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

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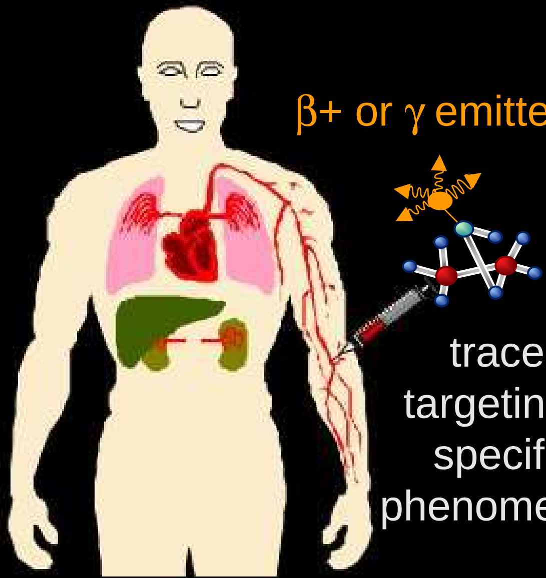
Outline

- 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

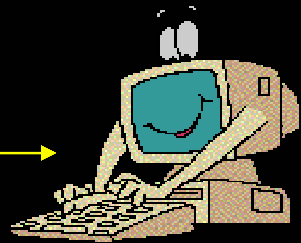
Emission tomography in Nuclear Medicine

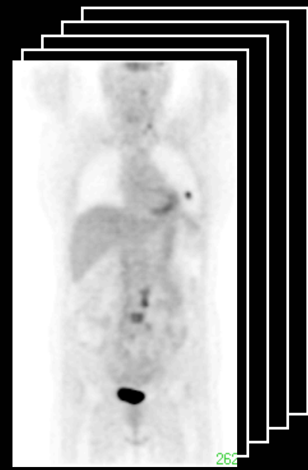
Non invasive techniques for assessing the in vivo distribution of a radiotracer administered to a patient



β+ or γ emitter

tracer targeting a specific phenomenon





3D distribution of the tracer

γ emitter: Single Photon Emission Computed Tomography (SPECT)

β+ 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.

- Zaidi, Relevance of accurate Monte Carlo modeling in nuclear medical imaging. *Med Phys* 26 (1999) 574-608

- 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

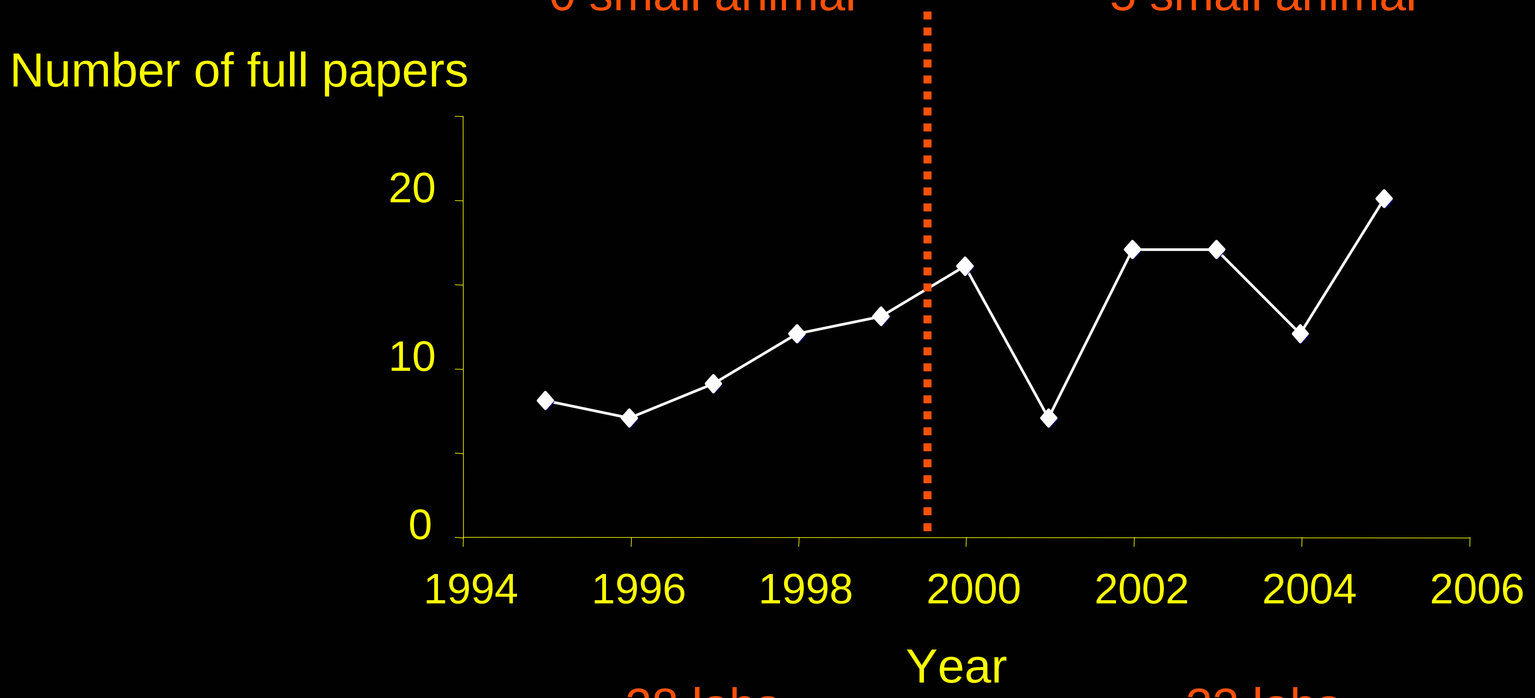
- 666 entries since 1995 at the date of the search (July 1995)
- Use of MC simulations to produce SPECT and PET images: 130 entries

