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Geant4 based simulation of the Leksell Gamma Knife for treatment planning validations

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Outline

- Strerotactic Radiosurgery with GammaKnife
- The TPS Leksell GammaPlan (LGP)
- Monte Carlo simulation of the device with Geant4
- Comparison with the experimental data
- Geant4 vs GammaPlan
- Presence of different density materials
- Simulation of a complete clinical treatment
- Last reviews of the application
- Conclusions and future developments

Stereotactic Radiosurgery with Gamma Knife

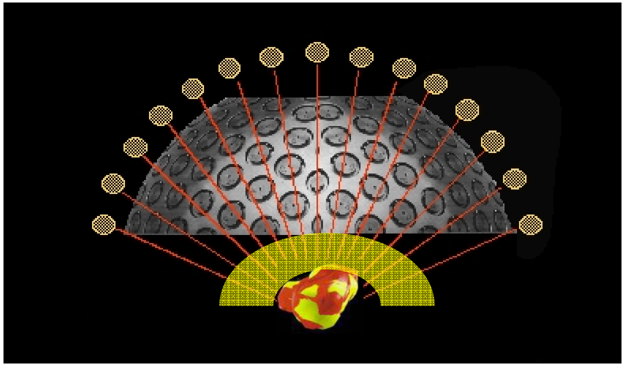
Stereotactic Radiosurgery with ***<u>Gamma Knife</u>***® is a technique used for treating brain disorders of different kind which are often inaccessible for conventional surgery → <u>one single high dose session</u>

Leksell Gamma Knife® C (Elekta)

Installed at the "Cannizzaro Hospital" in Catania and already in operation since 2005

201 ^{60}Co sources are arranged in a hemisphere

Gamma ray beams converge through a collimator system to a common focal point (isocentre) where the target volume has to be positioned

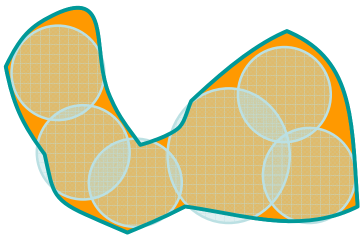


<u>irradiation of the target</u>

<u>sparing healthy tissues</u>

Radiation Unit

By combining different irradiations (***shots***) a complex target can be covered

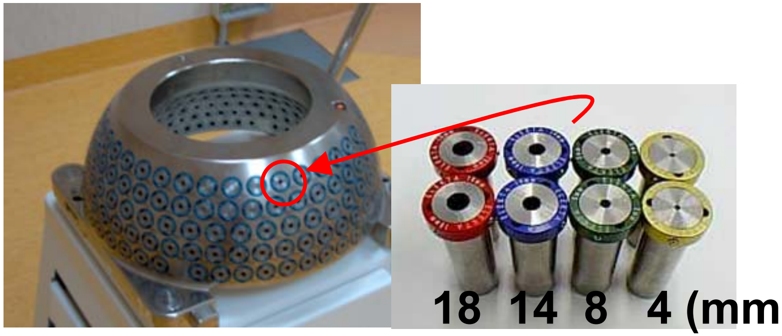


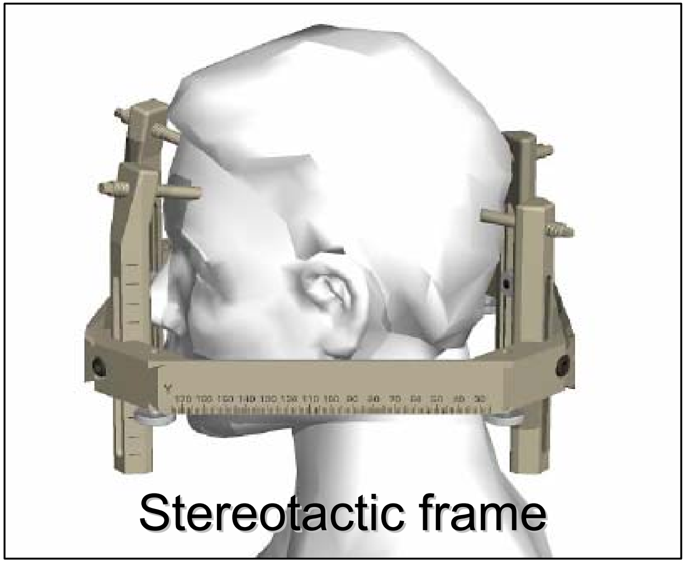
Multi-shots → complete treatment!

