GATE: a simulation toolkit for emission tomography in nuclear medicine and molecular imaging

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Outline

• Evolution of the use of MC simulations in ET since 1995
• OpenGATE motivation and short history
• New features in MC simulators in ET
• New applications for MC simulations
• Upcoming developments in MC simulations
• Conclusion
Emission tomography in Nuclear Medicine

Non invasive techniques for assessing the in vivo distribution of a radiotracer administered to a patient

$\beta$ or $\gamma$ emitter

tracer targeting a specific phenomenon

$\gamma$ emitter: Single Photon Emission Computed Tomography (SPECT)
$\beta^+$ emitter: Positron Emission Tomography (PET)
Evolution of the use of MC simulations in ET since 1995

Important role in SPECT and PET, for optimizing detector design, designing and assessing acquisition and processing protocols.


• Buvat and Castiglioni, Monte Carlo simulations in SPET and PET. *Q J Nucl Med* 46 (2002) 48-61

QuickTime™ et un décompresseur TIFF (LZW) sont requis pour visionner cette image.
Evolution of the use of MC simulations in ET since 1995

- 666 entries since 1995 at the date of the search (July 1995)
- Use of MC simulations to produce SPECT and PET images: 130 entries

Number of full papers

- 86% SPECT
- 14% PET
- 65% SPECT
- 35% PET

0 small animal
5 small animal

Year


28 labs
33 labs
Evolution of the codes used for MC simulations in ET since 1995

1995-1999

• 14 different codes:
  - 10 « home-made »
  - 4 publicly released or available from authors

2000-2004

• 15 different codes:
  - 8 « home-made »
  - 7 publicly released or available from authors

No « standard » code for Monte Carlo simulations in SPECT and PET

Most frequently used

- SimSET
- SIMIND

And recently

- Geant 4
- GATE
- Penelope
Most recent code for ET modeling: GATE

• Motivation in 2001: provide a public code
  - based on a standard code to ensure reliability
  - enabling SPECT and PET simulations (possibly even more)
  - accommodating almost any detector design (including prototypes)
  - modeling time-dependent processes
  - user-friendly

• Developed as a collaborative effort
The OpenGATE collaboration

From 4 to 21 labs worldwide

- Delft University of Technology, Delft, The Netherlands
- Ecole Polytechnique Fédérale de Lausanne, Switzerland
- Forschungszentrum Juelich, Germany
- Ghent University, Belgium
- National Technical University of Athens, Greece
- Vrije Universiteit Brussel, Belgium

- U601 Inserm, Nantes, France
- U650 Inserm, Brest, France
- U678 Inserm, Paris, France

- LPC CNRS, Clermont Ferrand, France
- IReS CNRS, Strasbourg, France
- UMR5515 CNRS, CREATIS, Lyon, France

- SHFJ CEA, Orsay, France
- DAPNIA CEA, Saclay, France
- Joseph Fourier University, Grenoble, France

- John Hopkins University, Baltimore, USA
- Memorial Sloan-Kettering Cancer Center, New York, USA
- University of California, Los Angeles, USA
- University of Massachusetts Medical School, Worcester, USA
- University of Santiago of Chile, Chile
- Sungkyunkwan University School of Medicine, Seoul, Korea
Product of OpenGATE: GATE

• Publicly released on May 2004 [http://www.opengatecollaboration.org](http://www.opengatecollaboration.org)


• More than 400 subscribers to the Gate users mailing list
GATE today: technical features

• Based on GEANT 4
• Written in C++
• User-friendly: simulations can be designed and controlled using macros, without any C++ writing
• Appropriate for SPECT and PET simulations
• Flexible enough to model almost any detector designs, including prototypes
• Explicit modeling of time (hence detector motion, patient motion, radioactive decay, dead time, time of flight, tracer kinetics)
• Can handle voxelized and analytical phantoms
GATE today: practical features

• Can be freely downloaded, including the source codes
• Can be run on many platforms (Linux, Unix, MacOs)
• On-line documentation, including FAQ and archives of all questions (and often answers) about GATE that have been asked so far
• Help about the use of GATE can be obtained through the gate-user mailing list
• Many commercial tomographs and prototypes have already been modeled
• The GATE project is currently based only on volunteer participation and on the active contribution of GATE users and developers
Monte Carlo simulations today
Modeling time dependent processes

