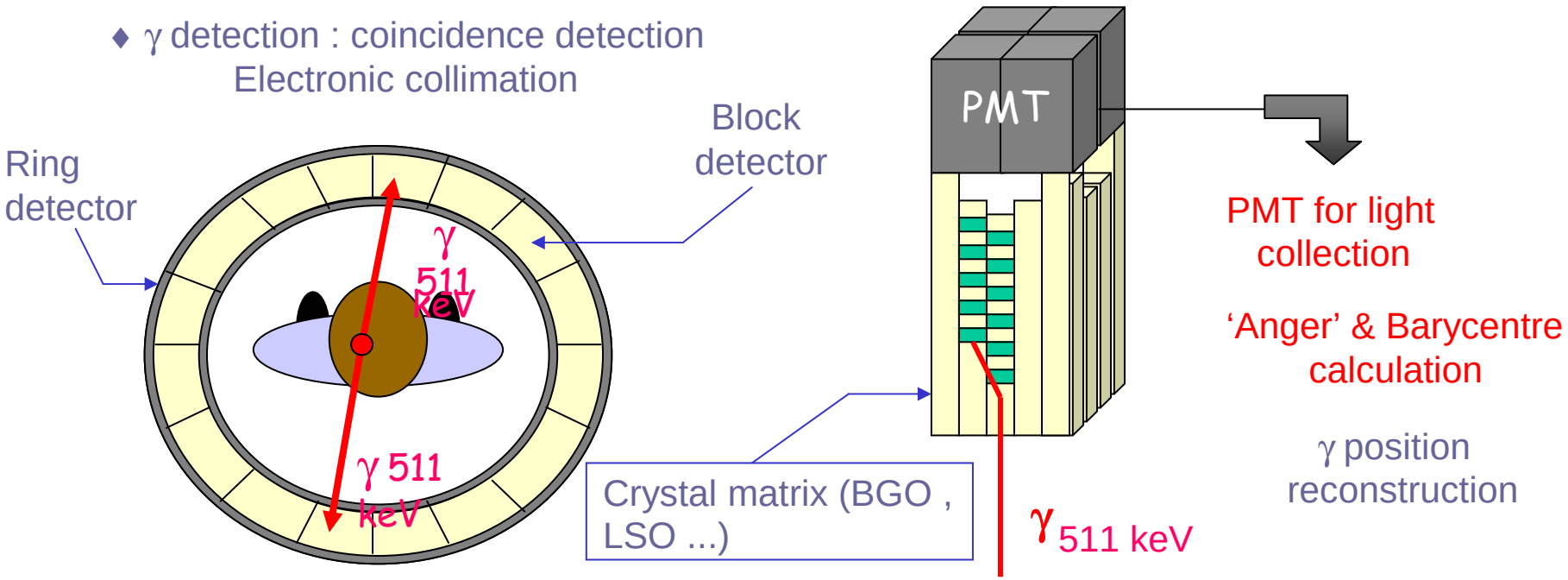


Which physics for the simulation ?

- Physical processes
  - β^+ decay
  - Multi-scattering & multi-ionisation for e^+ in the tissue
  - Annihilation : $e^+e^- \rightarrow \gamma\gamma$
  - γ interactions : compton, rayleigh, photoelec.

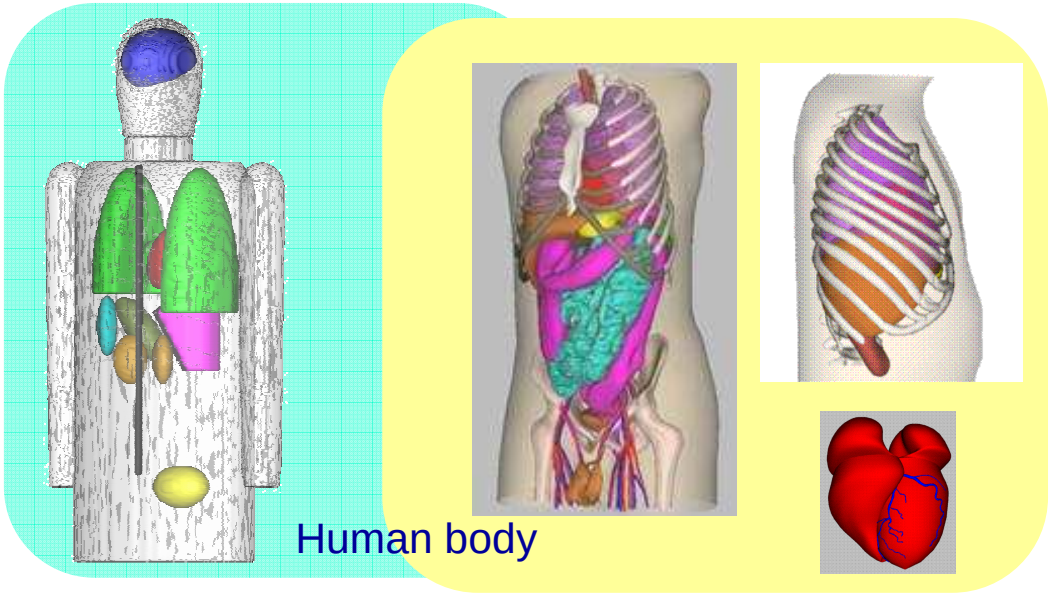


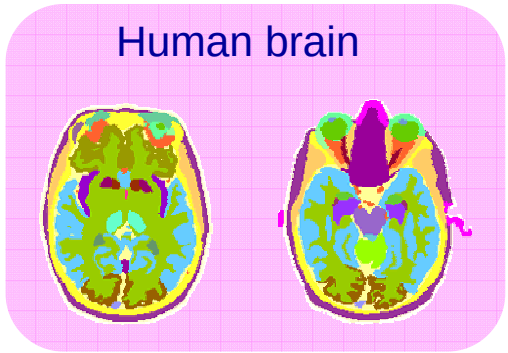
- Detection and signal acquisition
  - γ detection : coincidence detection
    Electronic collimation

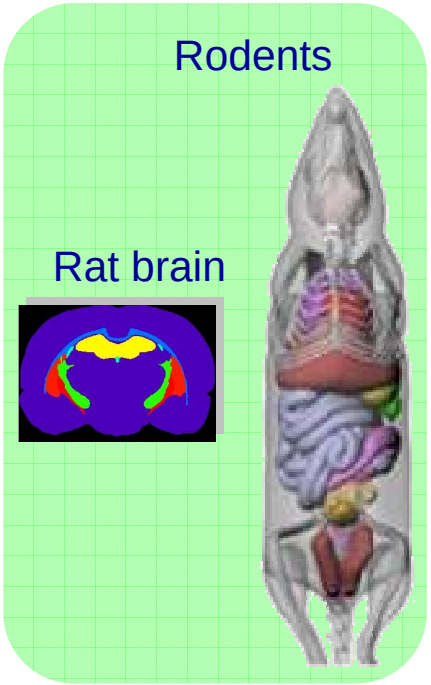


Modelling the activity distribution

- Organ and structure descriptions







For each organ or structure :

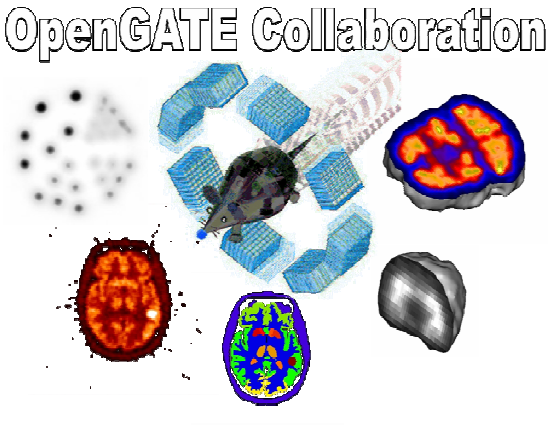
- Material (μ(E))
- Isotope ($T_{1/2}$) and activity concentration (Bq/ml(*t*))

