Simulations in emission tomography using GATE

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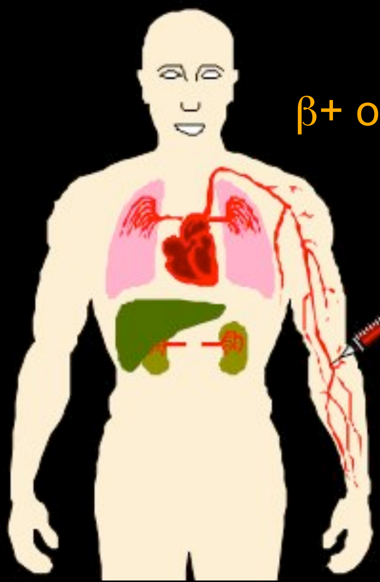
Outline

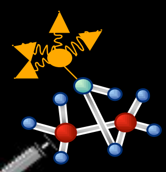
- Emission tomography and need for simulations
- GATE short history and main features
- Usefulness of GATE for assisting in detector design :
    - Flexibility
    - Modeling of time dependent processes
    - Modeling the electronic response
    - Others
- Current priorities in the development of GATE
- Conclusion

Emission tomography in functional imaging

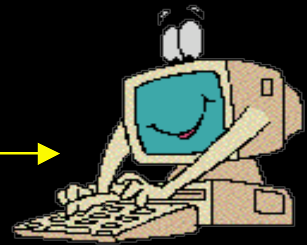
Non invasive techniques for assessing the in vivo distribution of a radiotracer administered to a patient

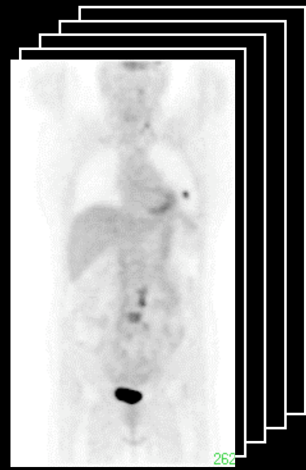


β+ or γ emitter



tracer targeting a specific biological phenomenon





3D distribution of the tracer

γ emitter: Single Photon Emission Computed Tomography (SPECT)
β+ emitter: Positron Emission Tomography (PET)

Need for simulations in emission tomography

- Scanner design, protocol optimization, image reconstruction, (scatter) corrections, dosimetry (for image guided radiotherapy), etc

- Monte Carlo simulations are widely used in addition to analytical simulations and phantom experiments

- No standard code, but about 15 different codes, many of them “home made”

SimSET

SIMIND

Geant 4

GATE

Penelopet
Sorteo
PET-EGS
…

- Various types of users (medical physicists, research scientists…), not necessarily with a strong background in particle physics

GATE short history

- July 2001:
  - ❑ 2-day brainstorming meeting on Monte Carlo simulations in Paris involving French and European labs
  - ❑ Decision to develop a new code, based on GEANT4, to overcome the limitations of existing codes

- December 2001:
  - ❑ First developments of the code, with 4 labs deeply involved at first (EPFL Lausanne, LPC Clermont Ferrand, University of Ghent, U494 Inserm Paris)

- Early 2002:
  - ❑ Creation and development of the OpenGATE collaboration
  - ❑ More and more labs joined the collaboration, up to 23 today, and worked on the development of the code and the preparation of a public release

- May 2004:
  - ❑ First public release of GATE

- Yesterday (March 8th, 2007):
  - ❑ 953 registered users

GATE today: technical features

- Based on GEANT 4
- Written in C++
- Can be run on many platforms (Linux, Unix, MacOs)
- User-friendly: simulations can be designed and controlled using macros, without any knowledge in C++
- Appropriate for SPECT and PET simulations
- Flexible enough to model almost any detector design, 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
- Modular design: new extensions easily added

GATE today: practical features

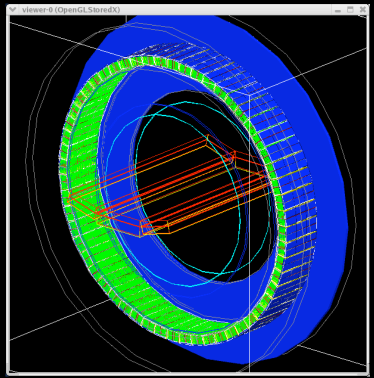
- Can be freely downloaded, including the source codes (registration required, LGPL license)
- On-line documentation, including FAQ and archives of all questions (and often answers) about GATE that have been asked so far
- Help about the use of GATE can be obtained through the gate-user mailing list
- Many commercial tomographs and prototypes have already been modeled 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.

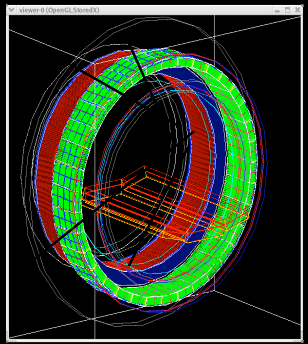
- Website: http://www.opengatecollaboration.org
- GATE workshops at the IEEE Medical Imaging Conferences (2003, 2004, 2005, 2006)
- GATE training sessions

Usefulness of GATE for assisting in detector design: flexibility

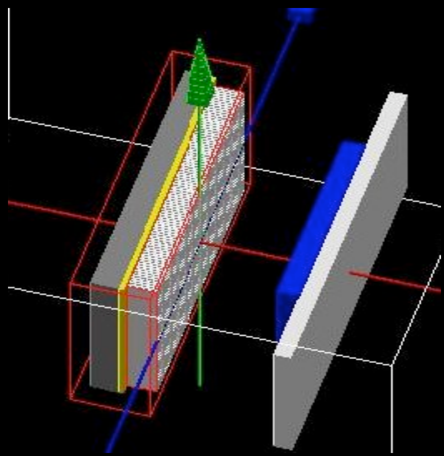
• 8 commercial PET systems, 4 commercial SPECT systems and 5 prototypes have already been modelled, including validation of the models



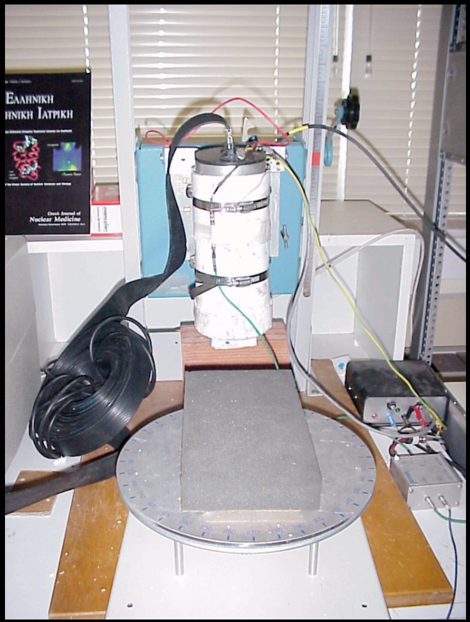
GE Advance/Discovery LS PET scanner
Schmidtlein et al, Med Phys 2006



GE Advance/Discovery ST PET, 3D mode
Schmidtlein et al. MSKCC



DST Xli camera
Assié et al, Phys Med Biol 2005



IASA CsI(Tl) gamma camera
Lazaro et al, Phys Med Biol 2004

Modeling time dependent processes in GATE

SPECT and PET intrinsically involves time:

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

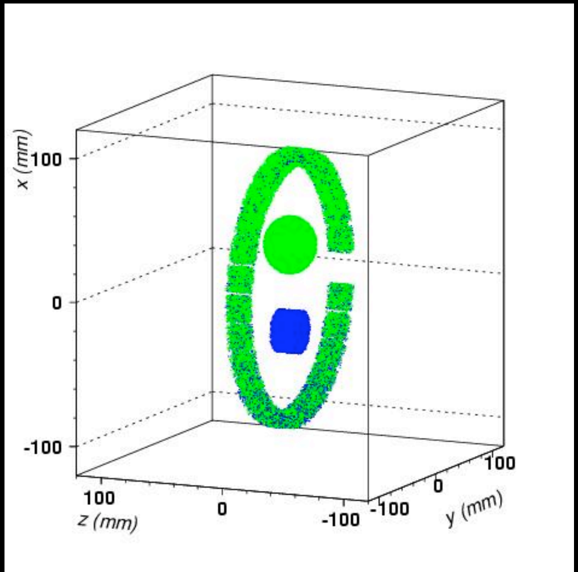
Principle of time modelling in GATE:

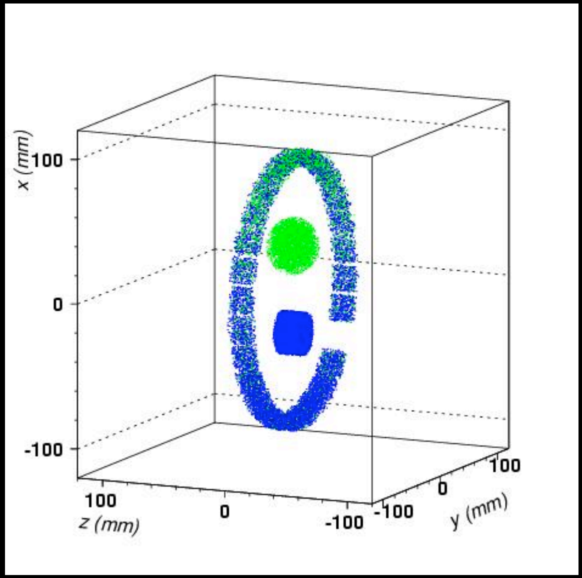
- Customized G4 radioactive decay module
- A clock models the time changes during the experiment
- The user defines the experiment timing (time slices)
- Time-dependent and synchronized objects are updated when time changes

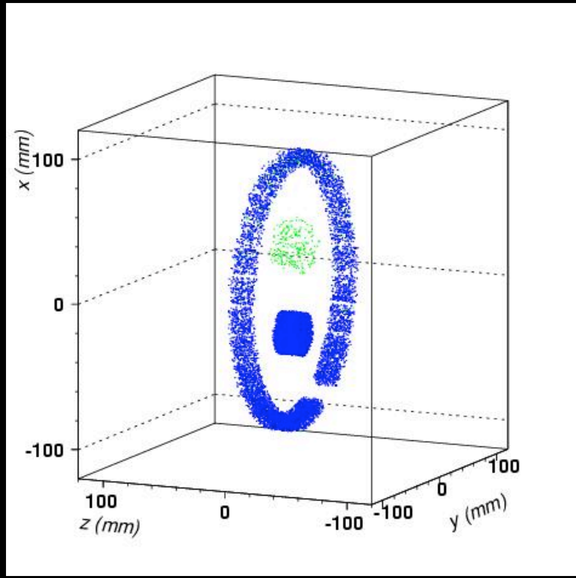
All of the above features can be modeled

Modeling of radioactive decay

^{15}O (2 min)
^{11}C (20 min)

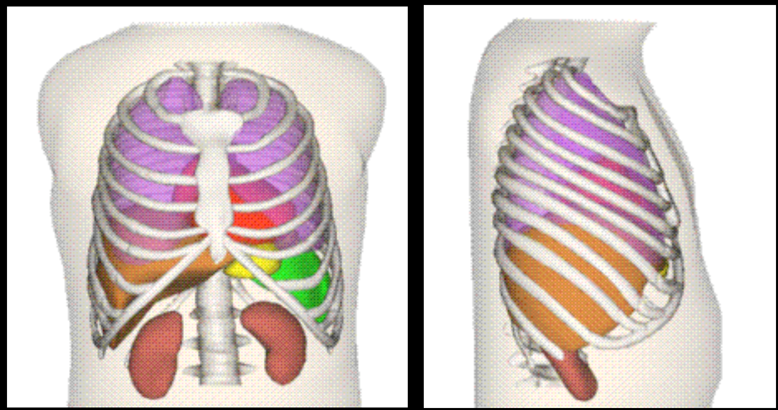




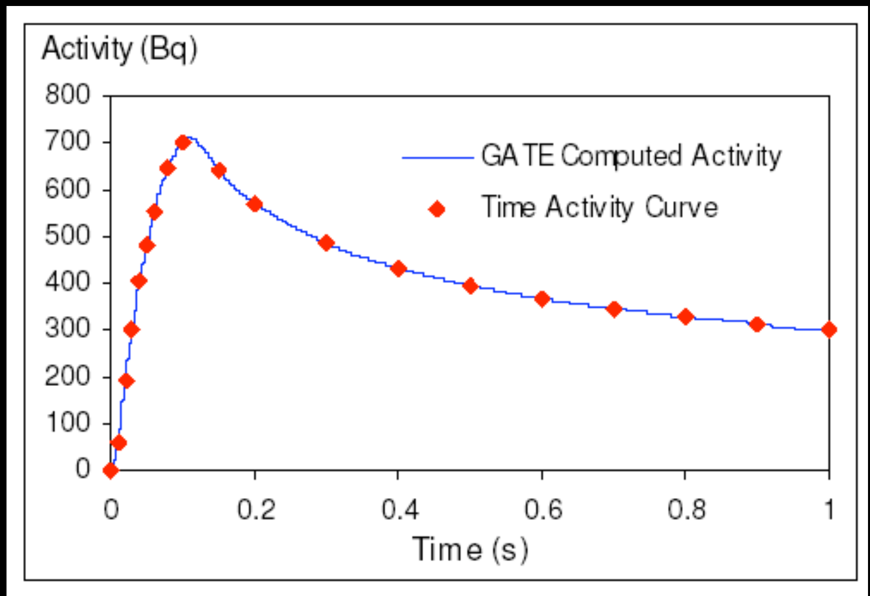


Santin et al, IEEE Trans Nucl Sci 2003

Modeling moving phantoms and change of tracer distribution



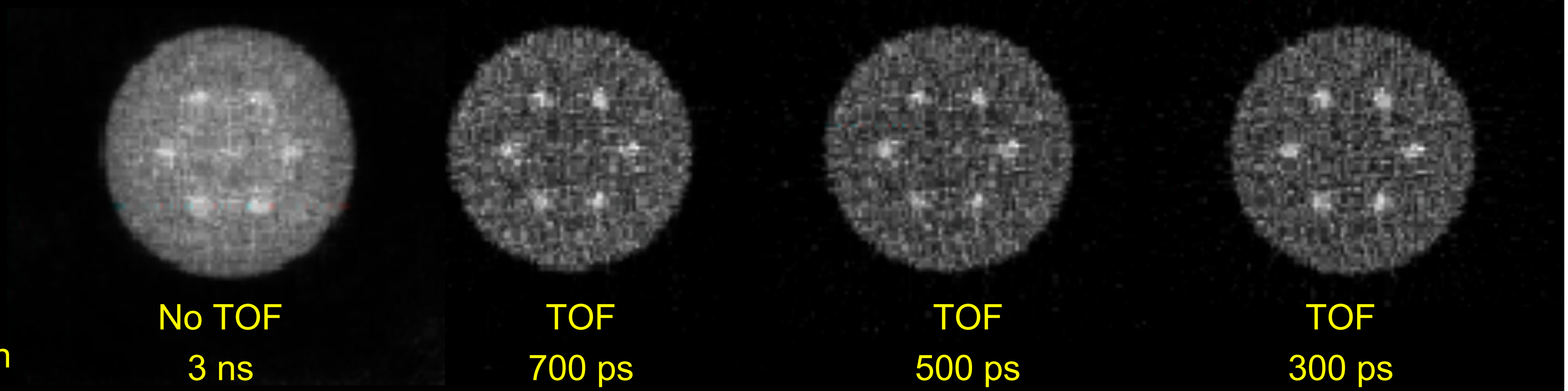
Segars et al, IEEE Trans Nucl Sci 2001



Descourt et al, IEEE MIC Conf Records 2006

Modeling of time of flight PET

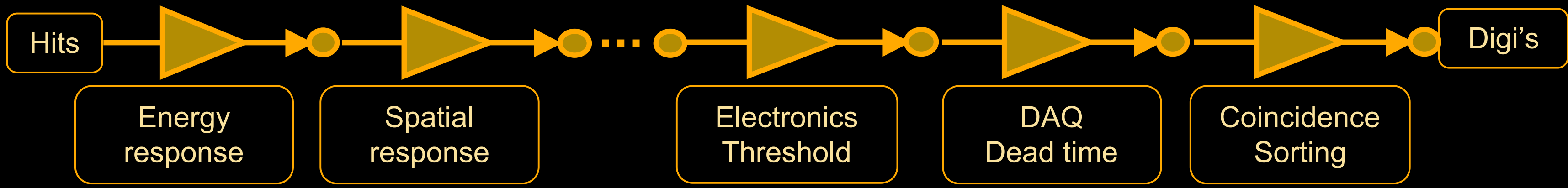
3D ML-EM



Type of study	Detector	Energy resolution (FWHM)	Low energy threshold (keV)	Coincidence time window (ns)
No TOF	GSO	15%	410	8
TOF	LaBr3	6.7%	470	6