86% SPECT
14% PET

0 small animal

65% SPECT
35% PET

5 small animal



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

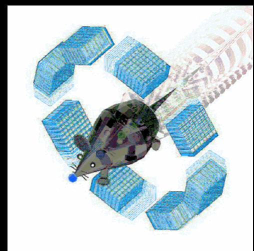
Most frequently used

SimSET

SIMIND

And recently

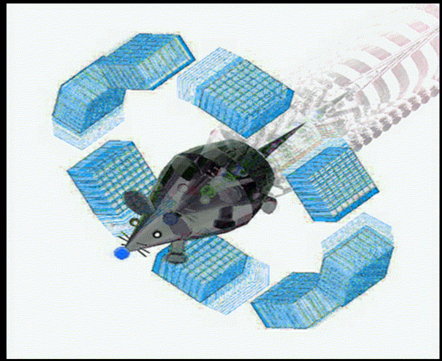
Geant 4



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

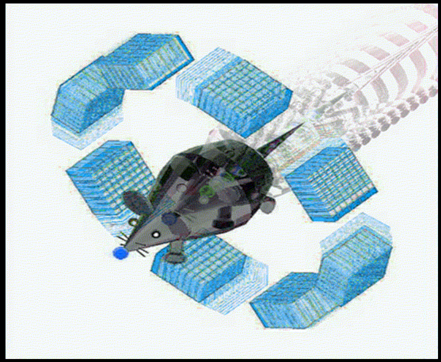
- LPC CNRS, Clermont Ferrand, France
- IReS CNRS, Strasbourg, France
- UMR5515 CNRS, CREATIS, Lyon, France

- SHFJ CEA, Orsay, France
- DAPNIA CEA, Saclay, France

- Joseph Fourier University, Grenoble, France

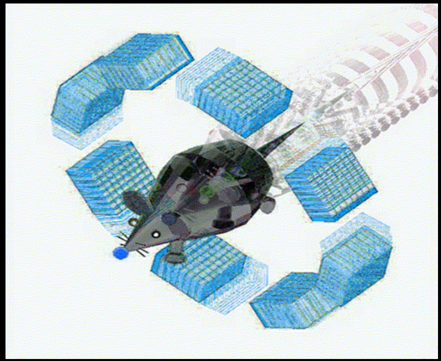
- John Hopkins University, Baltimore, USA
- Memorial Sloan-Kettering Cancer Center, New York, USA
- University of California, Los Angeles, USA
- University of Massachusetts Medical School, Worcester, USA
- University of Santiago of Chile, Chile
- Sungkyunkwan University School of Medicine, Seoul, Korea

Product of OpenGATE: GATE



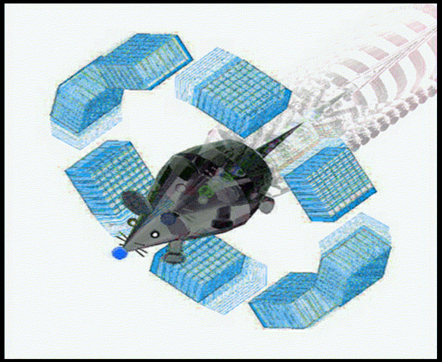
- Publicly released on May 2004 http://www.opengatecollaboration.org
- An official publication: Jan et al, Phys. Med. Biol. 49: 4543-4561, 2004.
- More than 400 subscribers to the Gate users mailing list

GATE today: technical features



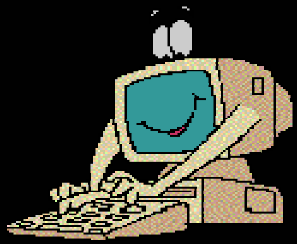
- Based on GEANT 4
- Written in C++
- User-friendly: simulations can be designed and controlled using macros, without any C++ writing
- Appropriate for SPECT and PET simulations
- Flexible enough to model almost any detector designs, including prototypes
- Explicit modeling of time (hence detector motion, 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