Outline

- How to define a Monte Carlo simulation ?
- **GATE : A platform for Monte Carlo Simulation**
- Pre-clinical imaging applications
- Clinical imaging applications

GATE : Geant4 Application for Tomographic Emission

❑ OpenGATE international collaboration

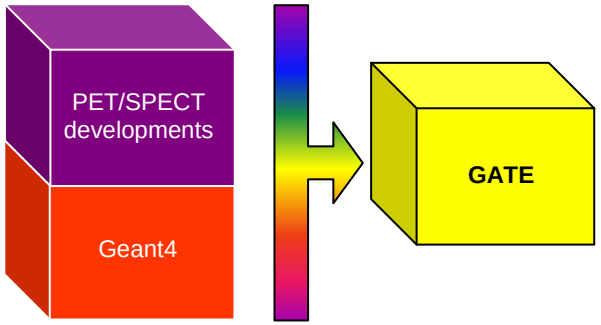


- 23 laboratories
- ~ 60 scientists
- ***Technical coordinator : Sébastien JAN - CEA***
- ***Spokesperson : Irène Buvat - INSERM***

❑ GATE software

- **First developments :** 2002
- **General simulation platform for emission tomography**

First public release: 3 mai 2004
Today : more than 900 users – 10 releases – version 3.1.1



♦ Geometry and materials
- **System selection :** SPECT or PET
- **detector description**
  - Block geometry
  - Crystal dimension
  - Active medium (LSO-BGO-LuYAP……)
- **Phantom description**

♦ General configuration
- **Isotope & Source Selection**
- **Activity**
- **Acquisition parameters**
  - energy resolution
  - Detector & Source Movements
  - Time parameters
  - Detector modelling
- **Physical processes**

GATE today: practical features

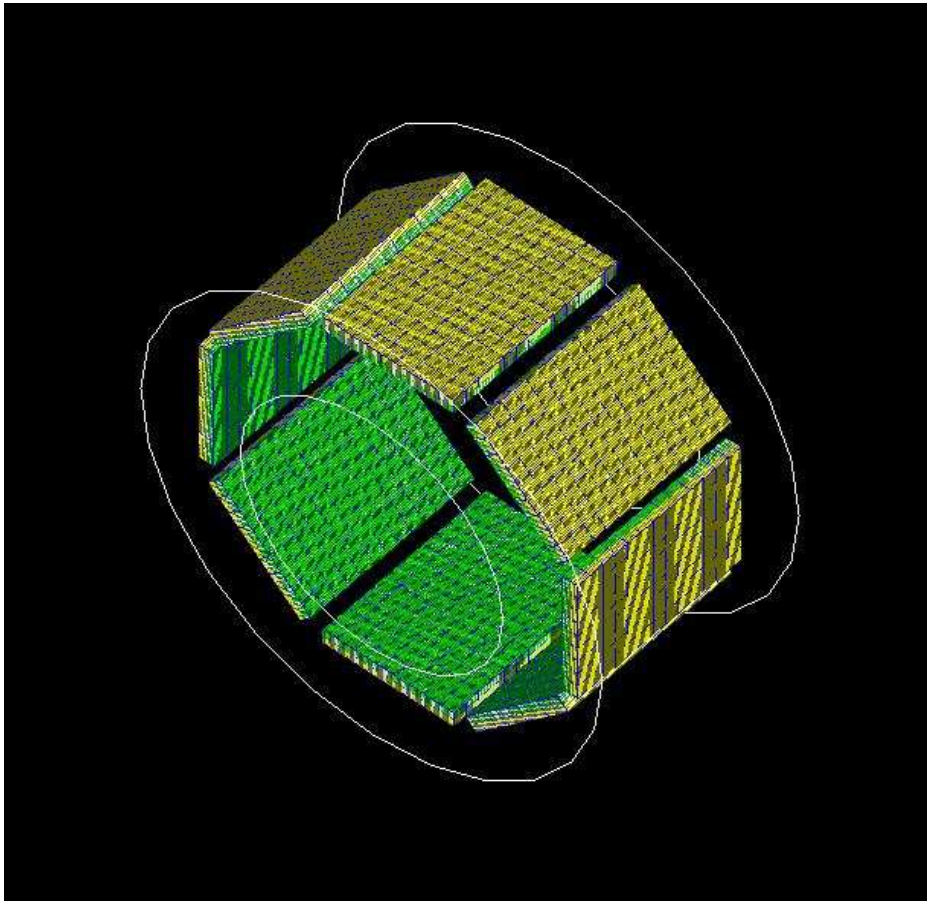
- *Can be freely downloaded, including the source codes*
- **On-line documentation**
- *Help about the use of GATE can be obtained through the gate-user mailing list*
- **Many commercial tomographs and prototypes have already been modeled and models have been validated**
- *Developed as a collaborative effort (23 labs worldwide)*
- **2 public releases each year**
- *An official publication:*
Jan S, et al. GATE: a simulation toolkit for PET and SPECT. Phys Med Biol 49: 4543-4561, 2004.
- **Website: http://www.opengatecollaboration.org**
- *GATE workshops at the IEEE Medical Imaging Conferences (2003, 2004, 2005, 2006)*
- **GATE training sessions – 1 / year**

GATE : detector and scanner geometry

- Geometry description by script

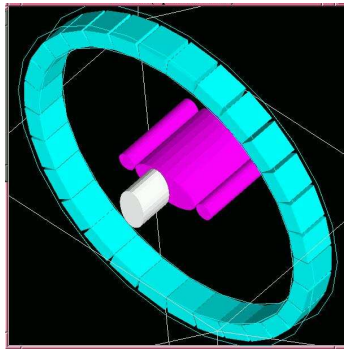
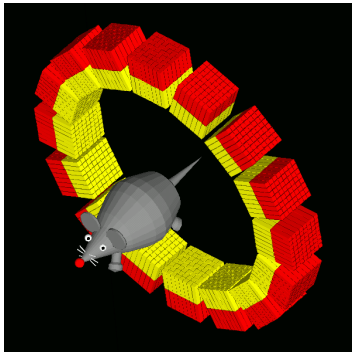
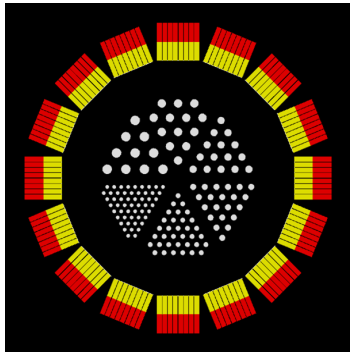
```
#                REPEAT BLOCK
/gate/block/repeaters/insert cubicArray
/gate/block/cubicArray/setRepeatNumberX 1
/gate/block/cubicArray/setRepeatNumberY 8
/gate/block/cubicArray/setRepeatNumberZ 12
/gate/block/cubicArray/setRepeatVector 0.0 1.6 2.0 cm
/gate/block/daughters/insert box
/gate/crystal/placement/setTranslation 0.0 0.0 0.0 cm
/gate/crystal/geometry/setXLength 3.0 cm
/gate/crystal/geometry/setYLength 3.0 mm
/gate/crystal/geometry/setZLength 3.8 mm
/gate/crystal/setMaterial Air
/gate/crystal/vis/setVisible 0

#                REPEAT CRYSTAL
/gate/crystal/repeaters/insert cubicArray
/gate/crystal/cubicArray/setRepeatNumberX 1
/gate/crystal/cubicArray/setRepeatNumberY 5
/gate/crystal/cubicArray/setRepeatNumberZ 5
/gate/crystal/cubicArray/setRepeatVector 0.0 3.2 4.0 mm
```