Groiselle et al, IEEE MIC Conf Rec 2004

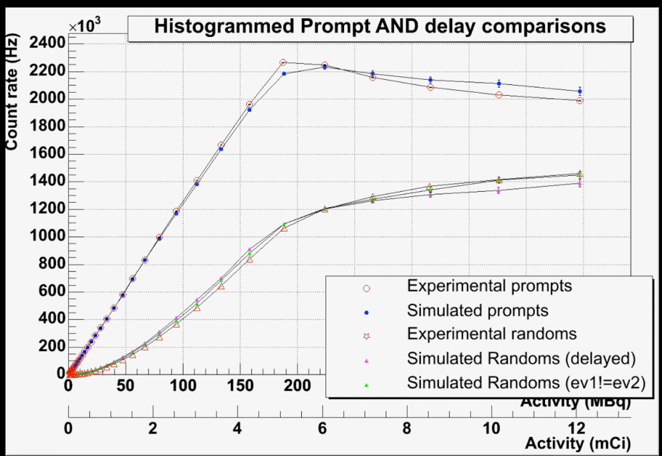
Modeling the electronic response of the system



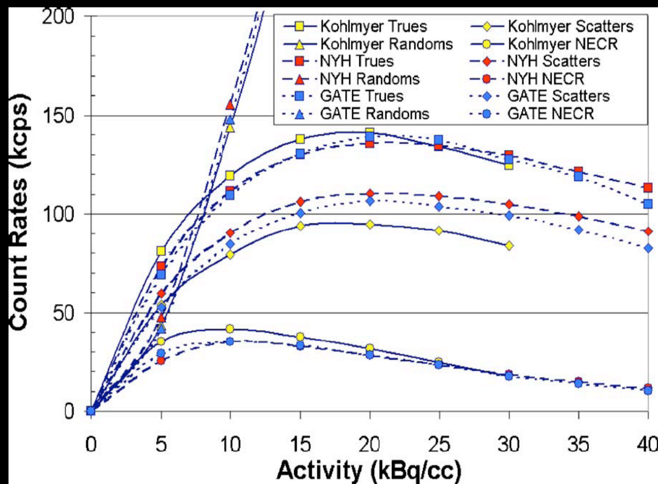
Using the “digitizer”:

- Linear signal processing
- Modular (set-up via scripting)
- Several dead time models available

Makes it possible to accurately reproduce count rate curves



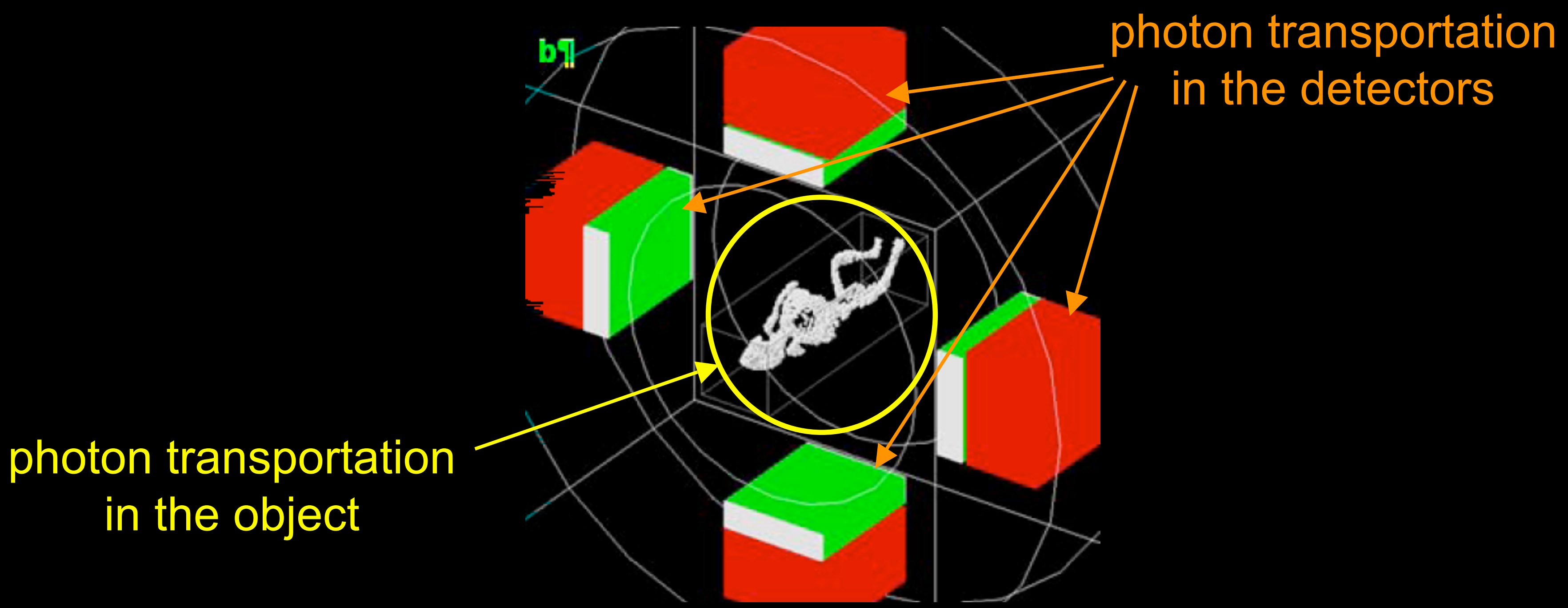
HRRT, Guez et al, DAPNIA and SHJF



GE Advance, Schmidtlein et al, Med Phys 2006

Other GATE features useful for helping in detector design

A simulation can be broken into 2 simulations*:

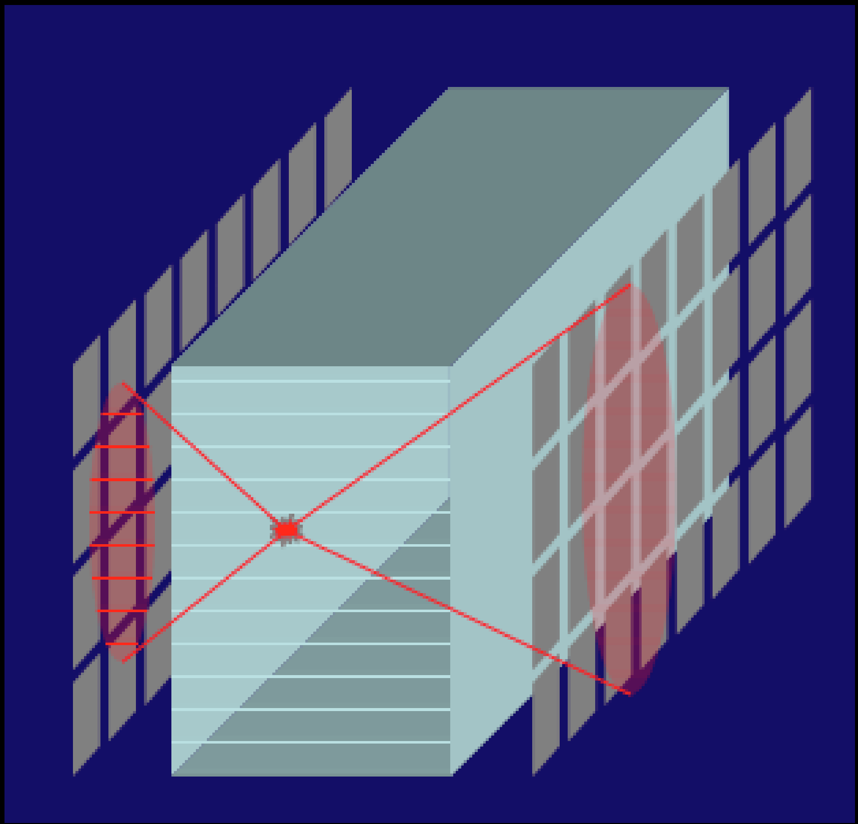


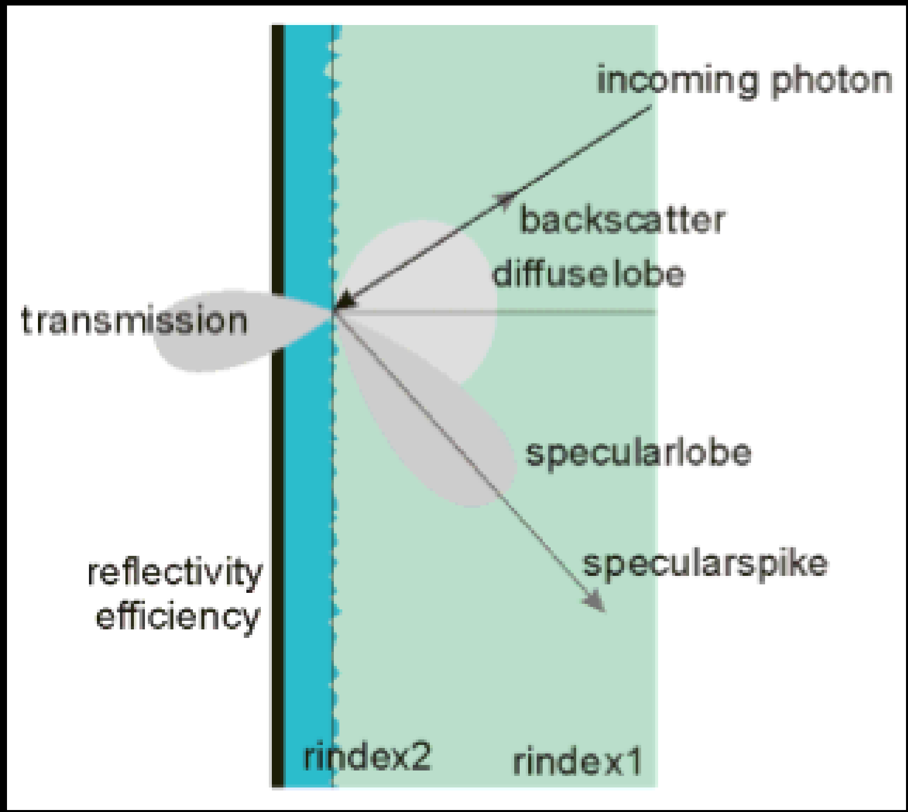
• Output from photon transportation in the object stored in a phase space
• Useful to test several detector designs without having to repeat the whole simulation through the object

** to be released soon*

Other GATE features useful for helping in detector design

Tracking of optical photons in the crystal*





• Based on Geant4 classes

** currently available in GATE*

Current priorities in GATE developments

• Improving the simulation throughput for efficient production of clinical and preclinical data*

Simulation time is 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

More than 17000 h CPU are needed to model a realistic whole body PET scan

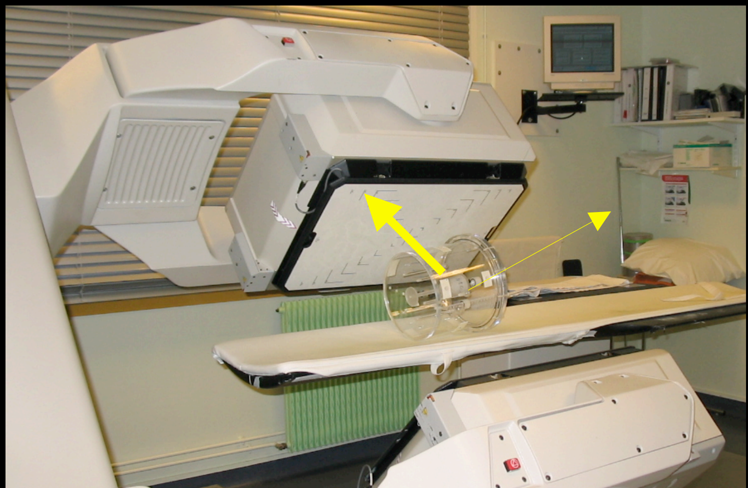
At least 4 approaches can be used to increase the throughput of the simulations

** Funded by the French ANR under contract ANR-06-CIS-004 (2007-2009)*

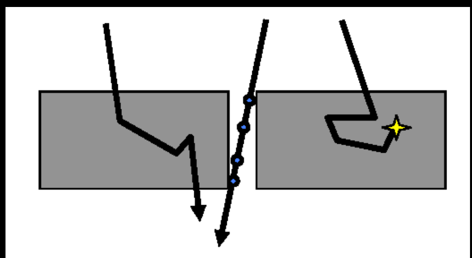
Improvement of simulation efficiency

Acceleration methods

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

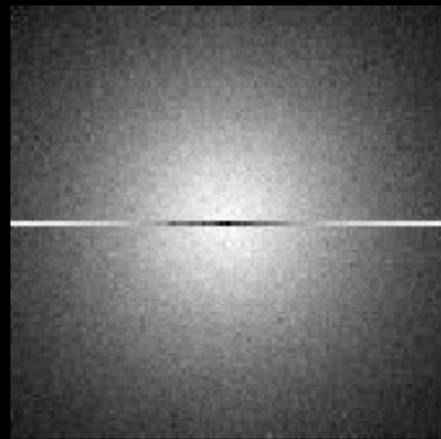


• Fictitious cross-section (or delta scattering)