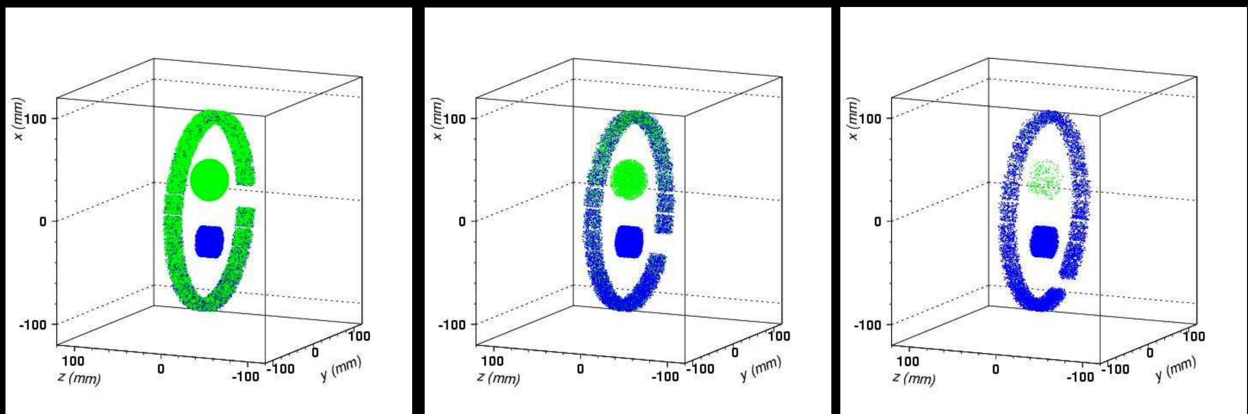


Modeling time dependent processes

SPECT and PET intrinsically involves time:

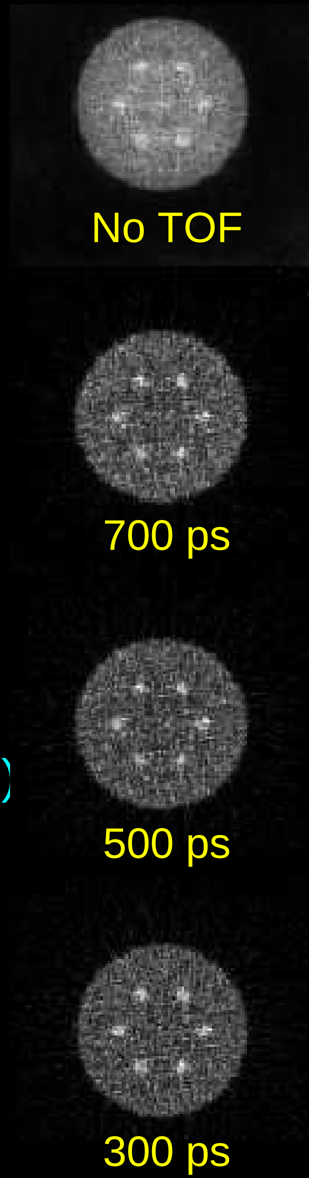
- Change of tracer distribution over time
- Detector motions during acquisition
- Patient motion
- Radioactive decay
- Dead time of the detector
- Time-of-flight PET

GEANT 4 (hence GATE) is perfect in that regard



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

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

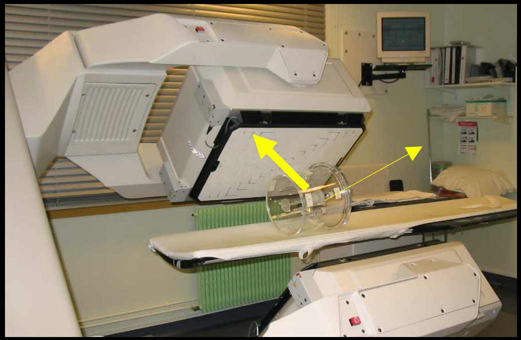
- Large number of particles to be simulated
  - low detection efficiency
  - in SPECT, typically 1 / 10 000 is detected
  - in PET, 1 / 200 is detected

Increasing the throughput of the simulations

Using acceleration methods

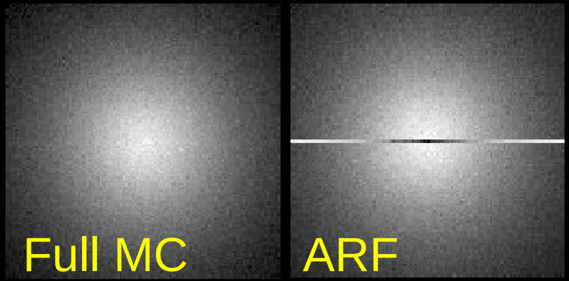
- Variance reduction techniques such as importance sampling (e.g. in SimSET)

→ speed-up factors between 2 and 15

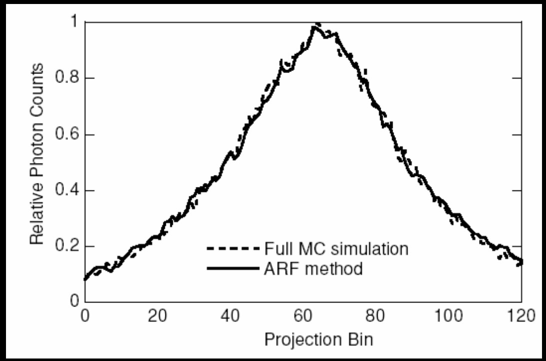


- Fictitious cross-section (or delta scattering)