A complete tomograph

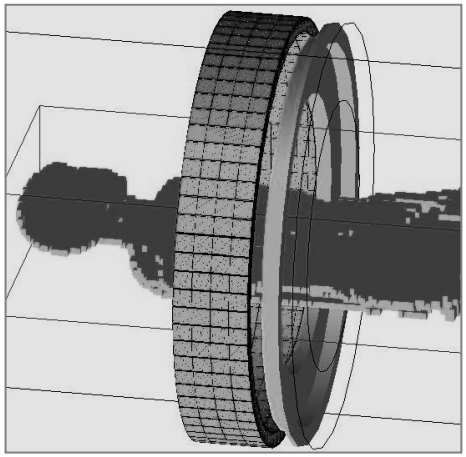
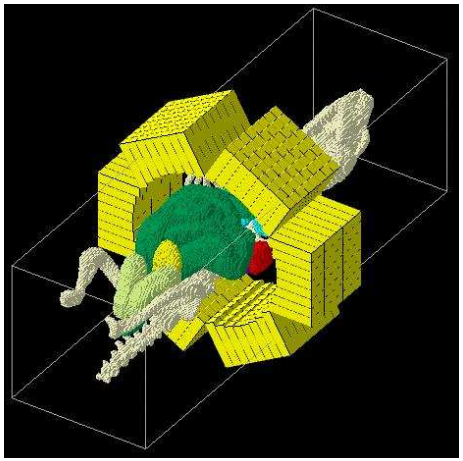


GATE : phantom geometry

- Geometrical description

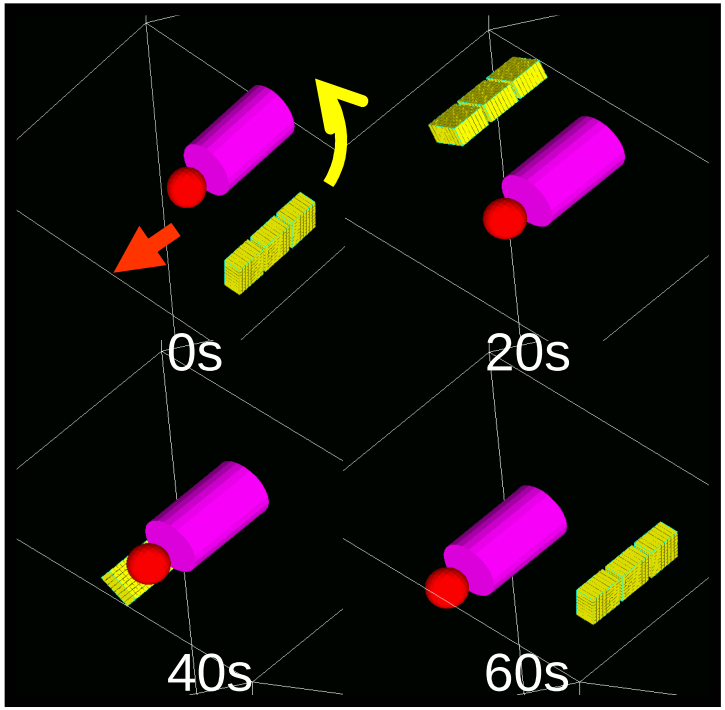




- Voxelized description

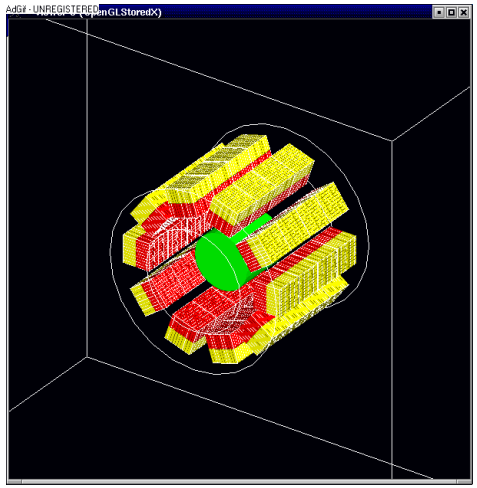
GATE : Time and Movement

❑ Phantom and detector movements

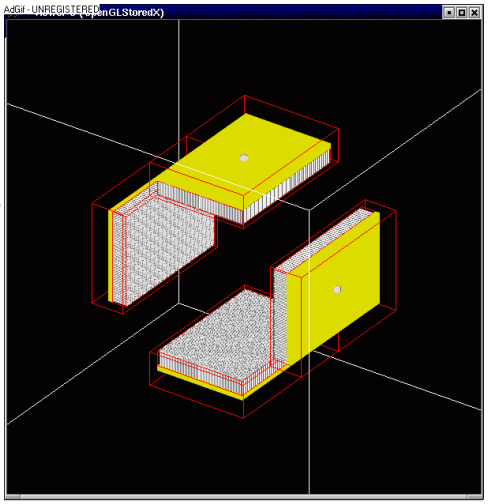


- Source translation
- Scanner rotation

- Rotation of PET scanner

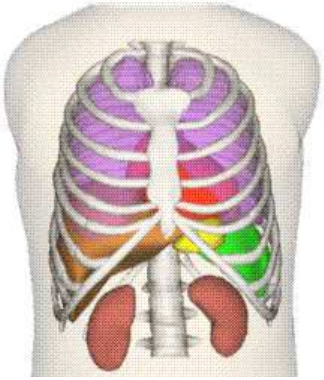


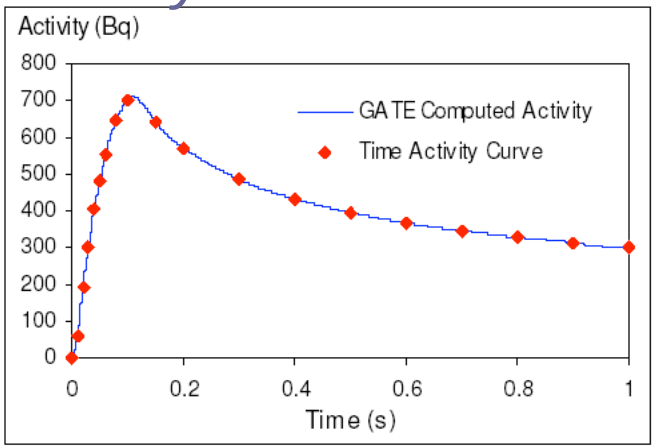
- Rotation of SPECT scanner



GATE : Time and Movement

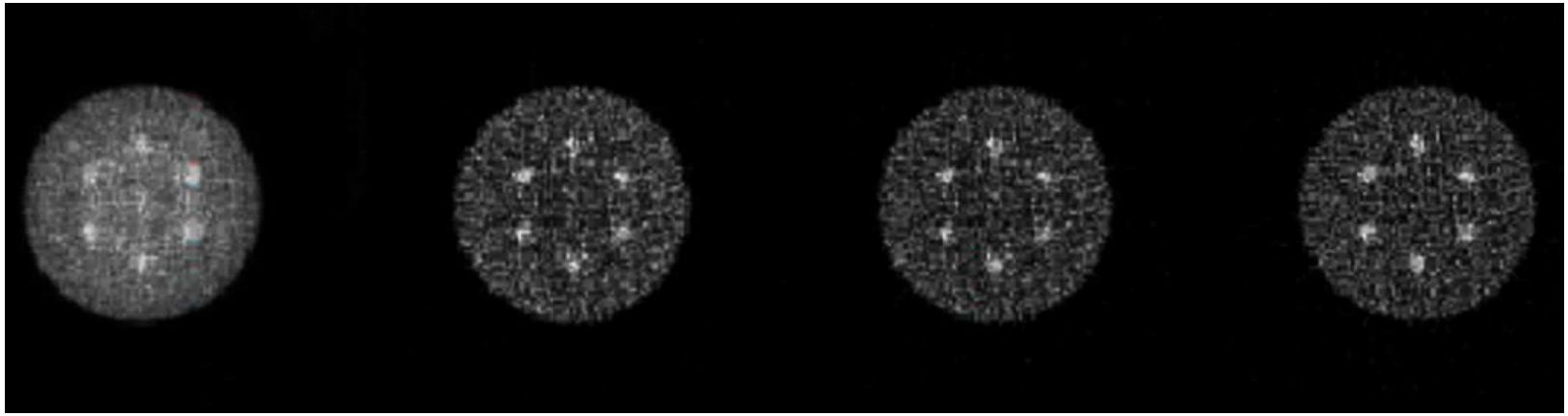
Modelling the "Time Activity Curve" for each organ