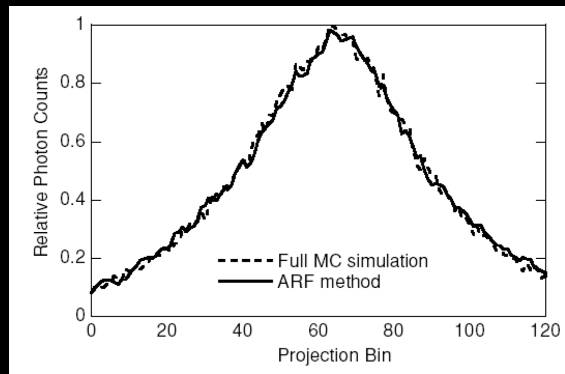


Combining MC with non MC models

Full MC



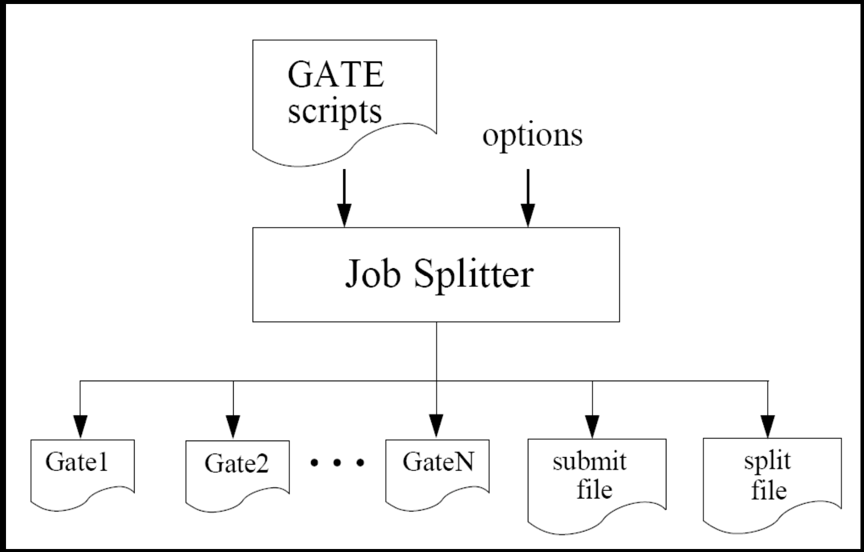
Collimator Angular Response Function

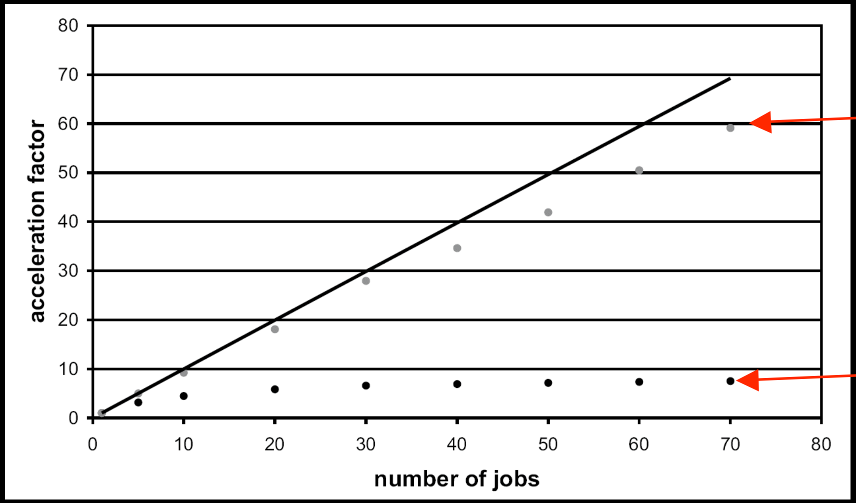


increase in efficiency > 100

Song et al, Phys Med Biol 2005

Parallel execution of the code on a distributed architecture



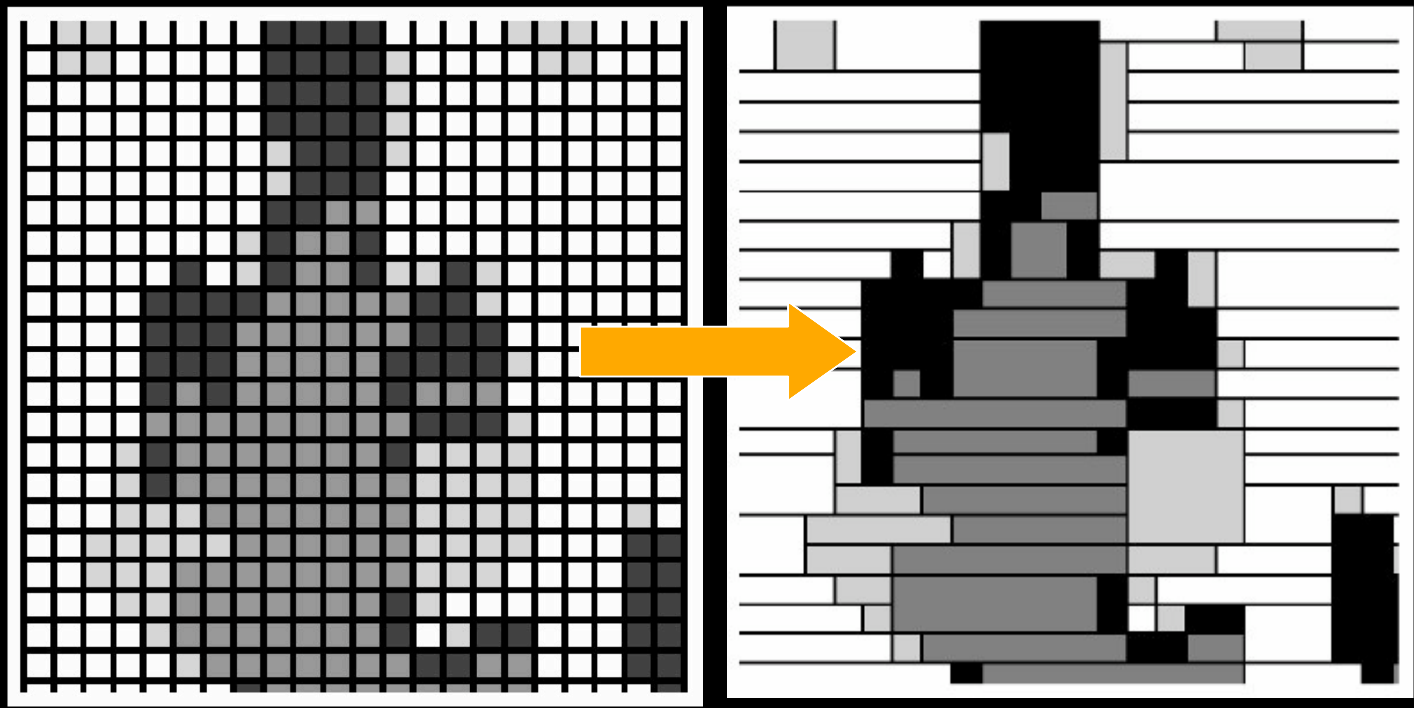


PET

Speed-up factor
~ number of jobs

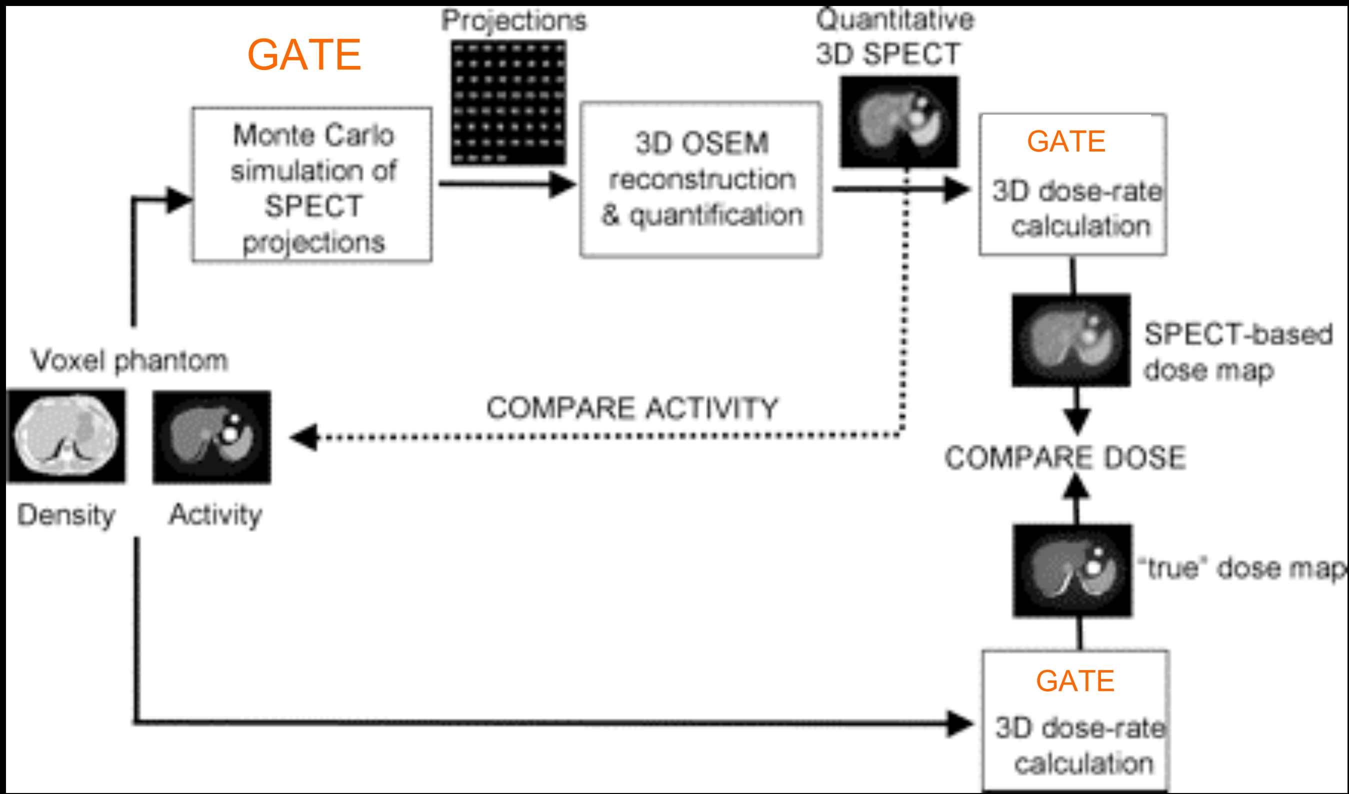
De Beenhouwer et al, IEEE MIC Conf Records 2006