Automatic Position System (APS)

Connected to a stereotactic frame fixed to the patient's head (precise localization of the target volume)

Mobile collimators (helmet)



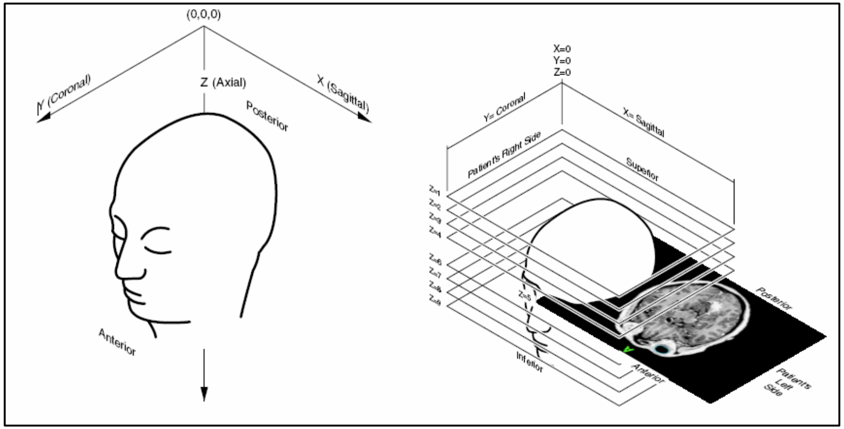


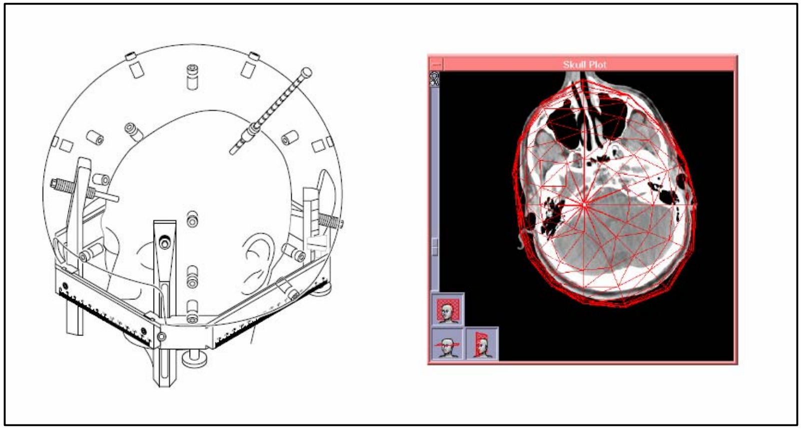
APS

Leksell GammaPlan

Leksell GammPlan® (LGP) is the Treatment Planning System

It is a semi-empirical algorithm which computes the delivered dose according to the image data of the patient (TC or MRI or angiography)





TPS assumptions

- Average of emitted gamma: 1.25 MeV
- <u>Target made up of **water**!</u>

$\mu = 0.0063\ mm^{-1}$

These approximations can achieve some uncertainties in the dose computation

A Monte Carlo simulation can be very important in order to validate the TPS dose distribution also in particular configuration