Descourt et al, IEEE MIC Conf Rec 2006

Modelling of time of flight for PET devices

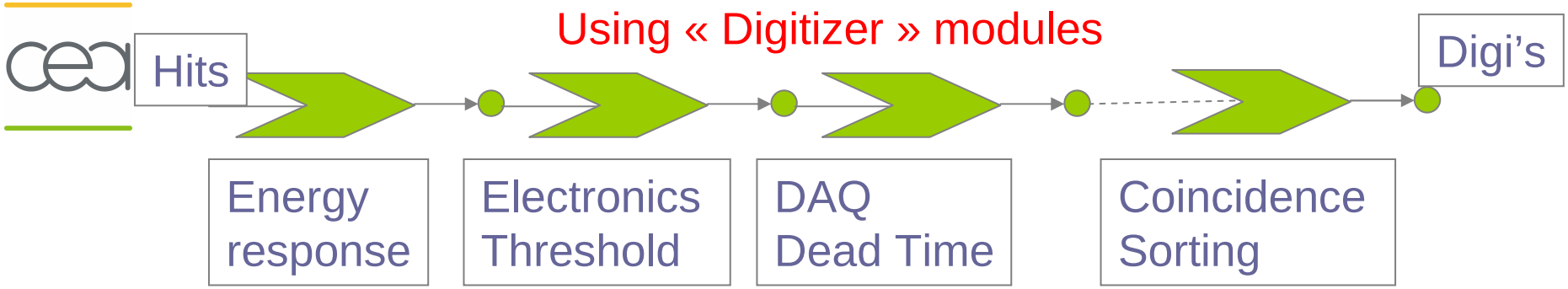


Timing resolution	No TOF 3 ns	TOF 700 ps	TOF 500 ps	TOF 300 ps

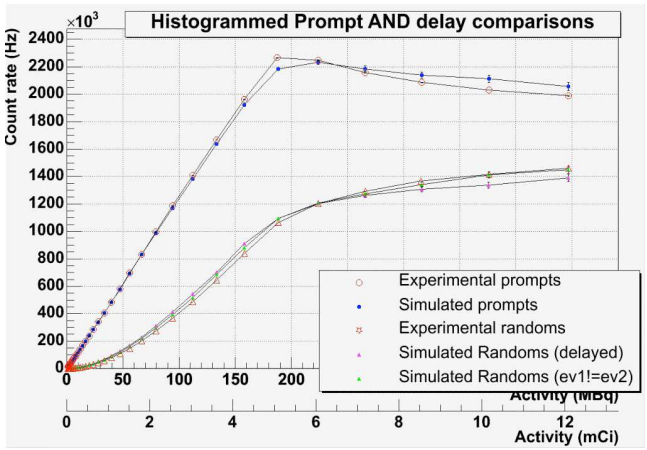
Groiselle et al, IEEE MIC Conf Rec 2004

GATE : Detector response

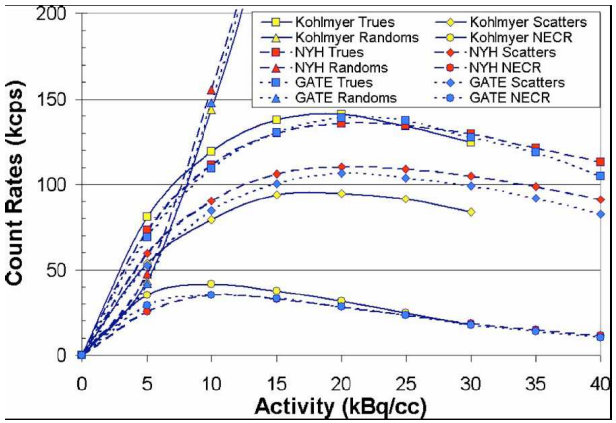
Modelling the detector response of the system