Smart sampling



Taschereau et al, Med Phys 2006

Bridging the gap between MC modeling in imaging and dosimetry



- Calculation of dose maps are already possible in GATE
- Further validation studies are still needed (comparison with other dosimetry software)

Dewaraja et al, J Nucl Med 2005

Using GATE for dosimetry

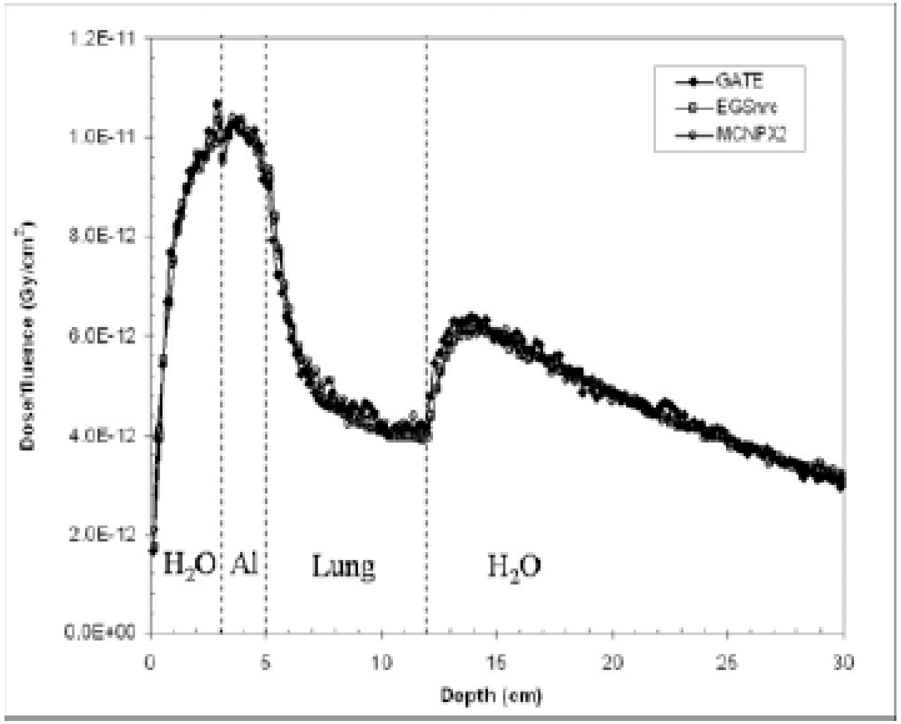


Fig. 1. Depth dose curve using the benchmark and the 18MV photon beam for GATE, EGSnrc and MCNPX2

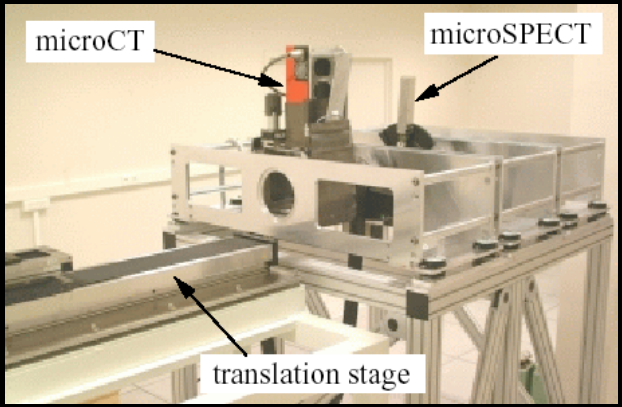
Visvikis et al NIM A 2006

Modeling hybrid machines (PET/CT, SPECT/CT, OPET)

PET/CT

SPECT/CT

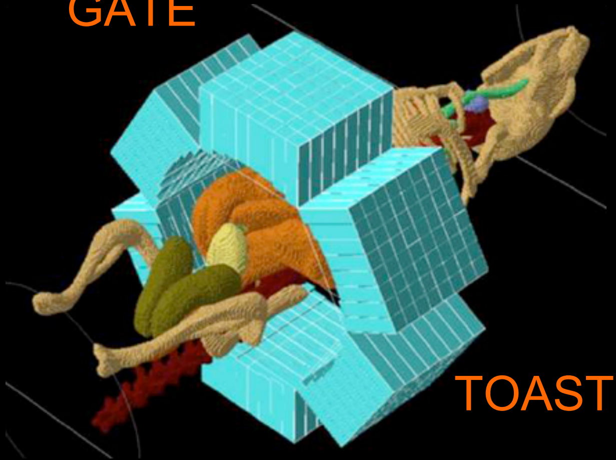
GATE



Brasse et al, IEEE MIC Conf Rec 2004

OPET

GATE



Alexandrakis et al, Phys Med Biol 2005

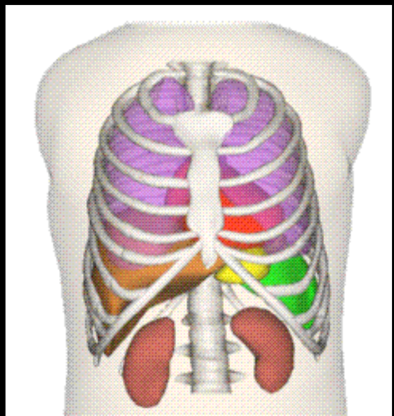
Integrating Monte Carlo modeling tools for:

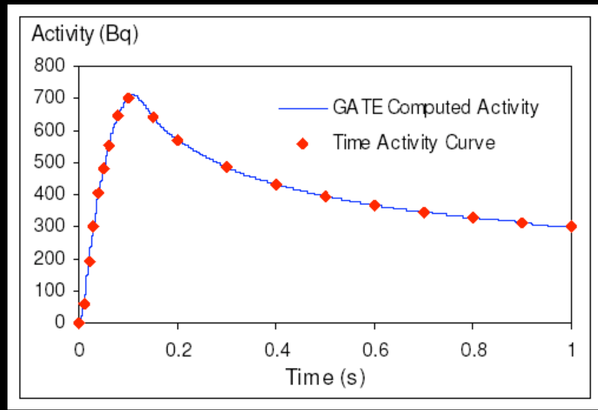
- common coordinate system
- common object description
- consistent sampling
- convenient assessment of multimodality imaging

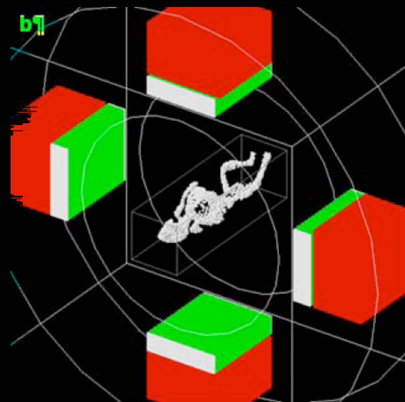
On-going studies regarding the use of GATE for CT simulations