Combining MC and non MC modeling

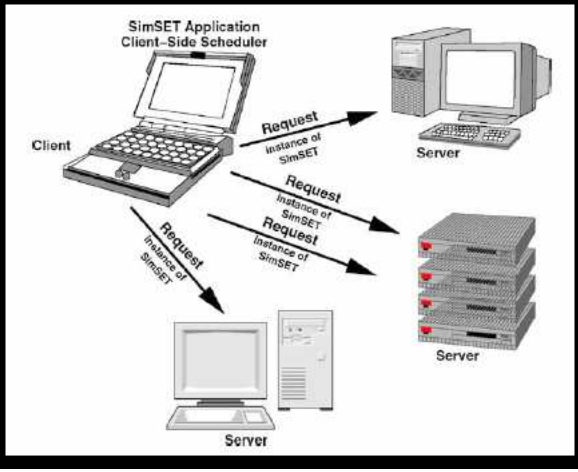


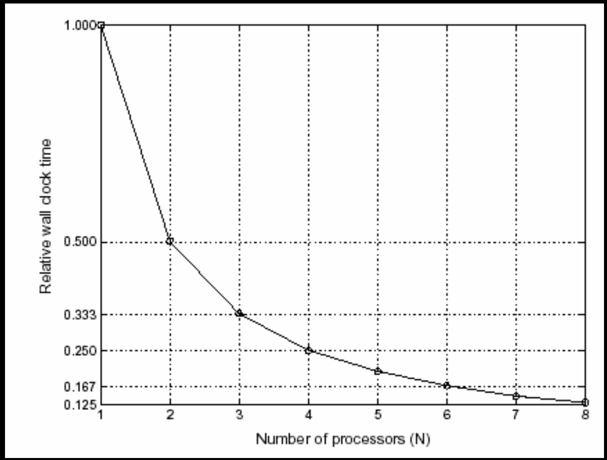
Song et al, Phys Med Biol 2005



increase in efficiency > 100

Parallel execution of the code





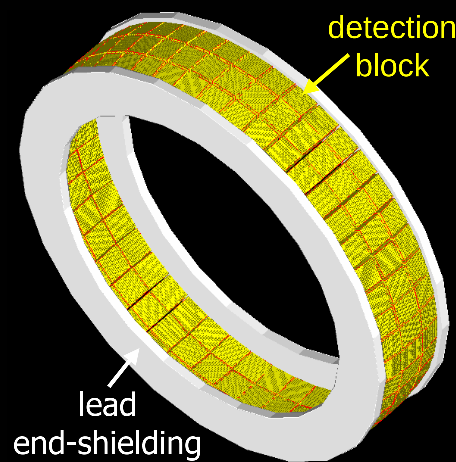
Thomason et al, Comp Methods Programs Biomed 2004

Modeling original detector designs

GEANT 4 is a very flexible tool

Non-conventional geometries

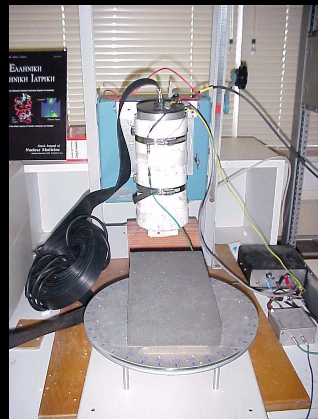
TEP/CT BIOGRAPH Siemens



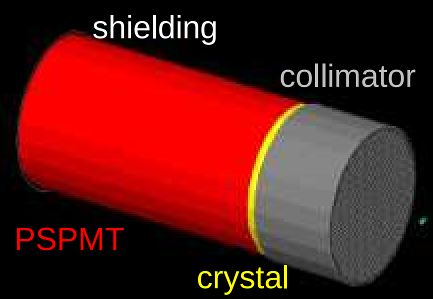
Spherical geometry of the Hi-Rez PET scanner