- Reproduce count rate curves



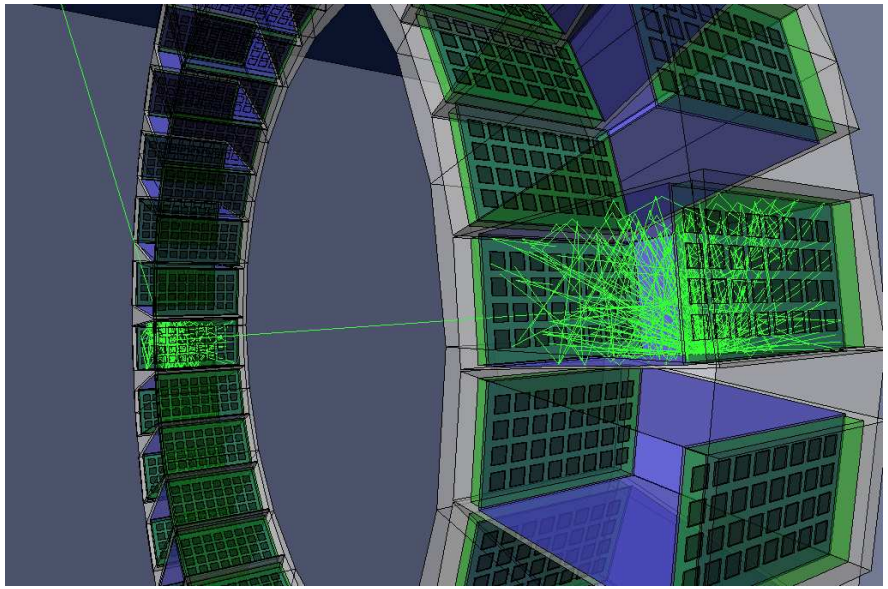
HRRT - Guez et al

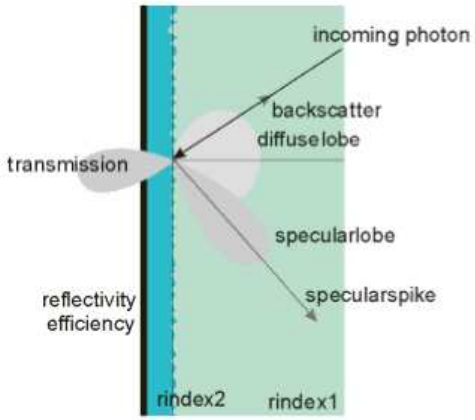


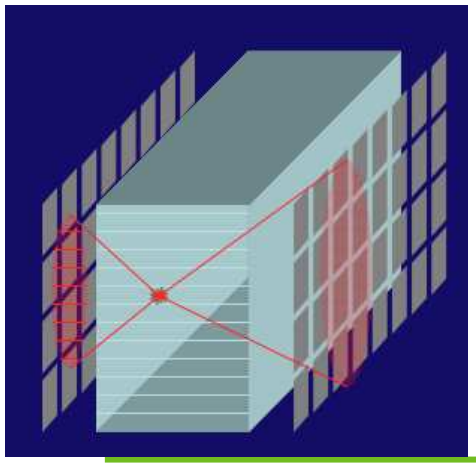
GE Advance - Schmidtlein et al

Simulations of the optical transport

Other GATE features useful for helping in detector design





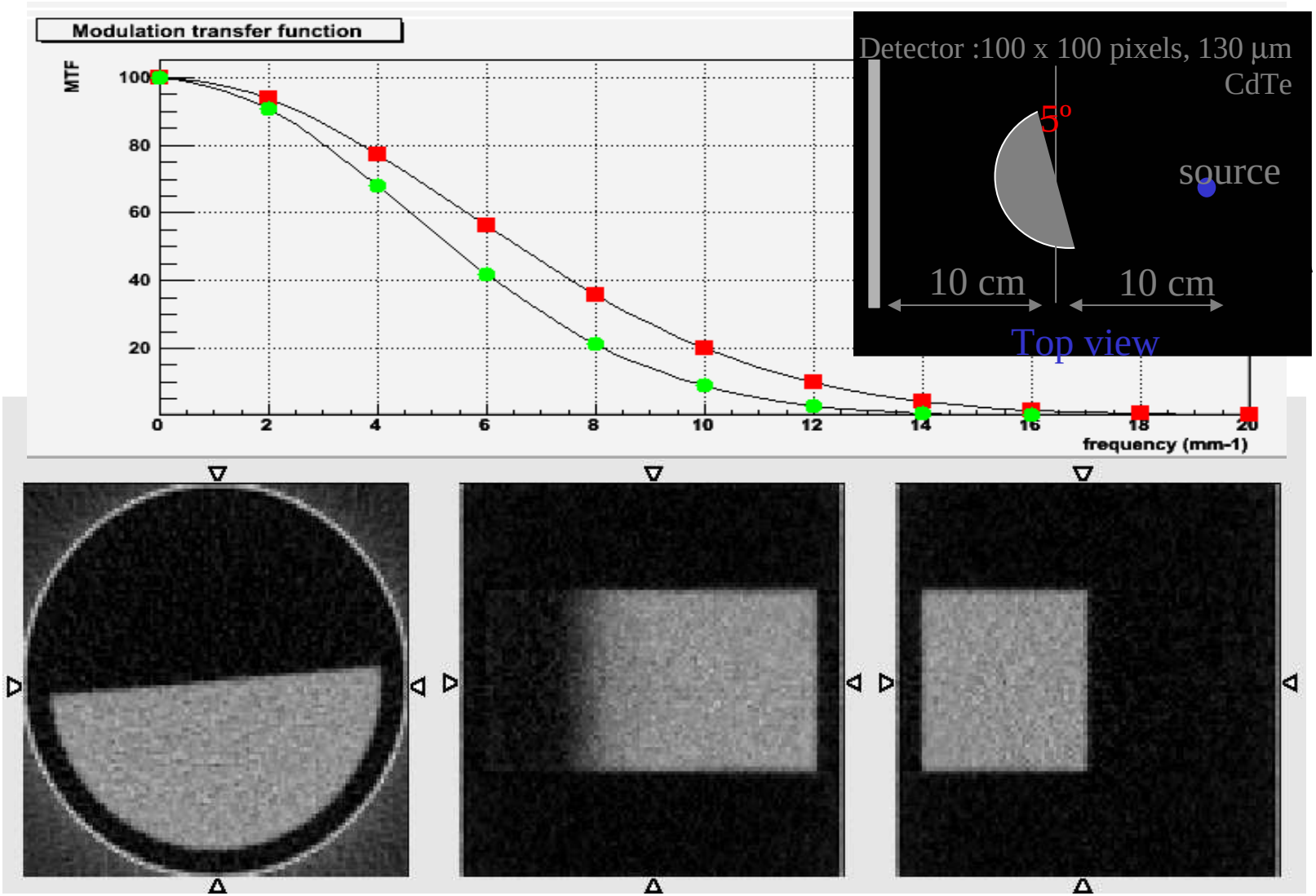


- Most PET/SPECT detectors based on scintillator coupled to light detector
- Can be used to investigate influence of detector geometry and surface finish on
  - Energy resolution
  - Spatial resolution
  - …

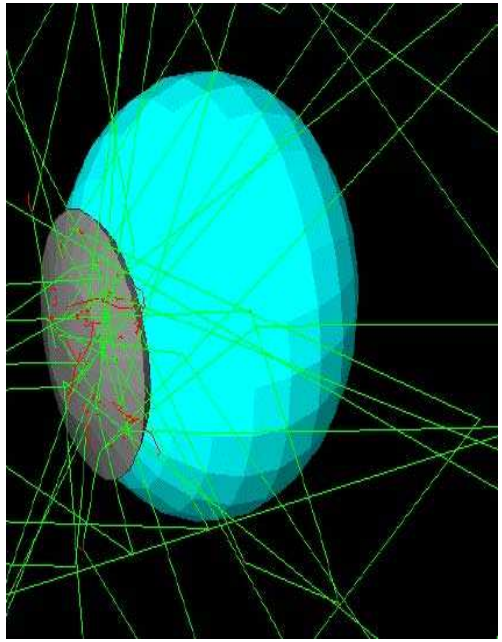
CT Scanner simulation

PIXSCAN developments

Morel et al. – CPPM Marseille



Simulations for dosimetry applications



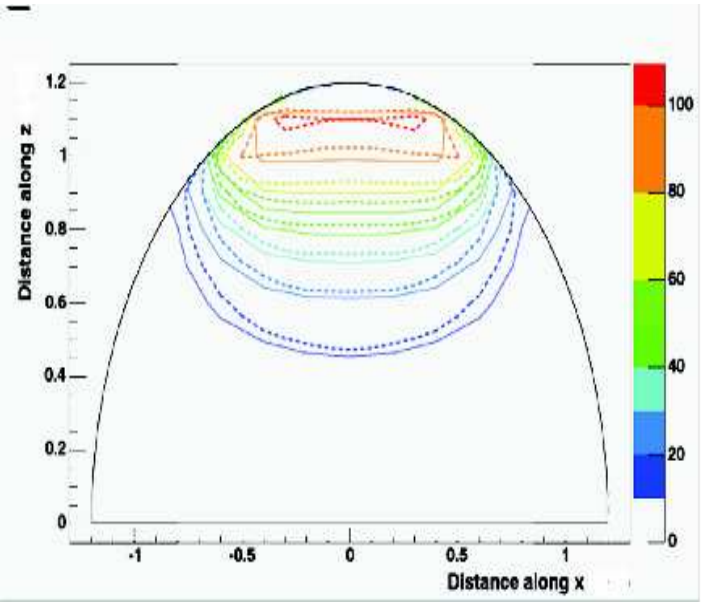
Ocular or Prostate Brachytherapy

L.Maigne et al. – LPC Clermont

Dose calculations in **(with a specific output included in GATE)** :