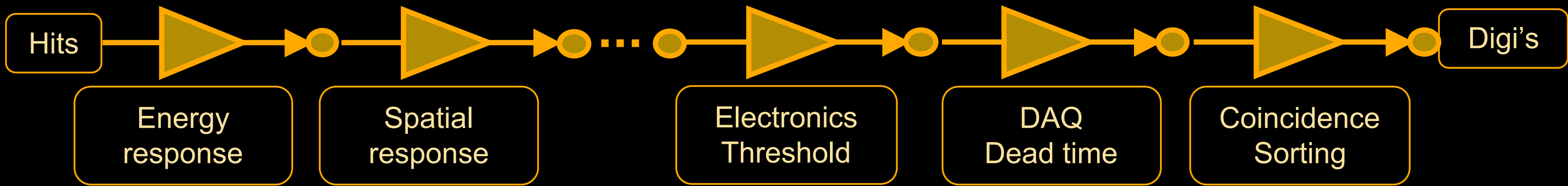
Conclusion

• GATE is a relevant tool for Monte Carlo simulations in ET









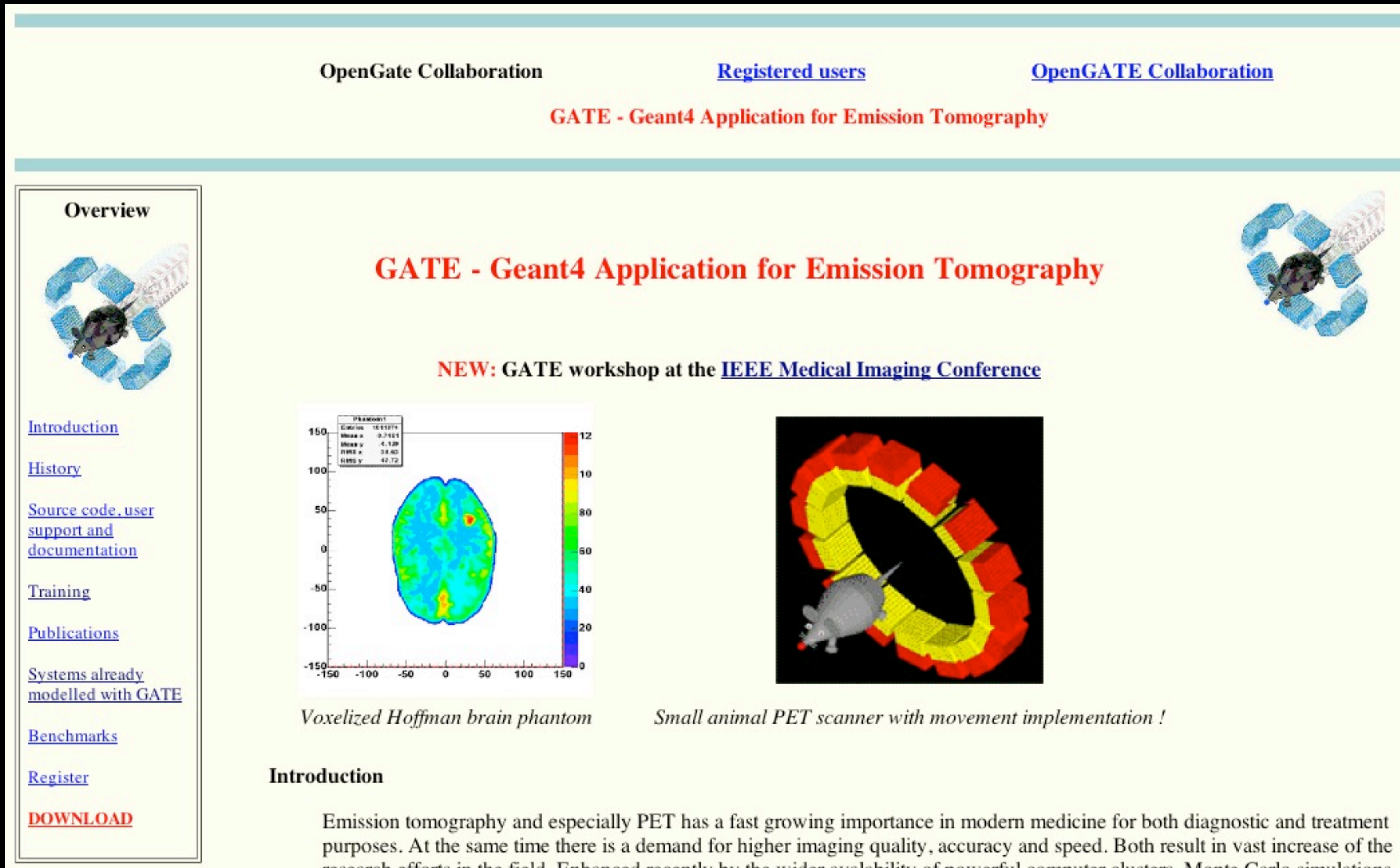
• GATE is appropriate for studying detector designs and how they impact image quality in very realistic configurations (including movement for instance)

Acknowledgments

The OpenGATE collaboration

To know more about GATE

http://www.opengatecollaboration.org



Answers to questions

PET systems already modeled by the OpenGATE collaboration

Scanner type	Studied FOM	Agreement	References
ECAT EXACT HR+, CPS	Spatial resolution Sensitivity Count rates Scatter fraction	about 3 % < 7 % good at activity concentrations < 20 kBq/ml about 3 %	Jan *et al* 2005
ECAT HRRT, Siemens	Spatial resolution Scatter fraction Scattered coinc profiles Count rates	excellent (<0.2 mm) < 1 % very good (visual) good (about 10%)	Bataille *et al* 2004
Hi-Rez, Siemens	Scatter fraction Count rates NEC curves	about 1 % good at activity concentrations < 40 Bq/ml good at activity concentrations < 40 Bq/ml	Michel *et al* 2006
Allegro, Philips	Count rate Scatter fraction	< 8 % 8 %	Lamare *et al* 2006
GE Advance, GEMS	Energy spectra Scatter fraction	not reported < 1 %	Schmidtlein *et al* 2006
MicroPET P4, Concorde	Spatial resolution Sensitivity Miniature Derenzo phantom	about 7 % < 4 % visual assessment	Jan *et al* 2003
MicroPET Focus 220, Siemens	Spatial resolution Sensitivity Count rates for mouse phantom	about 5 % about 3 % prompt coinc: < 5.5 % delayed coinc: < 13 %	Jan *et al* 2005
Mosaic, Philips	Scatter fraction Count rates	about 5 % 4-15 %	Merheb *et al* 2005

Answers to questions

SPECT systems already modeled by the OpenGATE collaboration

Scanner type	Studied FOM	Agreement	References
IRIX, Philips	None reported	n/a	Staelens *et al* 2004
AXIS, Philips	Spatial resolution Energy resolution Energy spectra Sensitivity Scatter profiles	< 5 % < 1 % visual assessment < 4.6 % visual assessment	Staelens *et al* 2003
DST Xli, GEMS	Energy spectra Spatial resolution Sensitivity	excellent < 2 % in air, < 12 % in water < 4 %	Assié *et al* 2005
Millennium VG Hawk-Eye, GEMS	I131 energy spectra Spatial resolution for I131	excellent (visual) acceptable (<3mm)	Autret *et al* 2005

Answers to questions

Prototypes already modeled by the OpenGATE collaboration

Scanner type	Studied FOM	Agreement	References
Solstice, Philips	Sensitivity	good with theoretical data	Staelens *et al* 2003 Staelens *et al* 2004 Staelens *et al* 2004
LSO/LuYAP phoswich PET	Sensitivity NEC curves	n/a n/a	Rey *et al* 2003
ATLAS	Spatial resolution Sensitivity Line phantom	< 6 % < 10 % visual assessment	Chung *et al* 2004 Chung *et al* 2005
CsI(Tl) SPECT camera	Energy spectra Energy resolution Spatial resolution Scatter fraction Sensitivity Line phantom	good < 1 % < 1 % < 2 % < 2 % visual assessment	Lazaro *et al* 2004
OPET	Spatial resolution Sensitivity	n/a n/a	Rannou *et al* 2004

Answers to questions

The list of systems that have already been modeled by the collaboration can be found on the Web site http://www.opengatecollaboration.org.