SPECT and PET intrinsically involves time:

- Change of tracer distribution over time
- Detector motions during acquisition
- Patient motion
- Radioactive decay
- Dead time of the detector
- Time-of-flight PET

GEANT 4 (hence GATE) is perfect in that regard

Santin et al, IEEE TNS 2003

Santin et al, IEEE TNS 2003

Groiselle et al, IEEE MIC Conf Rec 2004
Throughput of the simulations

- High throughput needed for efficient data production

The major problem with GATE and GEANT4!

- Big “World”:
  - detectors have a “diameter” greater than 1 m
  - emitting object (e.g., patient) is large (50 cm up to 1.80 m)
  - emitting object is finely sampled (typically 1 mm x 1 mm x 1 mm cells)
  - voxelized objects are most often used

- Large number of particles to be simulated
  - low detection efficiency
  - in SPECT, typically 1 / 10 000 is detected
  - in PET, 1 / 200 is detected
Increasing the throughput of the simulations

Using acceleration methods

• Variance reduction techniques such as importance sampling (e.g. in SimSET)
  speed-up factors between 2 and 15

• Fictitious cross-section (or delta scattering)

Combining MC and non MC modeling

Parallel execution of the code

Song et al, Phys Med Biol 2005

Thomason et al, Comp Methods Programs Biomed 2004

Full MC

ARF

increase in efficiency > 100
Modeling original detector designs

GEANT 4 is a very flexible tool

Non-conventional geometries

- Spherical geometry of the Hi-Rez PET scanner
  *Lazaro et al, SNM 2005*

Prototypes

- IASA CsI(Tl) gamma camera
- GEANT 4 is a very flexible tool

Energy spectrum

- Number of counts
- Energy (keV)

Lazaro et al, Phys Med Biol 2004
New applications for Monte Carlo simulations

1995-1999

- Design and assessment of correction and reconstruction methods
- Study of an imaging system response
- Data production for evaluation purpose
- Use in the very imaging process
- Description and validation of a code

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Using Monte Carlo simulations for calculating the system matrix

\[ p = R f \]

“Object” \( f \)

Projection \( p \)

GATE is very appropriate but slow

\( R(i,j) \): probability that a photon emitted in voxel \( j \) be detected in pixel \( i \)

Calculating \( R \) using Monte Carlo simulations:
- for non conventional imaging design (small animal)
- to account for fully 3D and patient-specific phenomena difficult to model analytically (mostly scatter)

Using Monte Carlo for feeding database

http://www.ibfm.cnr.it/mcet/index.html

http://sorteo.cermep.fr

GATE is very appropriate but slow


Reilhac et al, IEEE TNS 2005
What next?
Bridging the gap between MC modeling in imaging and dosimetry

The validity of the physics at low energy will have to be checked. Problems in G4 have been identified, e.g., multiple scattering and corresponding energy deposit calculation.

Dewaraja et al, J Nucl Med 2005
Modeling hybrid machines (PET/CT, SPECT/CT, OPET)

Integrating Monte Carlo modeling tools for:
- common coordinate system
- common object description
- consistent sampling
- convenient assessment of multimodality imaging

Not started yet in GATE

Brasse et al, IEEE MIC Conf Rec 2004
Alexandrakis et al, Phys Med Biol 2005
Designing realistic phantoms

Interfacing realistic phantoms with simulator input

NCAT

MOBY

Segars et al, IEEE TNS 2001

Segars et al, Mol Imaging Biol 2004

Making it easier to model a wide range of body shape and physiological motions

Making GATE handle the description of object using splines
Conclusion

- GATE is a very relevant tool for Monte Carlo simulations in ET

- Simulations will be more and more present in (nuclear) medical imaging in the future:
  - as a invaluable guide for designing imaging protocols and interpreting SPECT and PET scans,
  - in the very imaging process of a patient
Last but not least

GATE training course 16-17 April 2006 in Clermont-Ferrand, France

Check [http://www.opengatecollaboration.org](http://www.opengatecollaboration.org) for updates