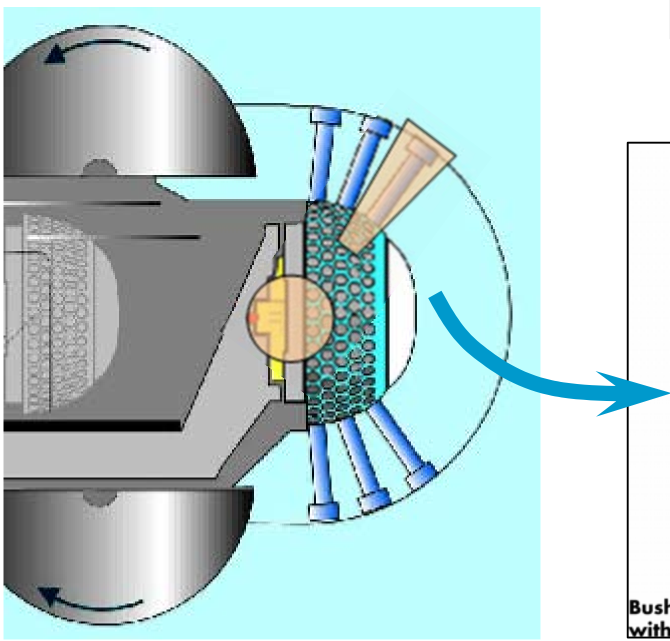
Monte Carlo simulation with GEANT4

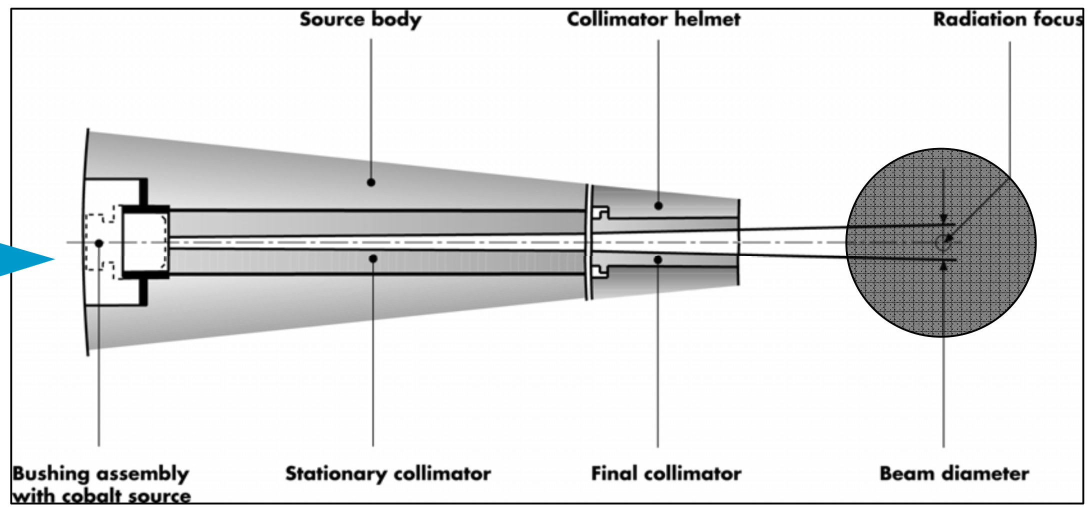
A Monte Carlo simulation of the Gamma Knife® was developed by using the toolkit ***GEANT4***

- ***geant4.9.2.p01***
- ***LowEnergyElectromagnatic package (Livermore)***
- *cut = 10 mm (in the whole system)*
- *cut = 0.01 mm (in the detector)*

All the 201 ^{60}Co sources (and the respective beam channels) are exactly the same!

simulation of an "elementary unit"



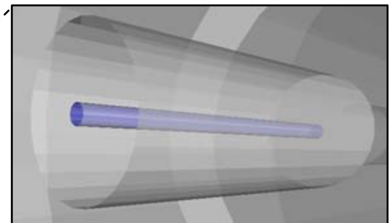


Monte Carlo simulation with GEANT4

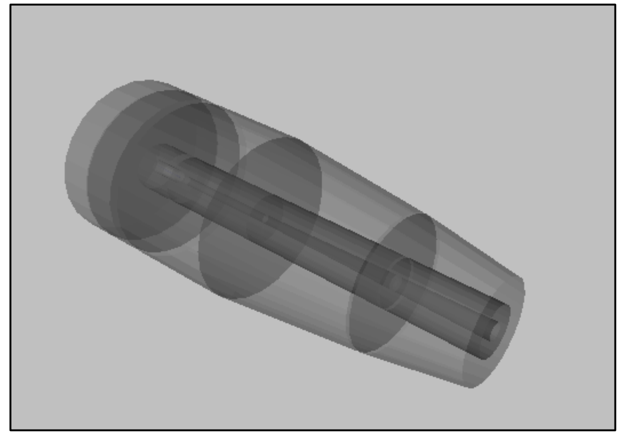
$$^{60}_{27}Co \Rightarrow ^{60}_{28}Ni + e^{-} + \overline{\nu}_e$$

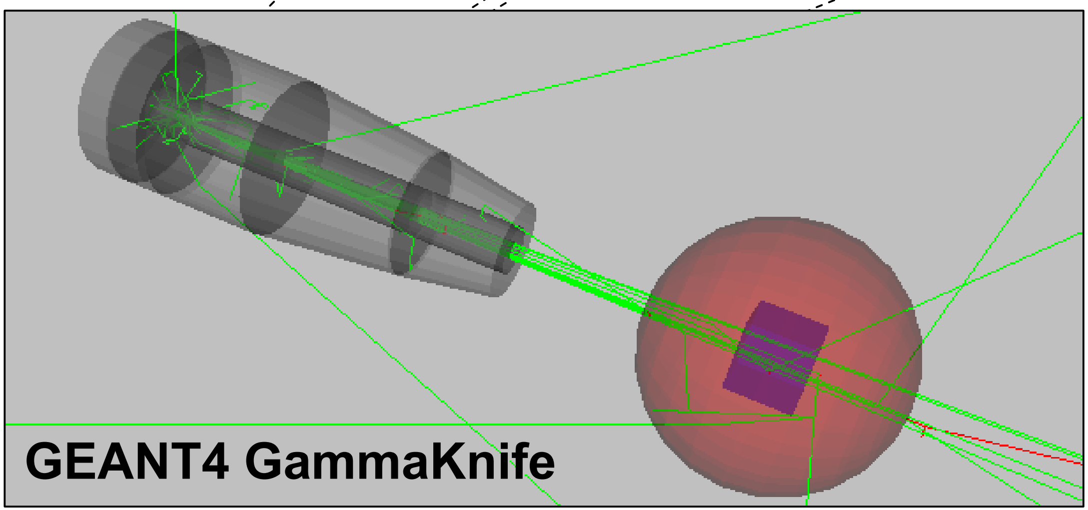
Two gamma:
$E_{\gamma 1}$ = 1.17 MeV
$E_{\gamma 2}$ = 1.33 MeV
(LGP®→1.25 MeV)