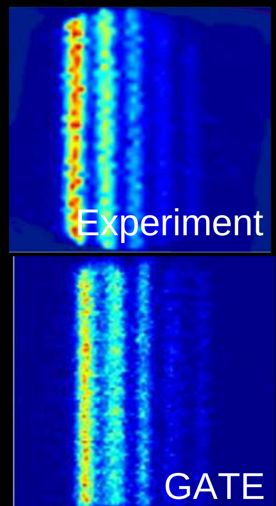
Lazaro et al, SNM 2005

Prototypes

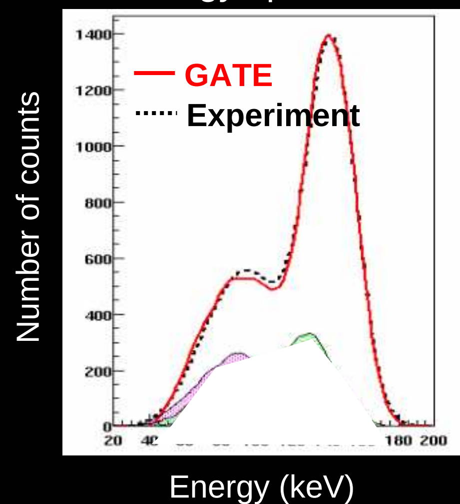


IASA CsI(Tl) gamma camera



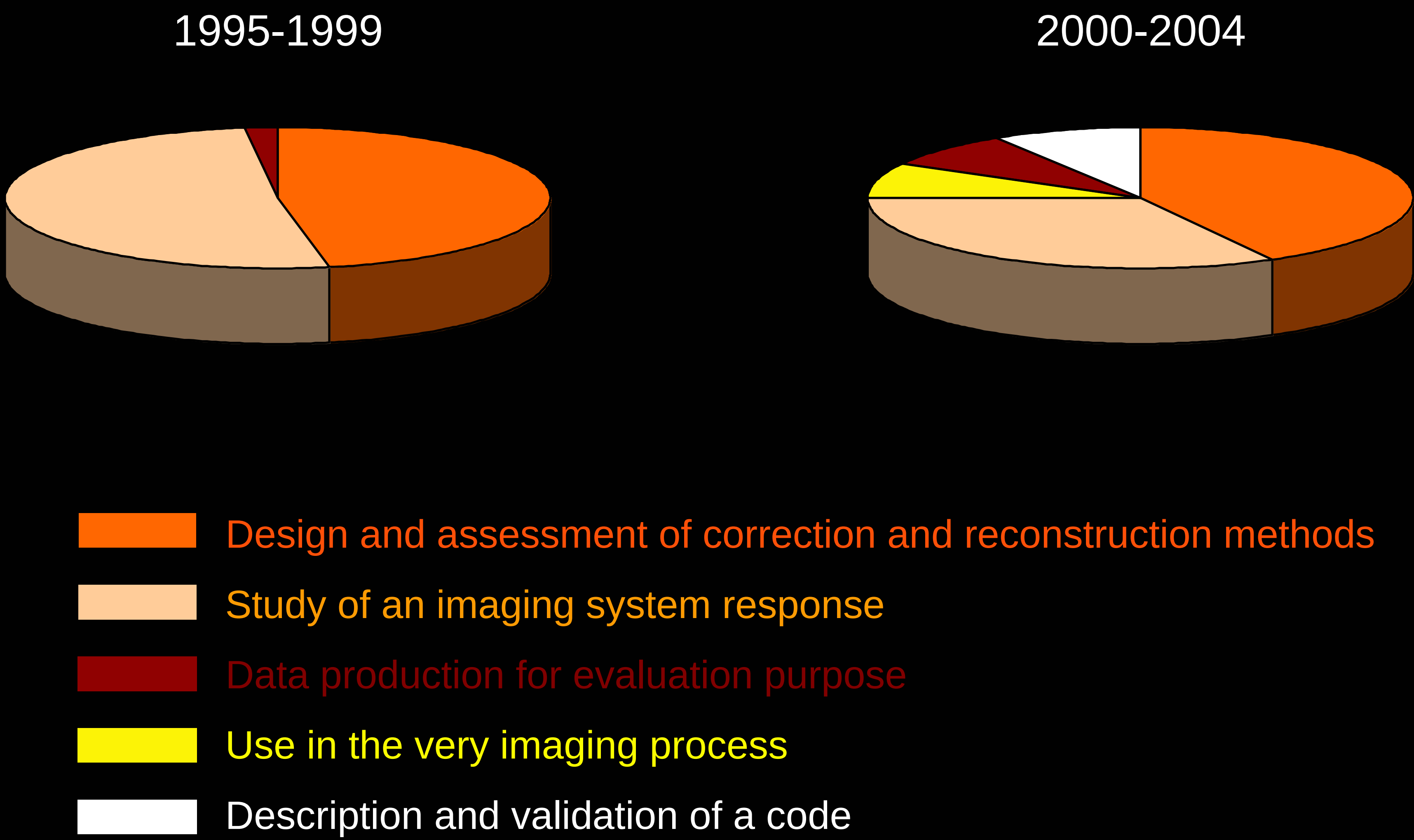


Energy spectrum

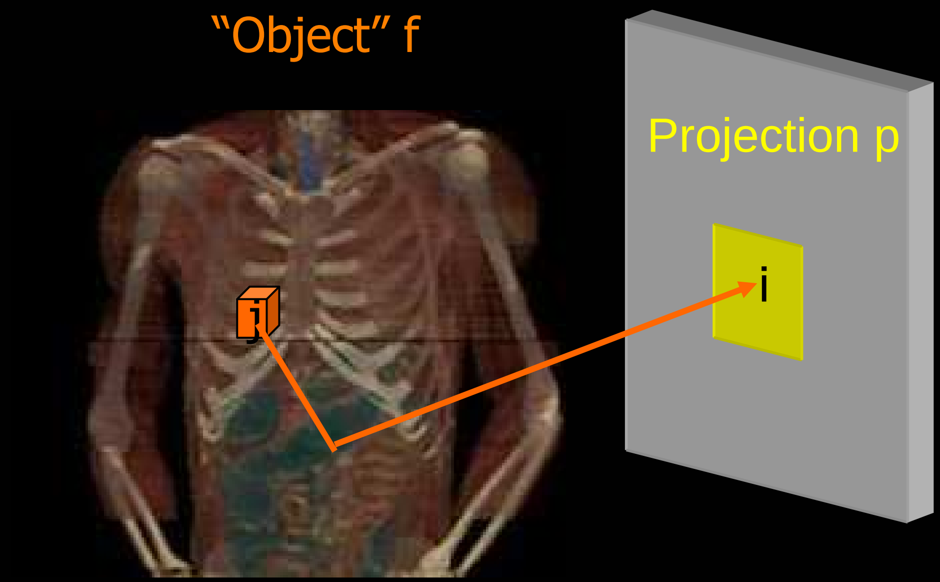


Lazaro et al, Phys Med Biol 2004

New applications for Monte Carlo simulations



Using Monte Carlo simulations for calculating the system matrix



GATE is very appropriate but slow

$$p = \mathbf{R}\, f$$

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

