GATE

A GEANT4-based toolkit for Medical Physics

Summary

- GATE runs as a generic GEANT4 application
- No programming skills required
- Everything is setup using script commands, basically macro files — no graphical interface, sorry…
- Different strategies for imaging applications and for dosimetry/radiotherapy
- See documentation here

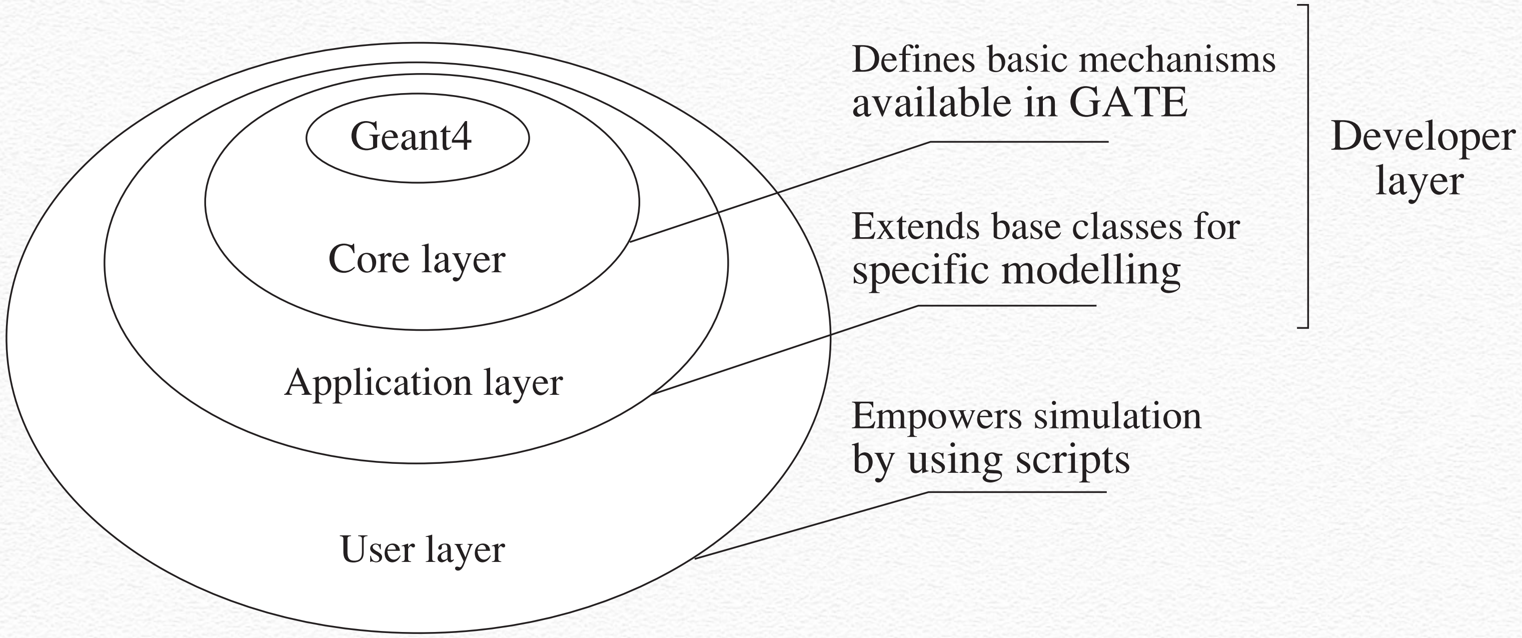


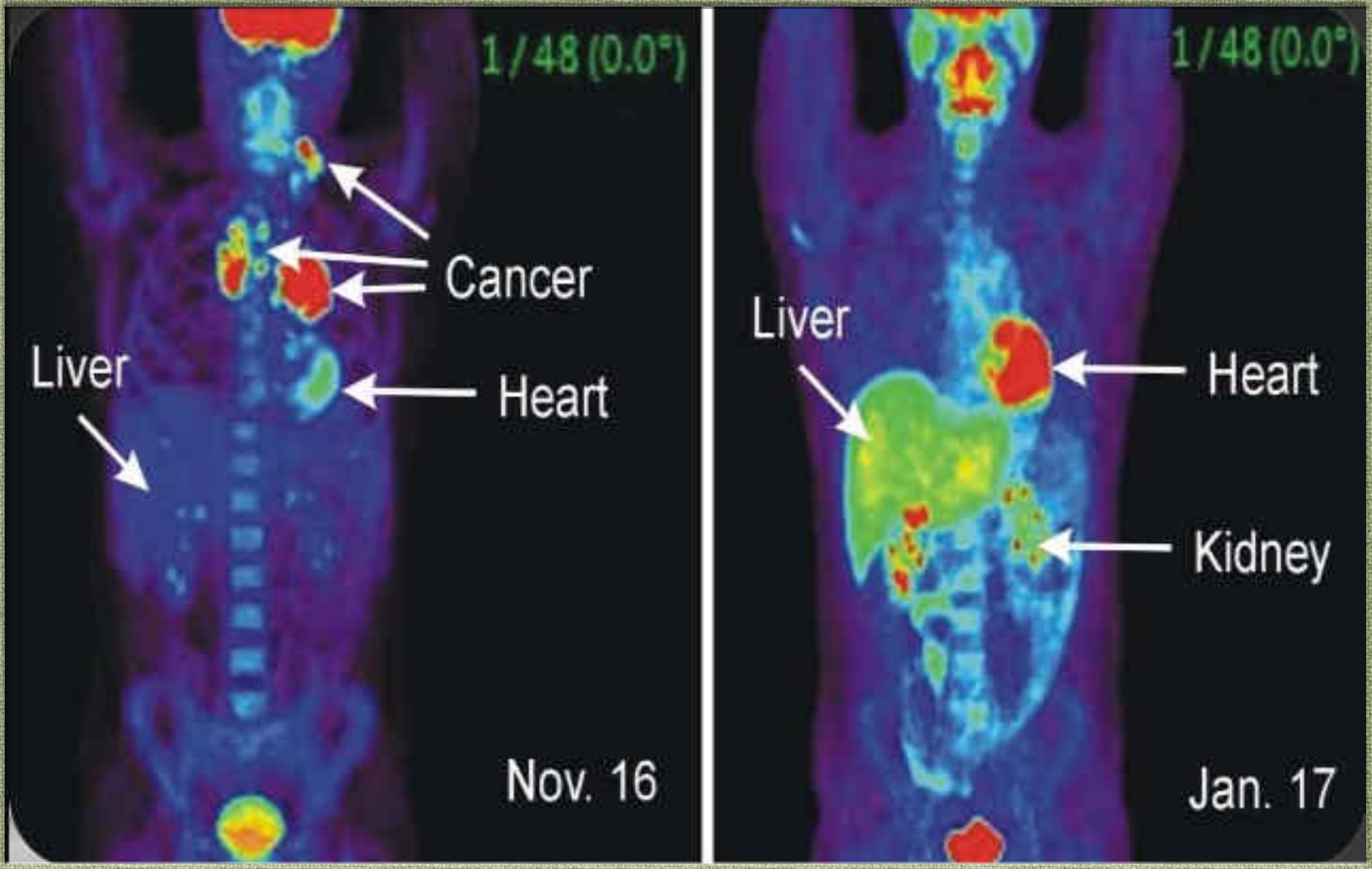
Figure 1. Sketch of the layered architecture of GATE.

Useful links

- GATE website with documentation and download instructions

- A long list of publications with overviews on Gate and many specific applications in Medical Physics, both for imaging and treatment planning