- Small animal imaging: ***microCT and FDG microPET***

- External beam electron radiotherapy



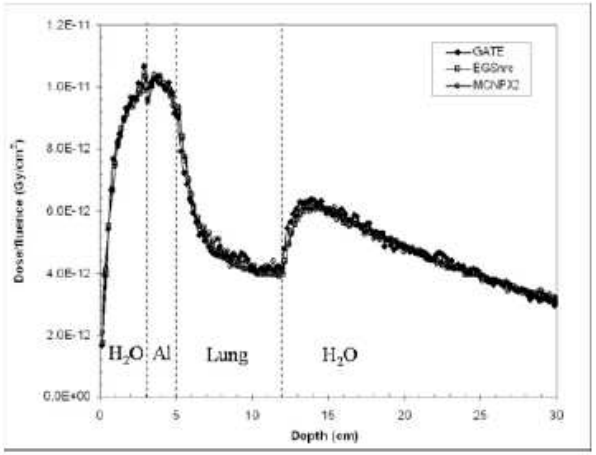


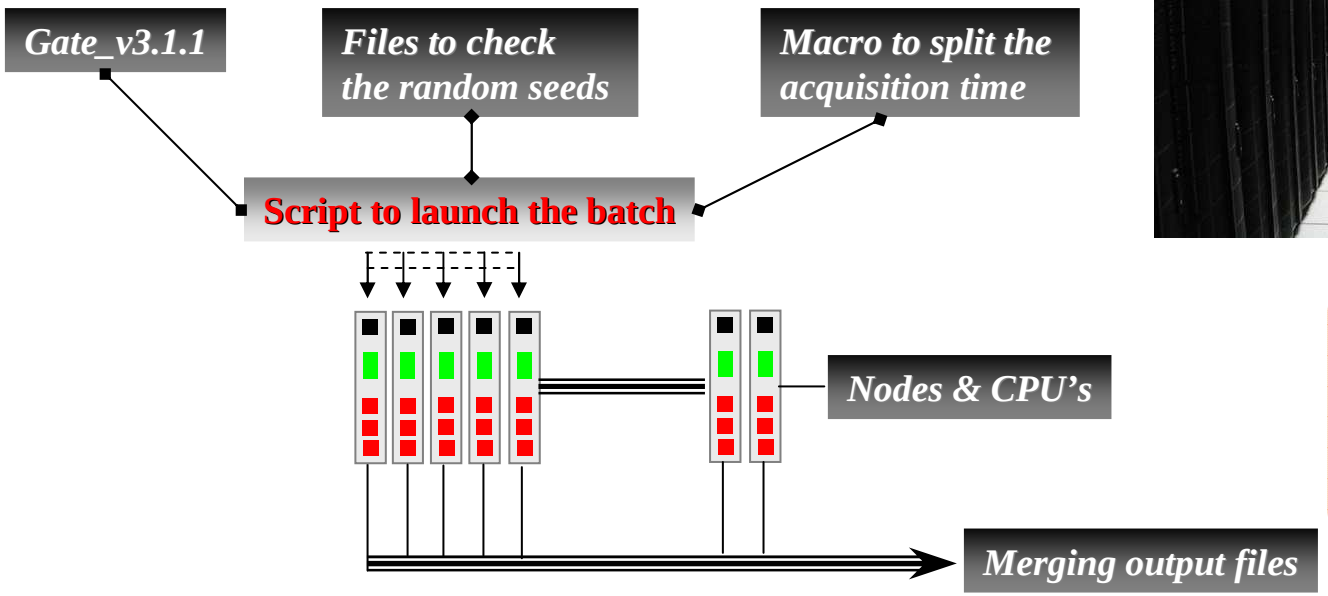
Fig. 1. Depth dose curve using the benchmark and the 18MV photon beam for GATE, EGSnrc and MCNPX2

Visvikis et al. NIM A 2006

Execution of the code on a distributed architecture

- Tools include in the last GATE release

De Beenhouwer et al, IEEE MIC Conf Rec 2006



Pseudo-parallel approach

Splitting acquisition time

Ex: 1 mCi injected dose

10' acquisition time

10 CPU's & 1' by CPU

Speed-up factor ~ number of jobs

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- GATE : A platform for Monte Carlo Simulation
- **Pre-clinical imaging applications**
- Clinical imaging applications

Objectives for biologic applications

Small Animal PET Imaging

Neurology

Receptor imaging

- Rat brain imaging
- [^{11}C]Raclopride & [^{18}F]LDOPA….

Oncology

Metabolic imaging

- Whole body imaging for rat and mouse
- [^{18}F]FDG

Monte Carlo Simulations for what ?.....

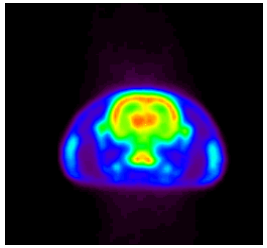
- ✓ Data corrections optimisation (Partial Volume, scatter correction…)
- ✓ Reconstruction optimisation
- ✓ A tool for quantitative analysis

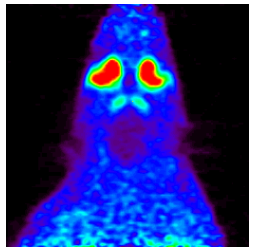
Main goal: Simulation of realistic exams

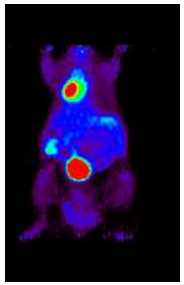
- ***Rat brain studies: [^{11}C]Raclopride***

… [^{18}F]FDG…

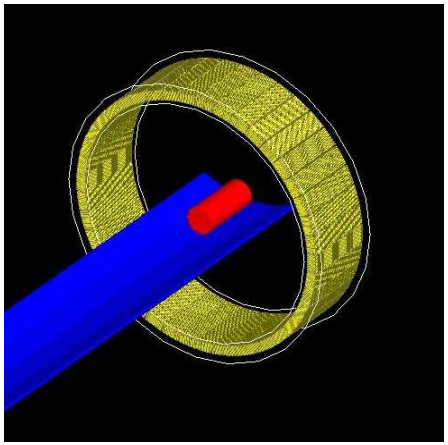
- ***Whole Body studies, Rat & Mouse : [^{18}F]FDG***





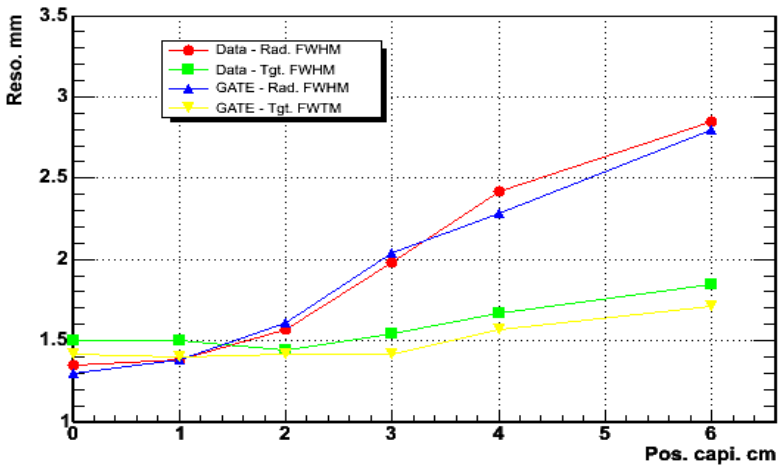


MicroPET® FOCUS simulation with GATE

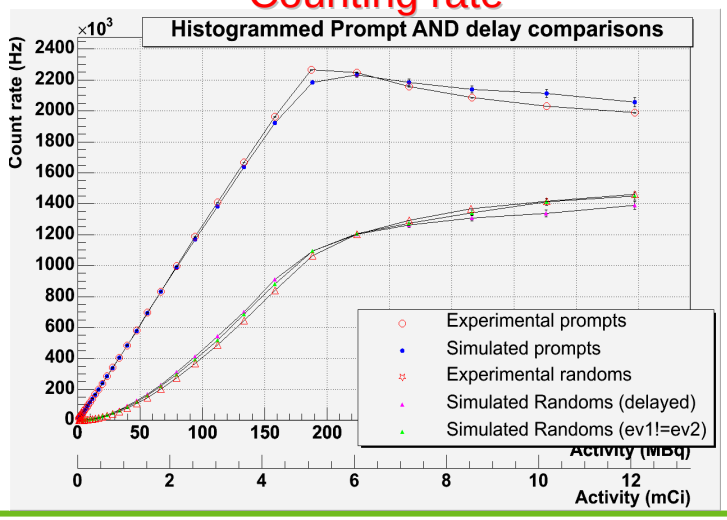


Validation results : ***Jan & al. "Monte Carlo Simulation of the microPET FOCUS system for small Rodents imaging applications" IEEE MIC Conference Proceedings, 1653-1657, Puerto Rico, October 2005***