~ 3 Gy/min

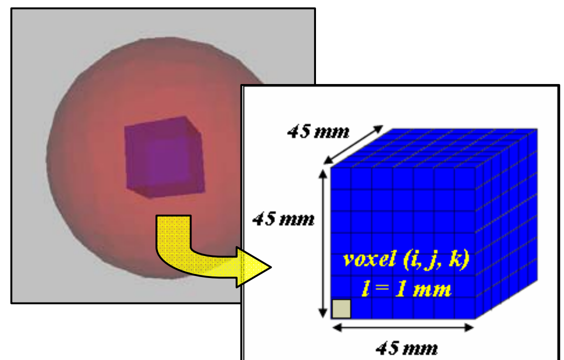


Collimators:
- fixed (W)
- helmet (Pb)





Water phantom



Sensitive detector (ROGeometry used)

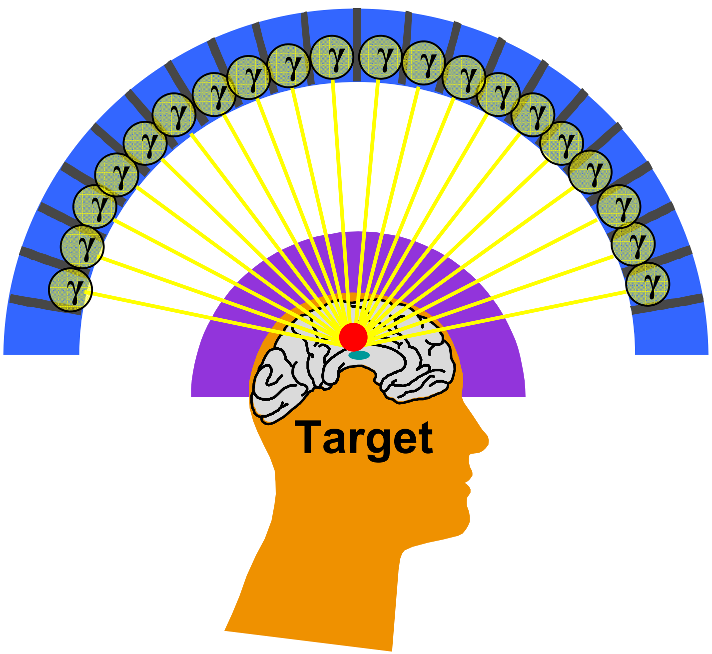
Monte Carlo simulation with GEANT4

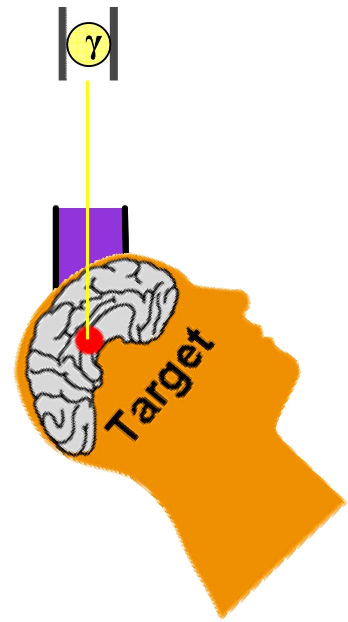
Simulation of the whole system

more simple and clear code

~~*201 sources and collimators, one fixed phantom*~~

one source and collimator, one rotating phantom





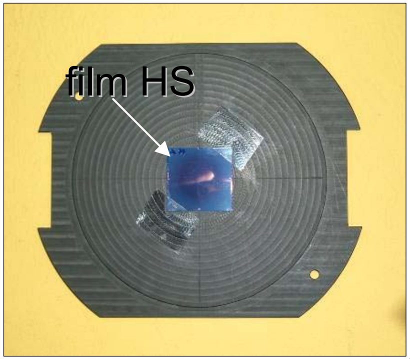
Comparison with the experimental data

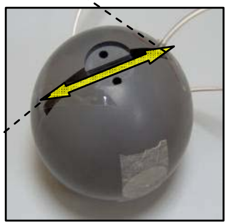
Dose delivered to a water phantom was measured by using ***GafChromic film HS***