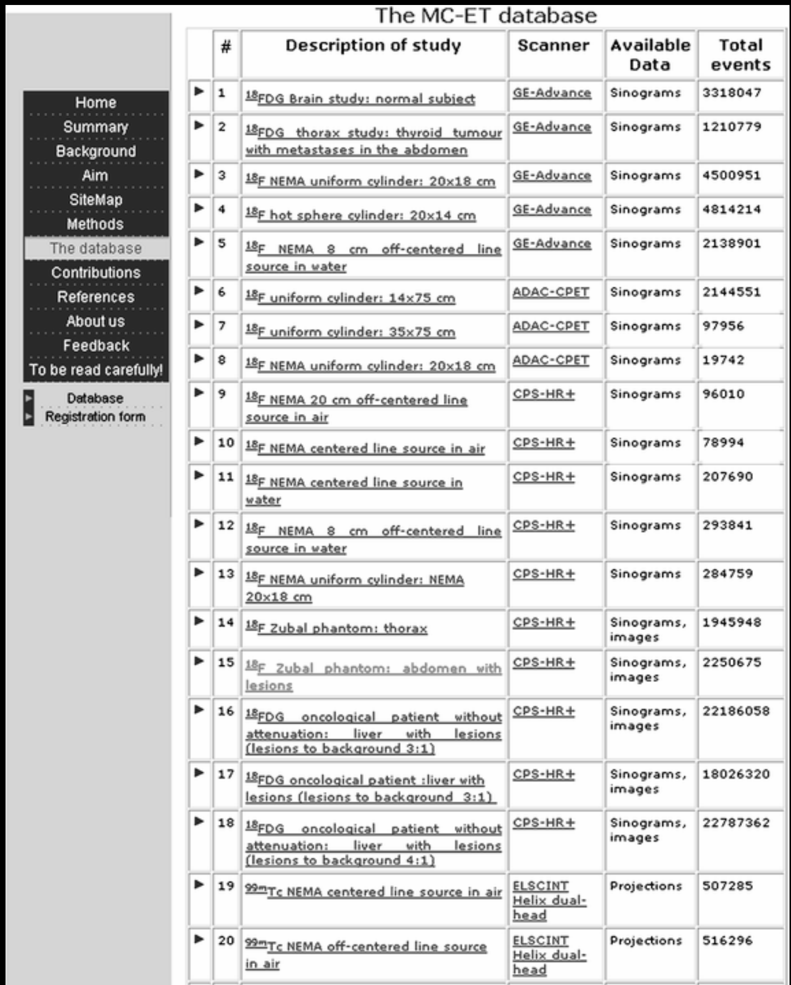
Calculating R using Monte Carlo simulations:

- for non conventional imaging design (small animal)
- to account for fully 3D and patient-specific phenomena difficult to model analytically (mostly scatter)

e.g., Lazaro et al Phys Med Biol 2005, Rafecas et al IEEE TNS 2004, Rannou et al IEEE MIC Conf Rec 2004

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

http://sorteo.cermep.fr

QuickTime™ et un décompresseur TIFF (LZW) sont requis pour visionner cette image.