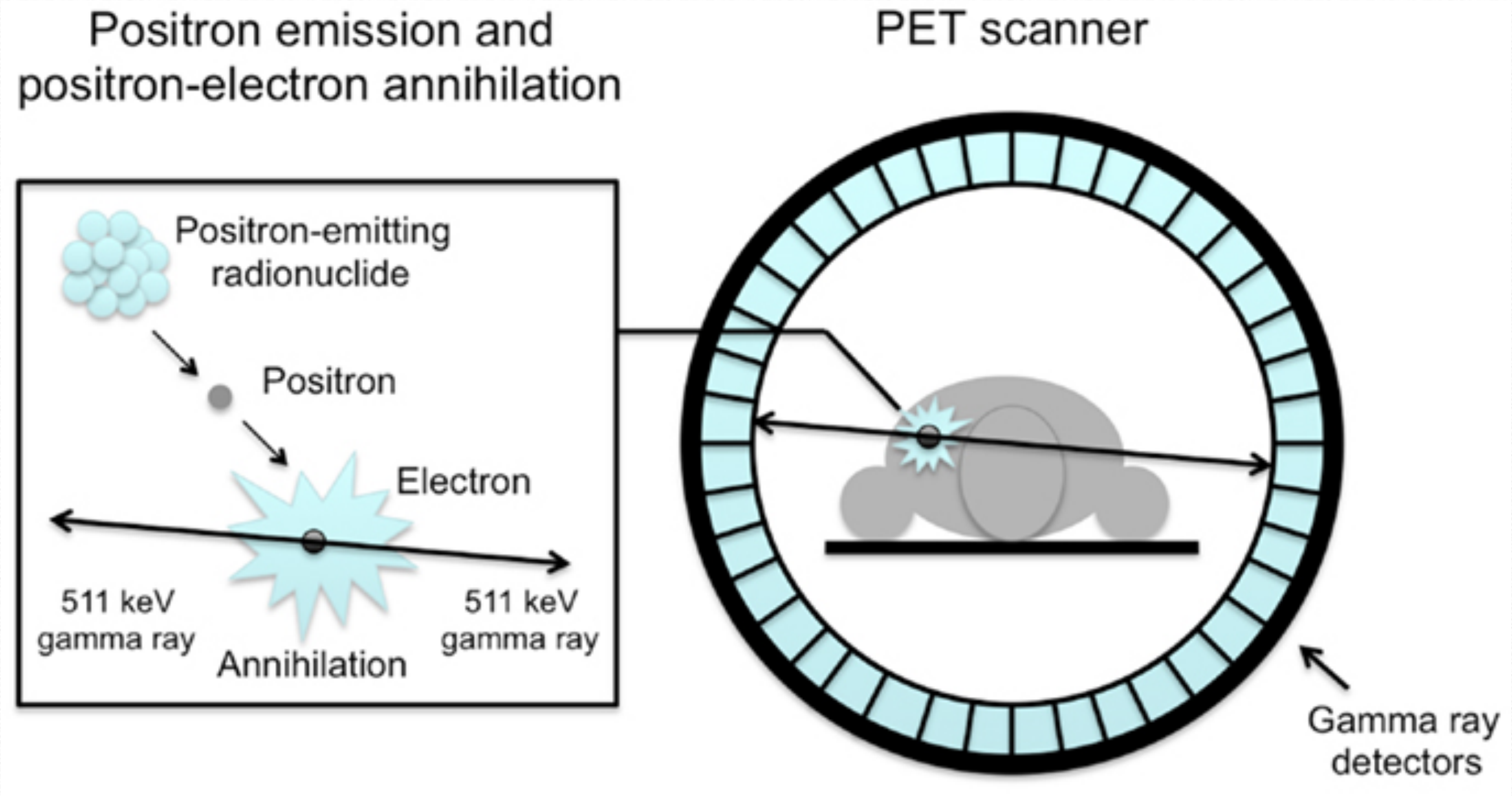
- Repository with plenty of examples



PET

Positron Emission Tomography

The concept



- Patient injected with positron emitting radioactive isotope, attached to a molecule preferably absorbed by the organ to study
- Isotope emits a positron, which thermalises and annihilates emitting two back-to-back 511 keV gammas
- One or more rings of detectors detect these gammas. Coincidences are used to produce an image of the emission region by overlapping many lines

Gate PET example

- The benchmarks folder has plenty of examples
- The benchPET consists of:
  - 8 detector heads (that can be rotated)
  - 400 detector blocks each
  - each block is a dual layer of LSO-BGO crystals
  - cylindrical water phantom with two linear sources (^{18}F, 109.8 min HL and ^{15}O, 2.03 min HL) 100 kBq each
  - total acquisition time is 4 min, in 2x 2 min frames
  - the heads rotate by 22.5 deg between frames
  - coincidence time window is set to 120 ns (to allow a large number of random coincidences)
  - takes **~12 hours** in a 1 GHz CPU (!)…