Films were irradiated with each final collimator (18, 14, 8 and 4 mm) (dose = 20 Gray)

Digital images (two dimensions) were taken 48 hours later by using a flatbed scanner in transmission mode

Spatial resolution = 0.2 mm





For each single shot, comparisons between simulation output and experimental data were performed superimposing *profiles* (one-dimensional) and 2-D *isodose curves* in the axial plane through the isocentre, normalized at the maximum

Data analysis was performed by using the ***γ index**** method

Dose difference (DD) **Distance to agreement (DTA)**

$\gamma > 1$ → points not passing the test

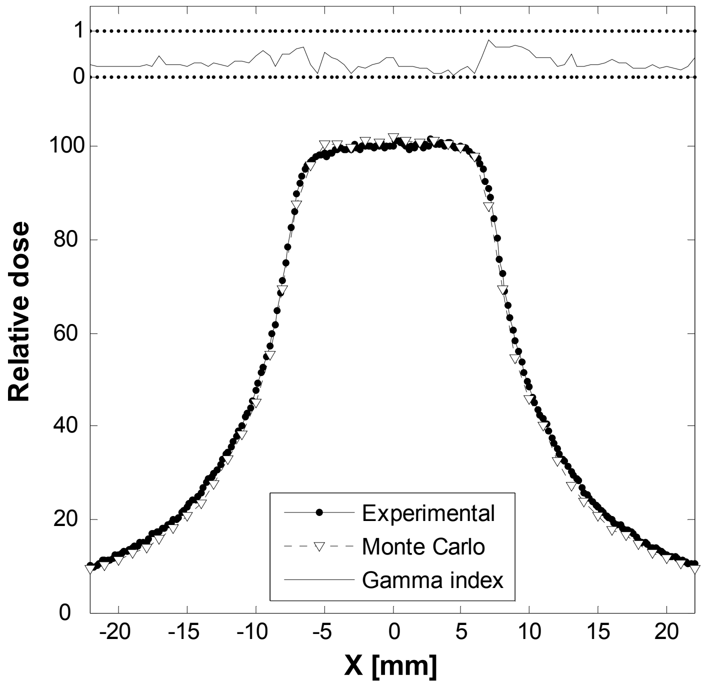
*A. Low et al., *A technique for the quantitative evaluation of dose distributions, Med. Phys.. 25 (5), May 1998*