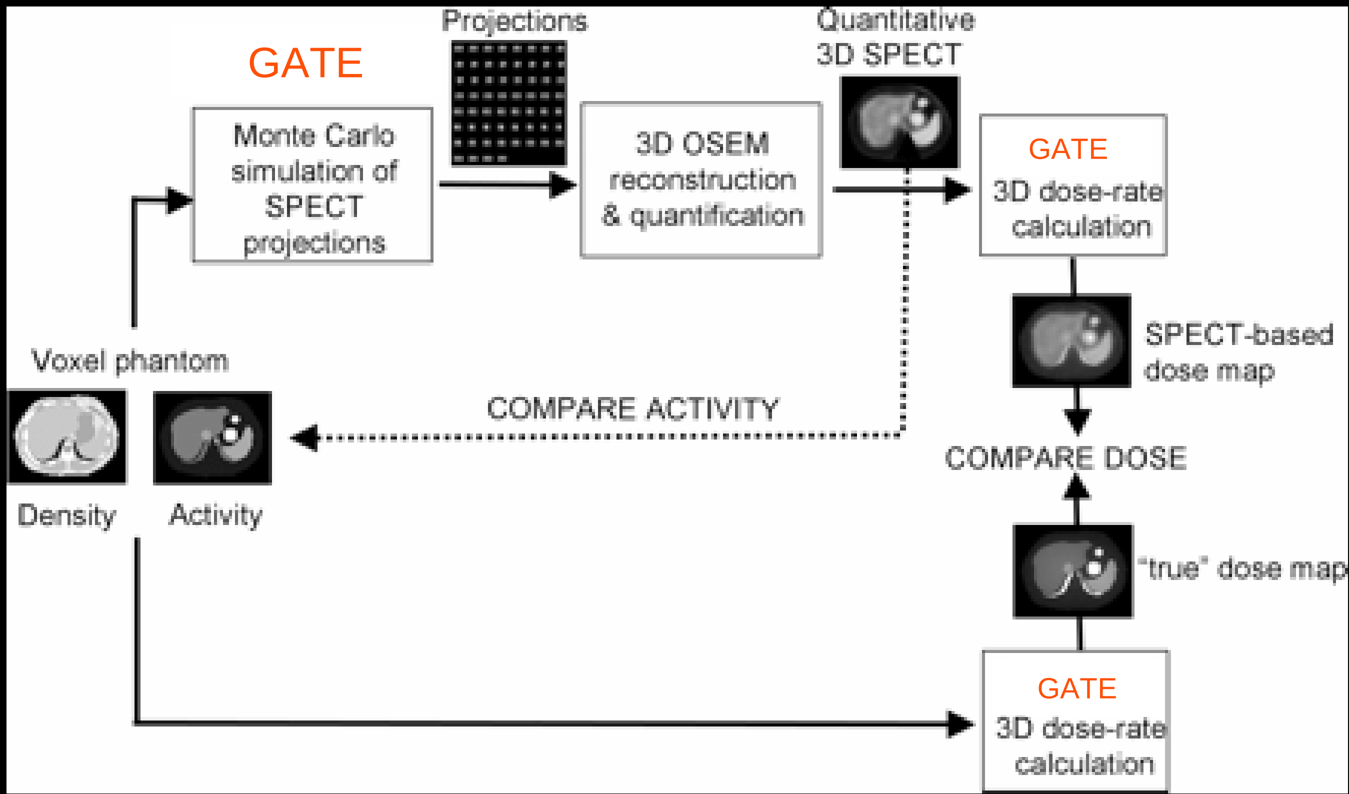
GATE is very appropriate but slow

Castiglioni et al, Eur J Nucl Med Mol Imaging 2005

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

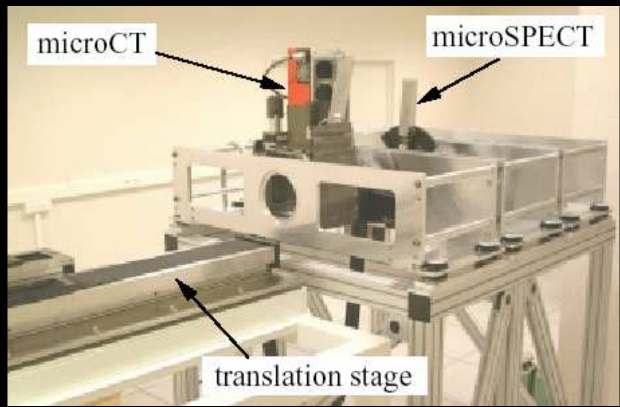
Dewaraja et al, J Nucl Med 2005

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

PET/CT

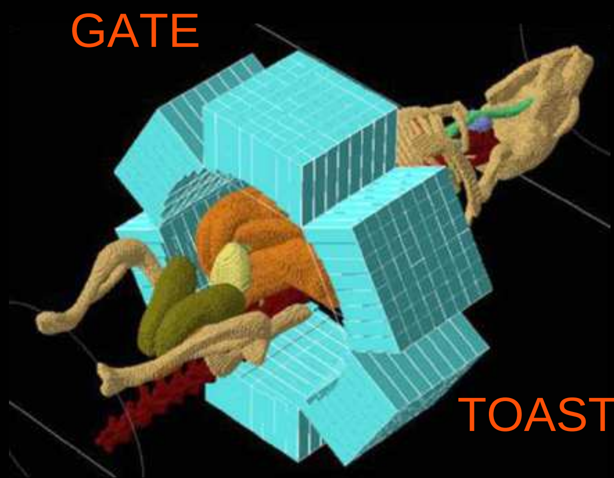
SPECT/CT

GATE



Brasse et al, IEEE MIC Conf Rec 2004

OPET



Alexandrakis et al, Phys Med Biol 2005

Integrating Monte Carlo modeling tools for:

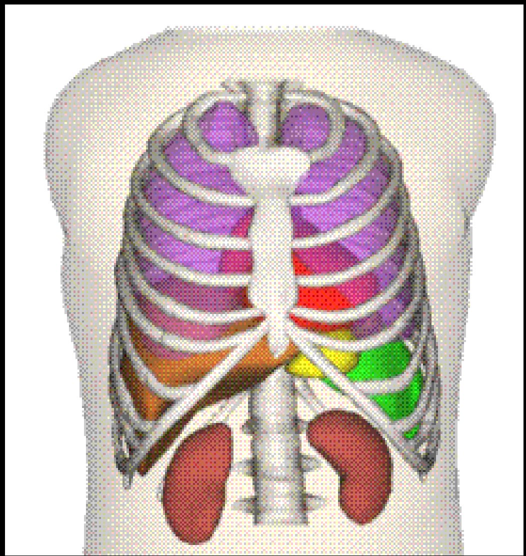
- common coordinate system
- common object description
- consistent sampling
- convenient assessment of multimodality imaging