Image from this paper

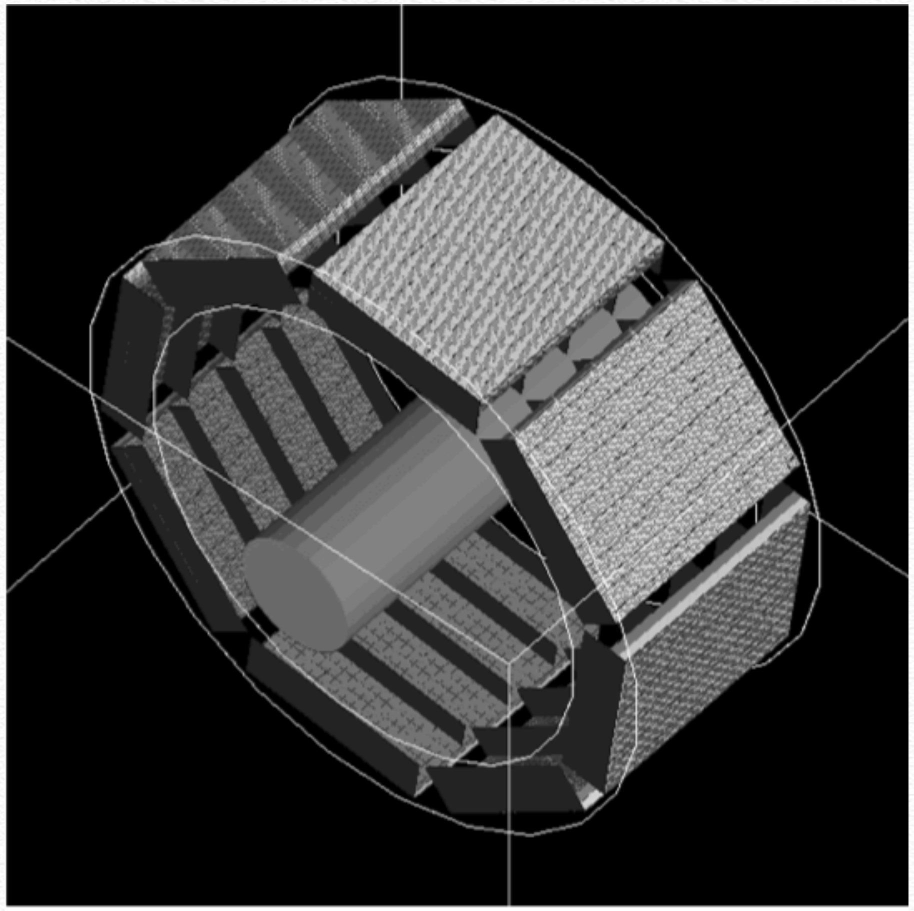


Figure 4. Illustration of the PET benchmark set-up.

PET Example

- We obviously don't have that long just to run the example, so let's build our own simplified PET system
- Download file myPET.zip from www.lip.pt/~alex and unzip it inside your working folder
- To keep things organised, we are going to use different macro files:
  - main.mac
  - geometry.mac
  - physics.mac
  - digitizer.mac
  - source.mac
  - output.mac
  - vis.mac

How to run Gate

- Instead of installing yet another software, let's use Docker
- The Gate collaboration provides a docker image with GEANT4 6.3 and Gate 9.0
- To make things easier, download the scripts setup_docker.sh and run_docker.sh from here and copy them inside your working folder
- To start the Gate container, open a terminal in your working folder

```
source setup_docker.sh
source run_docker.sh
cd /usershared/myPET
```

- You should now be in the folder we just unzipped

Step-by-step…

- Look inside main.mac — this is where we will control the flow and call the other macros
- You'll notice most commands are commented out. Let's slowly construct the geometry… using files `geometry_step1.mac` through `...step5.mac`
- To run the simulation, type `Gate main.mac`
- Unfortunately the GEANT4 in the Gate image was not compiled with OpenGL support. So we must use VRML2 files for visualisation
  - Uncomment the line that executes `vis.mac` from `main.mac`
  - Run the simulation again, you'll see a new file with .wrl termination
  - Open it with `view3dscene`

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- Unfortunately the GEANT4 in the Gate image was not compiled with OpenGL support. So we must use VRML2 files for visualisation
- Then uncomment the use of the remaining macros, analysing the commands inside them
- To have decent statistics run the simulation with at least 1M events (using */gate/application/setTotalNumberOfPrimaries*)
  - Remember to comment out the execution of `vis.mac`

Analysis

- There are several TTrees inside the .root file:
  - Hits — provides extensive information about all the hits in all the crystals
  - **Singles** — information for each crystal
  - **Coincidences** — information about events where a coincidence was detected
  - OpticalData (we don't use this)