Comparison with the experimental data

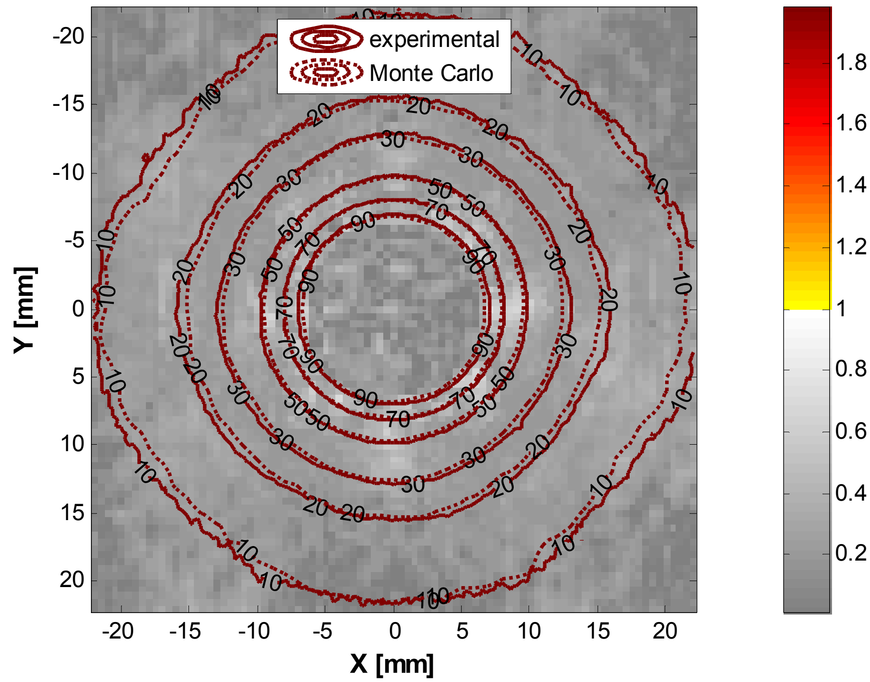
Geant4 vs *experimental data*

14 mm collimator

Comparison of Monte Carlo and experimental profiles



Comparison of Monte Carlo and experimental isodose curves

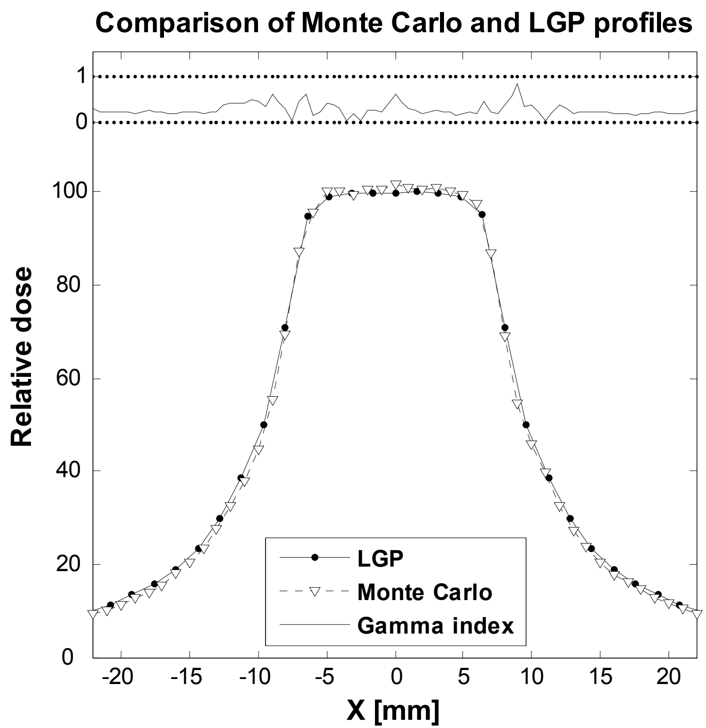


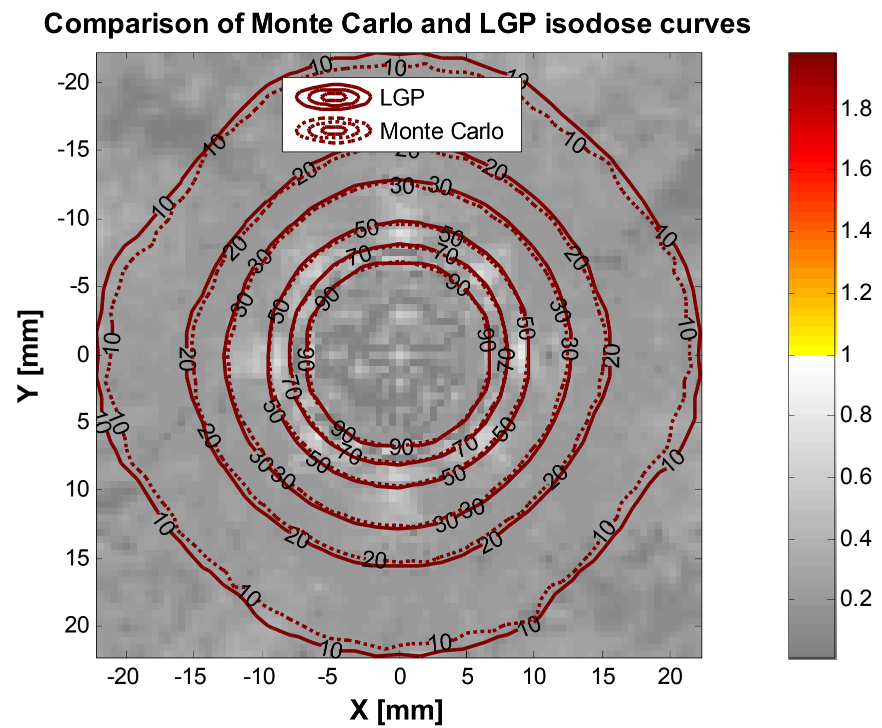
Overall good agreement between Geant4 simulation and the experimental dose distributions.