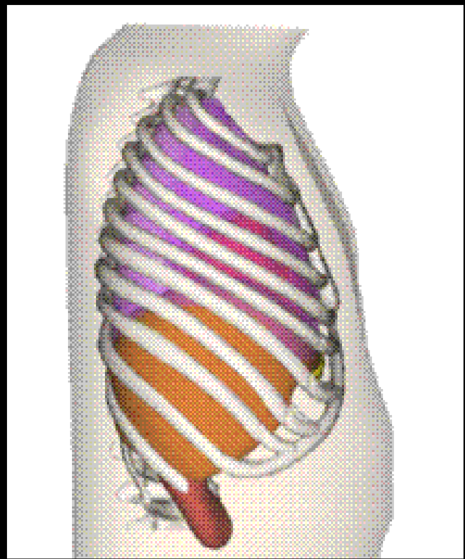
Not started yet in GATE

Designing realistic phantoms

Interfacing realistic phantoms with simulator input

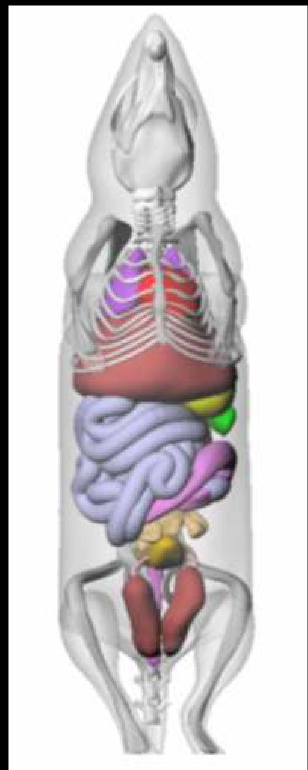
NCAT

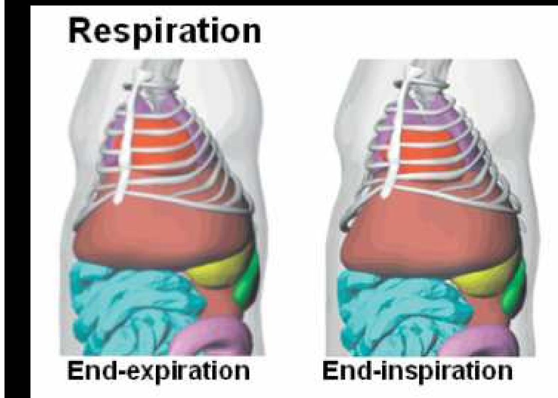




Segars et al, IEEE TNS 2001

MOBY





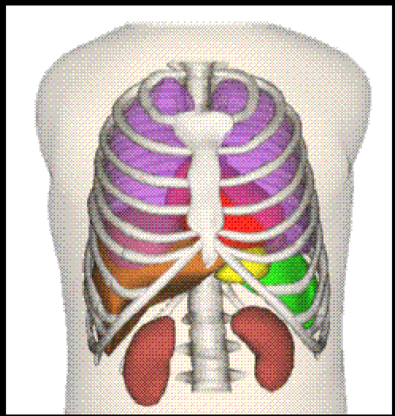
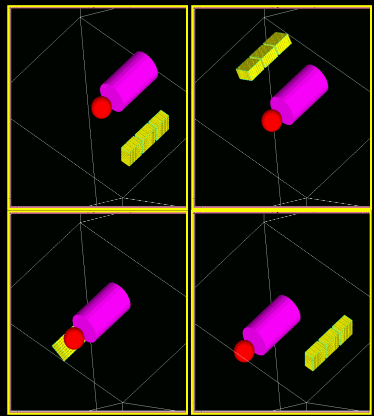
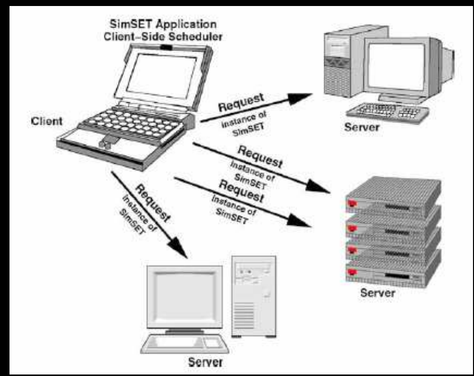
Segars et al, Mol Imaging Biol 2004

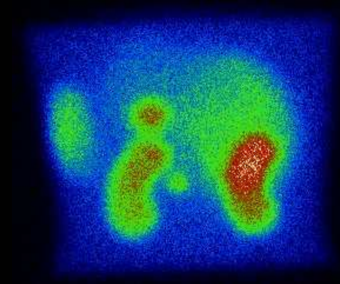
Making it easier to model a wide range of body shape and physiological motions

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 for updates