Analysis

- Some suggested plots:
  To see the full list of available variables, open ROOT and type
  `new TBrowser()`

- Have a look at the time distribution
  Singles->Draw("time")

- Check the position distribution of the source
  Singles->Draw("sourcePosZ:sourcePosY:sourcePosX")
  Singles->Draw("sourcePosZ:sourcePosX**2 + sourcePosY**2")

- Check the interactions in the crystals
  Singles->Draw("energy") — and fit a gaussian, is the resolution as expected?
  Singles->Draw("globalPosZ:globalPosY:globalPosX")
  Singles->Draw("globalPosX:globalPosZ")
  Singles->Draw("globalPosY:globalPosX")
  Singles->Draw("energy:sqrt(globalPosX**2+globalPosY**2)","","colz")

Coincidences

- A few interesting plots to try:
  - Coincidences->Draw("sourcePosZ1")
    Coincidences->Draw("sourcePosZ2")
    Do you expect these distributions to be identical?
  - The above distributions also show that not all the source emissions have the same probability of being detected — this is a direct effect of us having only one ring
  - Compare this distribution with sourcePosZ in the Singles TTree
  - Have a look at the photon travel time. How does that compare with our "coincidence window"?
    Coincidences->Draw("(time2-time1)*1.e12") — photon travel time difference (in picoseconds)
  - Coincidences->Draw("rsectorID2:rsectorID1","","colz") — photons are detected in approximately opposite modules (as expected) but not exactly
  - This is caused by Compton or Rayleigh scattering (in the phantom or crystals). Try adding cuts for no Compton/Rayleigh in the phantom)

Exercises

- Use the information on the Compton scatters in the phantom to get the energy of events with no energy loss in the phantom
  - Compare the energy spectrum of gammas with at least 1 Compton scatter in the phantom with the total — do you think we should adjust our energy window?
- What is the fraction of decays that produced a coincidence?
- Are all coincidences from gammas in the same decay?
- What is the fraction of coincidences with no scatter in the phantom?
- Estimate the distance between the detected gammas in coincidence, with and without phantom scatters
- Estimate the acollinearity angle. Again, check the effect on this angle in the case of no phantom scatters
- Double the radius of the phantom and redo the previous estimates. Also have a look at the coincidence time, has it changed?

A more realistic simulation

- So far we have not used the extra potential offered by GATE
- Instead of running a fixed number of events, let's set a running time and use the activity of our source
- Edit the main.mac macro to have an acquisition interval from 0 to 10 sec. Comment the line to have a fixed number of events
- Set the initial activity of the source as 100k Bq
- With 100k Bq x 10 sec we should still have ~1M events

False coincidences

- Have a look at the absolute time distribution — it now spans between the limits we defined
- Do you expect us to have false coincidences with the current setup?
  - How can you check this?
  - Hint: plot the coincidence time distribution
- Increase the coincidence time to see more false coincidences (e.g. 100 ns or 1 μs)
  - Redo the distance and angle distributions between coincident gammas now that you have false coincidences

A realistic source

- Instead of our ideal source, let's use ^{15}O
- This is a source frequently used in PET
- It decays by positron emission (99.9%), which then annihilates inside the patient
- The half-life of this source is ~2 min
- GATE can realistically simulate the effect of the decay of the source during the exam

A realistic source

- Edit the main.mac macro to use source_O15.mac to define the primaries
- Set the scan duration for 10 min. Set the duration of each time slice as 10 sec
  - GATE calculates the source activity in each time slice
- Use an initial activity of 1000 Bq
- Analyse the output file to check the decay of the source activity
  - Does it agree with the half-life of the source?

A moving patient

- GATE allows you to add movement to any of the geometry elements
- You can use it to rotate the PET ring and modules
- Or to simulate movement of the patient during the exam (e.g. breathing)
- Types of movement: translation, rotation, orbiting, wobbling (oscillating translation)

A moving patient

- We will make our phantom “wobble” in the x, y and z directions
- We can set the amplitude, period/frequency and initial phase
- For this, use the geometry_step6.mac macro file
- Note that it is important for the source to be attached to the phantom, to move with it
- Set your acquisition interval to 20 sec, in slices of 1 sec
    - GATE repositions the geometry at each time slice
- Increase the initial activity of the source by 10x to increase the statistics
- Can you tell from the data that the phantom/source is moving?