Geant4 vs LGP

Monte Carlo simulation has been used to study the trend of the LGP for a homogeneous phantom

Geant4 vs *LGP*
14 mm collimator

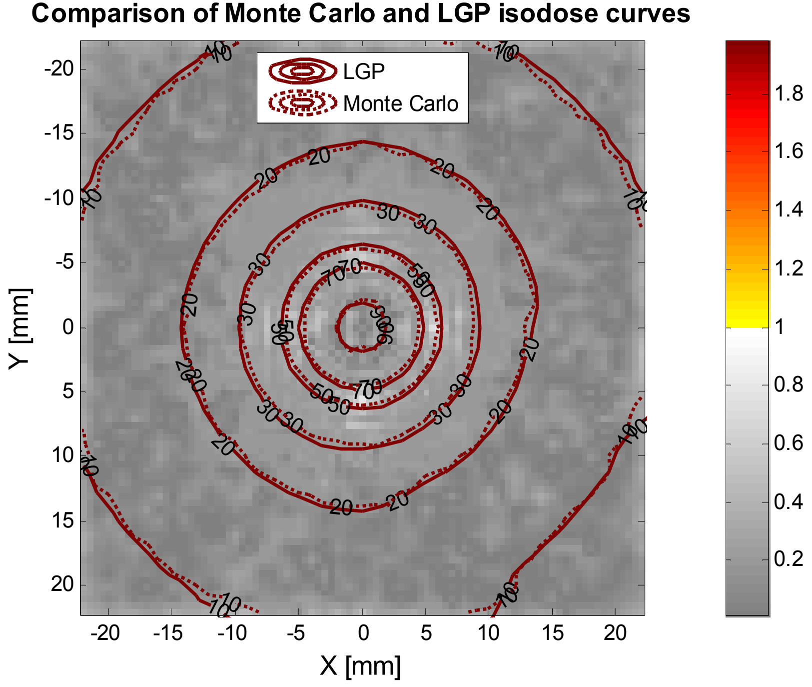




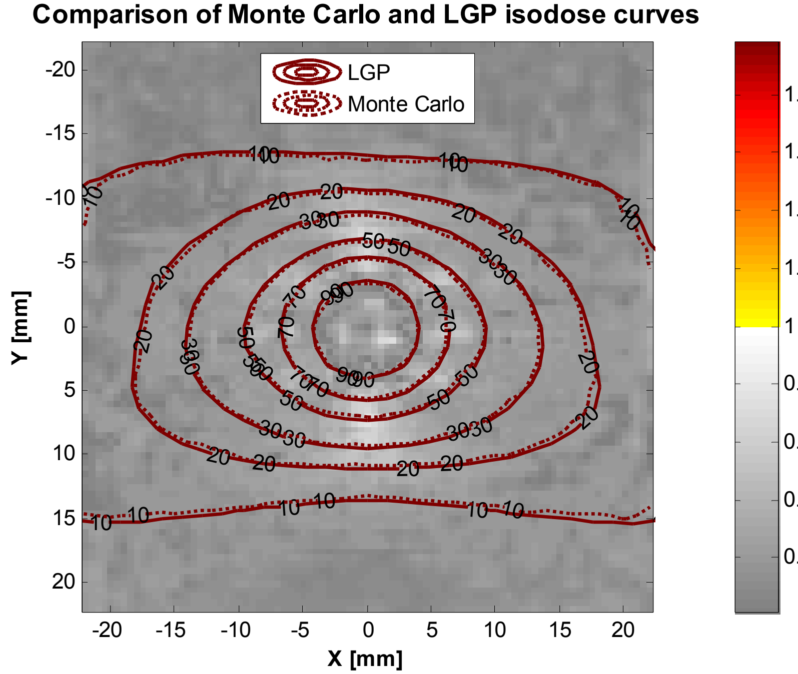
Geant4 vs LGP

Geant4 vs *LGP*

8 mm far from the centre (axial plane)