Spatial resolution

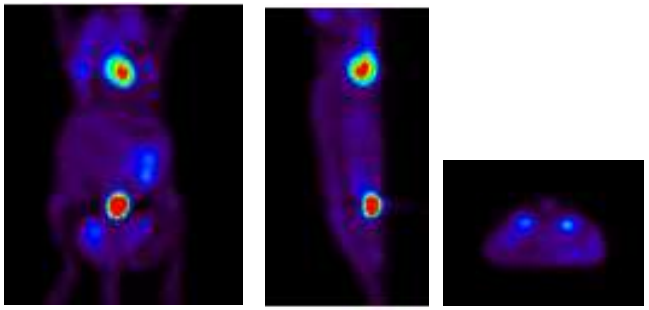


Counting rate

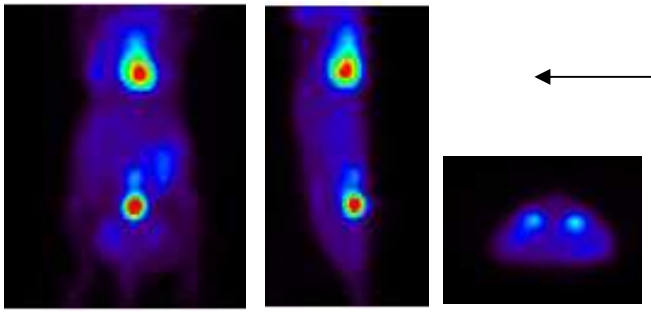


Metabolic PET imaging: Simulation of [^{18}F]FDG exam

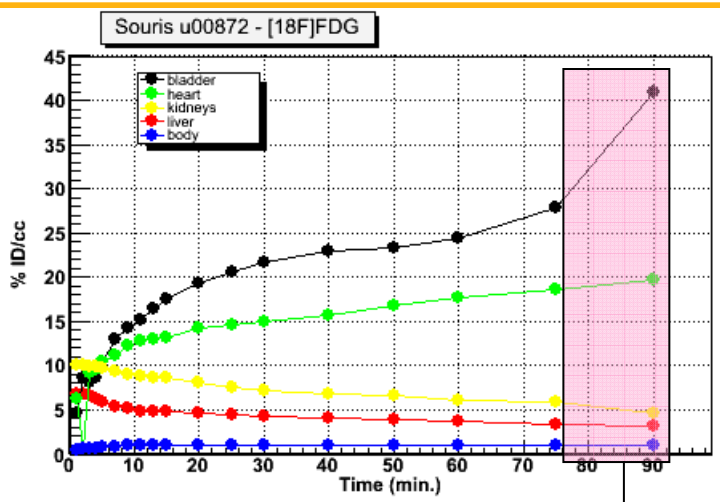
Real exam

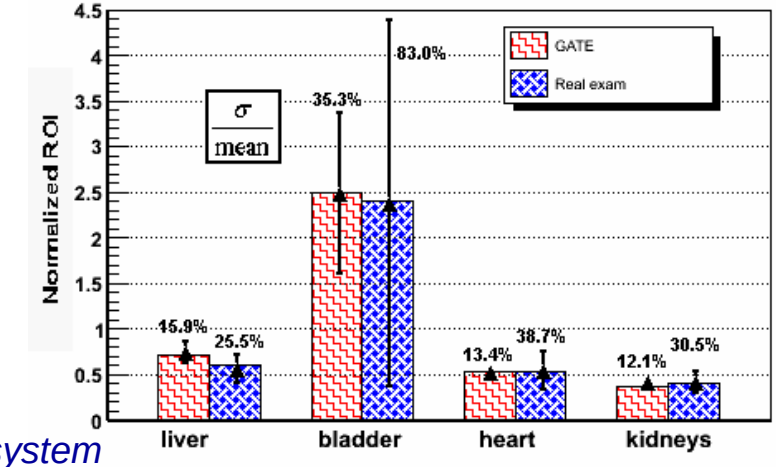


Simulation

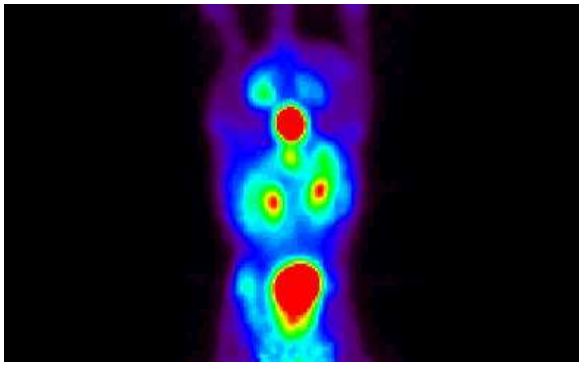


Coronal Sagital Transaxial





Simulation



FDG scan simulation

- *microPET FOCUS 220 system*
- *Injected dose: 200 µCi*
- *Start acquisition: 45 min. after injection*
- *Acquisition time: 15'*

Thesis of Susana Branco

Outline

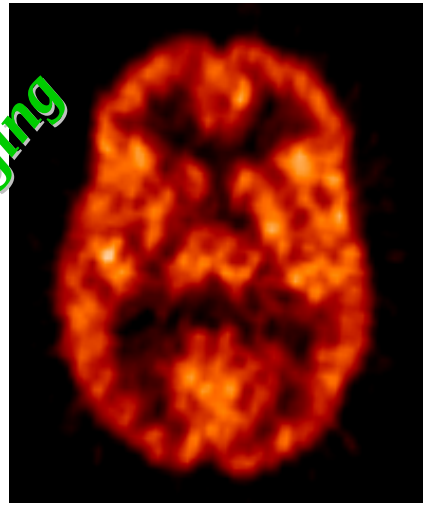
- How to define a Monte Carlo simulation ?
- GATE : A platform for Monte Carlo Simulation
- Pre-clinical imaging applications
- **Clinical imaging applications**

Brain an whole body simulations for clinical applications

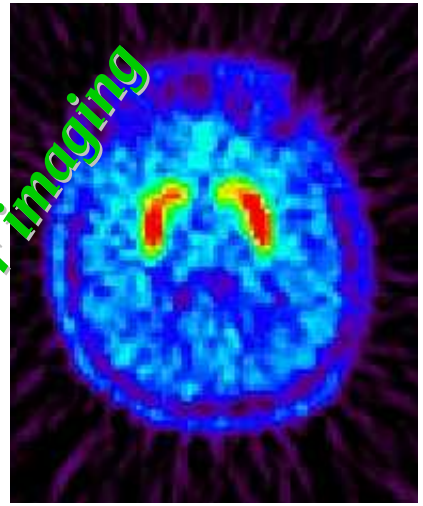
General objective with GATE

- Simulation of realistic exams
- Generation of realistic Monte Carlo Data Base

Metabolic imaging



Receptor imaging

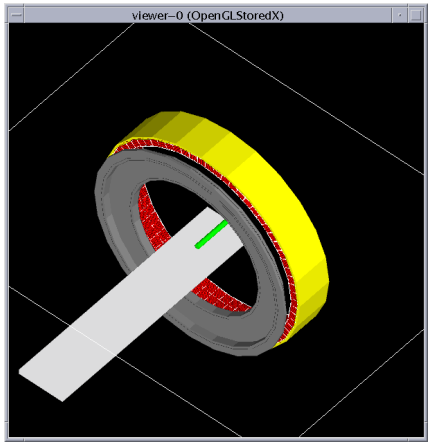


Oncology

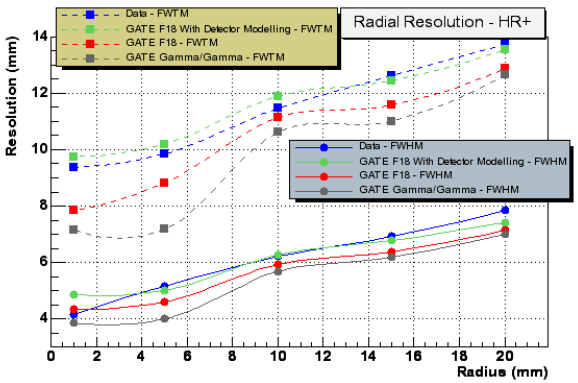
Optimisations with GATE:

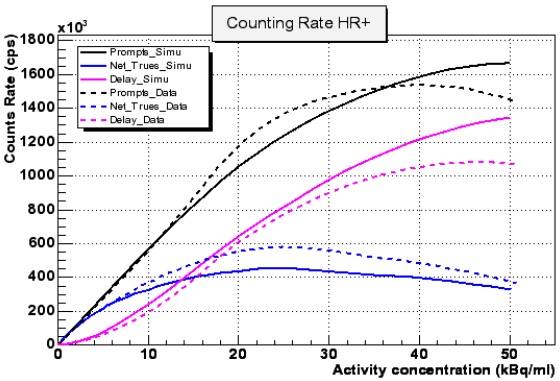
- ✓ Acquisition protocol *(injected dose, acquisition time, threshold…dedicated for each patient)*
- ✓ Algorithms for data corrections and reconstructions
- ✓ Quantitative analysis
- ✓ Dosimetry studies

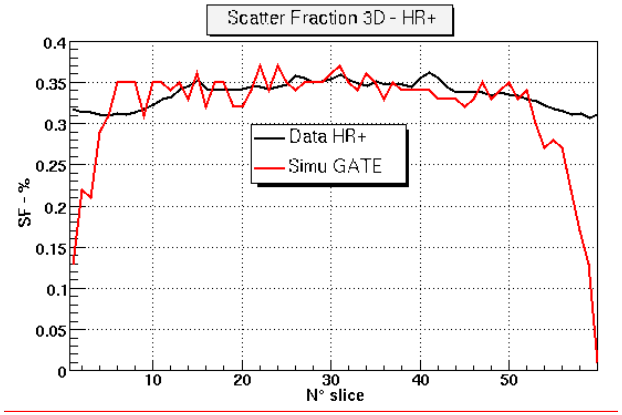
ECAT EXACT HR+ scanner



Validation results : ***Jan & al. "Monte Carlo Simulation for the ECAT EXACT HR+ System Using GATE" IEEE TNS, Vol. 52, NO. 3, June 2005***





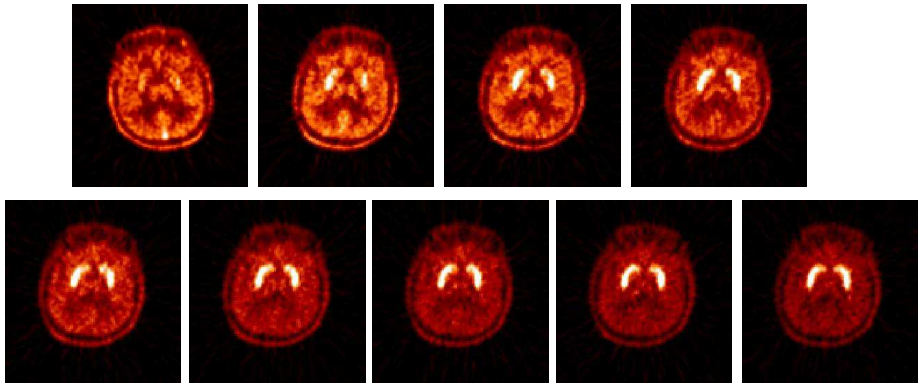


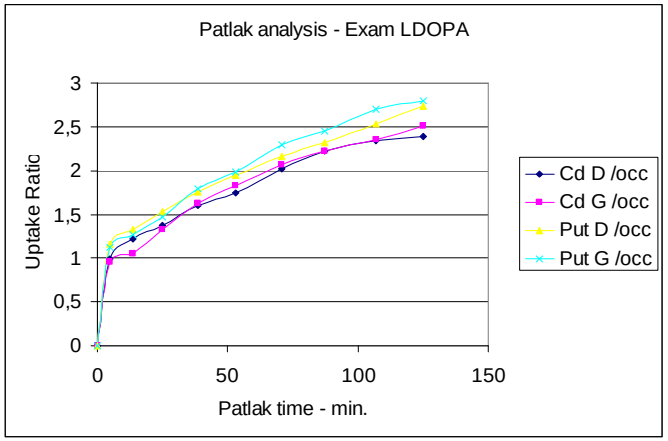
Real acquisition against simulation: *[^{18}F]FluoroDOPA* protocol

❑ Evaluation of the striatal uptake constant (Kc) values with a Patlak analysis

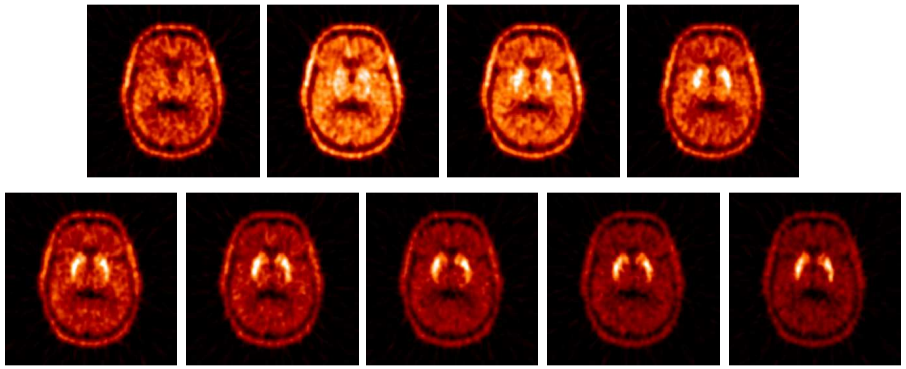
For clinical and simulation data sets, we used average time frame images to define regions of interest (ROIs) on the caudate, putamen (specific regions) and occipital lobe (reference region) in contiguous planes where these structures could be visualised. Time activity curves (TACs) were extracted from these ROIs. From these curves, the Fluoro-L-DOPA Kc values were determined for the caudate and putamen nuclei using the Patlak analysis – Ref. (5)

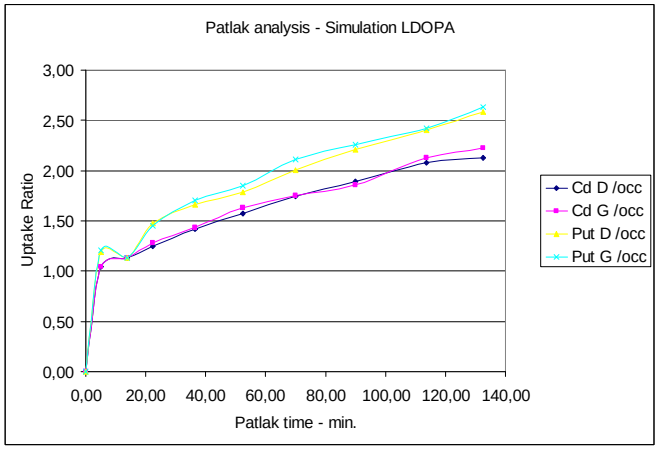
Real exam (Frame 0 to 8)





GATE simulation (Frame 0 to 8)





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http://www.opengatecollaboration.org