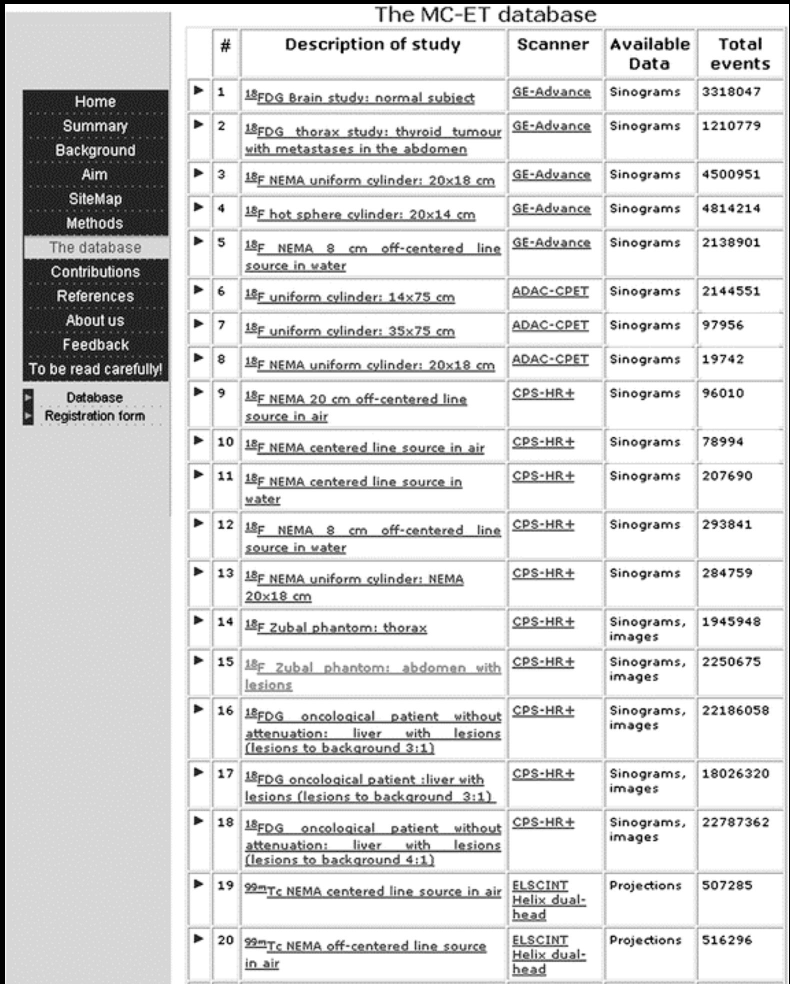
The specific macros corresponding to these models are not provided, as they include some parameters the companies do not want us to divulge, so please contact the group that has designed the macro (info on the GATE Web site) to see how you can get the macro.

Answers to questions

Data produced by GATE could be gathered in a public database, so that researchers interested in such data would not have to re-do the simulations. Such databases already exist (see next slide), although the data they contain have not been simulated using GATE, but using other Monte Carlo simulation software.

Using Monte Carlo for feeding database

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

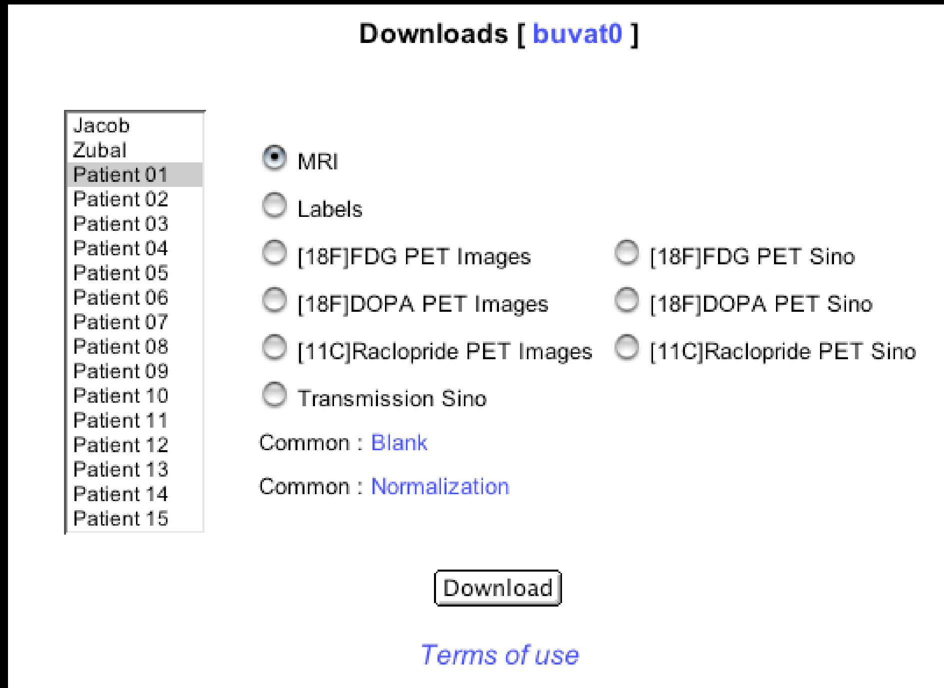


The MC-ET database

	#	Description of study	Scanner	Available Data	Total events
▶	1	^{18}FDG Brain study: normal subject	GE-Advance	Sinograms	3318047
▶	2	^{18}FDG thorax study: thyroid tumour with metastases in the abdomen	GE-Advance	Sinograms	1210779
▶	3	^{18}F NEMA uniform cylinder: 20x18 cm	GE-Advance	Sinograms	4500951
▶	4	^{18}F hot sphere cylinder: 20x14 cm	GE-Advance	Sinograms	4814214
▶	5	^{18}F NEMA 8 cm off-centered line source in water	GE-Advance	Sinograms	2138901
▶	6	^{18}F uniform cylinder: 14x75 cm	ADAC-CPET	Sinograms	2144551
▶	7	^{18}F uniform cylinder: 35x75 cm	ADAC-CPET	Sinograms	97956
▶	8	^{18}F NEMA uniform cylinder: 20x18 cm	ADAC-CPET	Sinograms	19742
▶	9	^{18}F NEMA 20 cm off-centered line source in air	CPS-HR+	Sinograms	96010
▶	10	^{18}F NEMA centered line source in air	CPS-HR+	Sinograms	78994
▶	11	^{18}F NEMA centered line source in water	CPS-HR+	Sinograms	207690
▶	12	^{18}F NEMA 8 cm off-centered line source in water	CPS-HR+	Sinograms	293841
▶	13	^{18}F NEMA uniform cylinder: NEMA 20x18 cm	CPS-HR+	Sinograms	284759
▶	14	^{18}F Zubal phantom: thorax	CPS-HR+	Sinograms, images	1945948
▶	15	^{18}F Zubal phantom: abdomen with lesions	CPS-HR+	Sinograms, images	2250675
▶	16	^{18}FDG oncological patient without attenuation: liver with lesions (lesions to background 3:1)	CPS-HR+	Sinograms, images	22186058
▶	17	^{18}FDG oncological patient :liver with lesions (lesions to background 3:1)	CPS-HR+	Sinograms, images	18026320
▶	18	^{18}FDG oncological patient without attenuation: liver with lesions (lesions to background 4:1)	CPS-HR+	Sinograms, images	22787362
▶	19	^{99m}Tc NEMA centered line source in air	ELSCINT Helix dual-head	Projections	507285
▶	20	^{99m}Tc NEMA off-centered line source in air	ELSCINT Helix dual-head	Projections	516296

Castiglioni et al, Eur J Nucl Med Mol Imaging 2005

http://sorteo.cermep.fr



Reilhac et al, IEEE TNS 2005

Running GATE on a grid

GATE can be run on a grid. It has already been deployed on the EGEE grid with success. See S. Staelens, J. De Beenhouwer, D. Kruecker, L. Maigne, F. Rannou, L. Ferrer, Y. D'Asseler, I. Buvat, I. Lemahieu. GATE: improving the computational efficiency. Nucl. Instr. Meth. A 569: 341-345, 2006.

Tools for running GATE on a distributed architecture will be included in the next release of GATE (March 2007)

GATE and Litrani

The GATE digitizer could be replaced by another module performing a more sophisticated simulation of the electronic processing. This module would have to use the GATE output (events as detected in the crystal and their associated characteristics) as an input. Some interface has to be developed for that, but this is feasible.

The software Litrani (http://gentit.home.cern.ch/gentit/litrani/) could also be used to precisely model optical photon tracking in a specific detector, and determine how the GATE digitizer should be set up for accurately reproducing the detector response. A systematic tracking of optical photons in the context of the simulation of a real PET or SPECT scan would be unrealistic in terms of computational time.