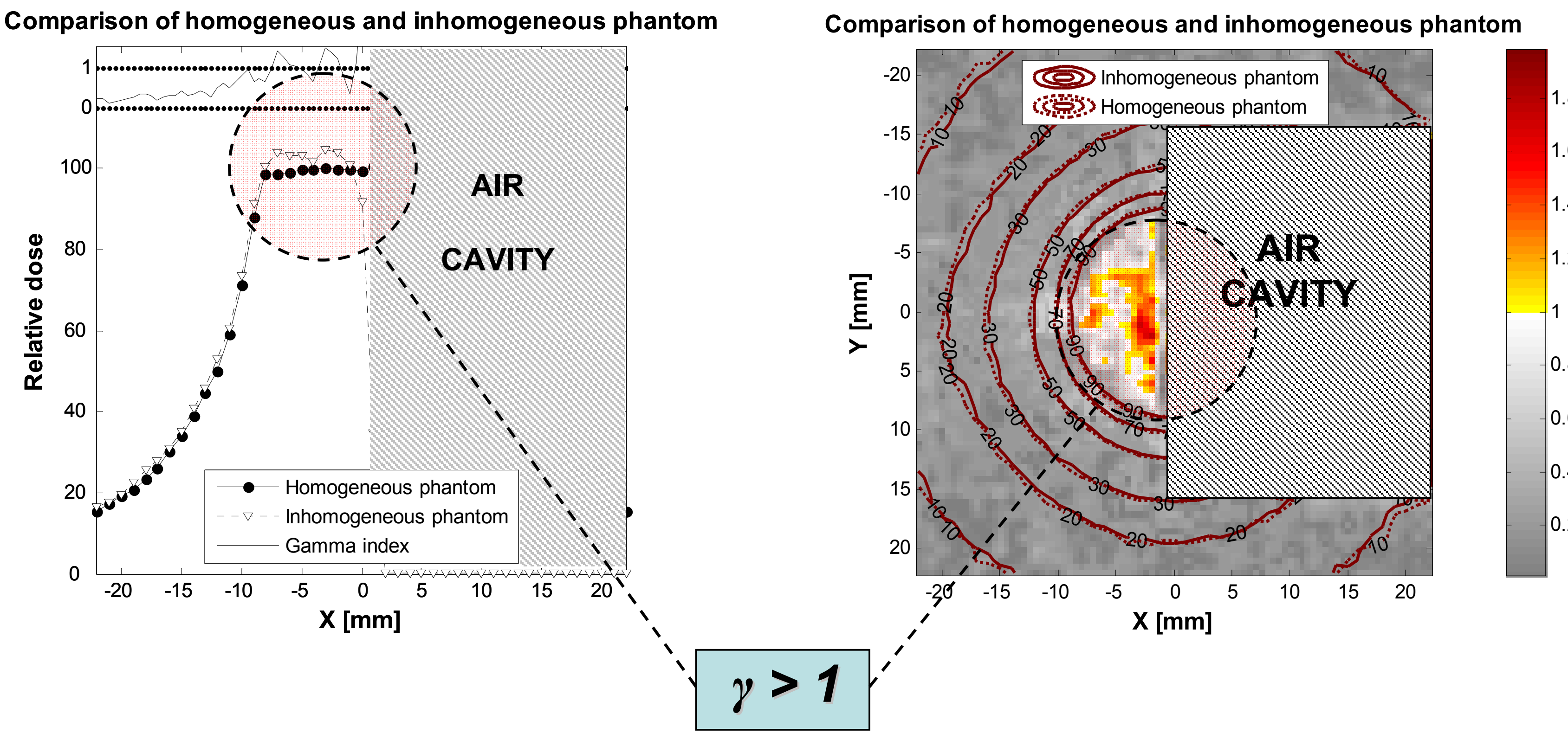
8 mm far from the centre (coronal plane)



LGP correctly computes delivered dose for <u>homogeneous phantom</u>

Presence of different density materials

A cubic air cavity 3 cm of side was placed near the target volume to simulate the presence of different density materials (i.e.: nasal cavity).



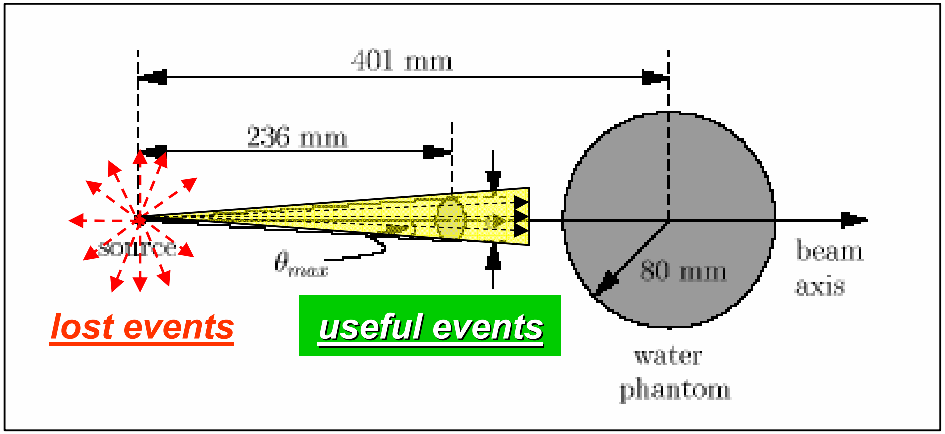
Differences in dose distribution up to 4%

LGP underestimates the dose delivered to the target if it is located close to air cavities

Improving computing performance

Gamma with isotropic direction
very long CPU time!

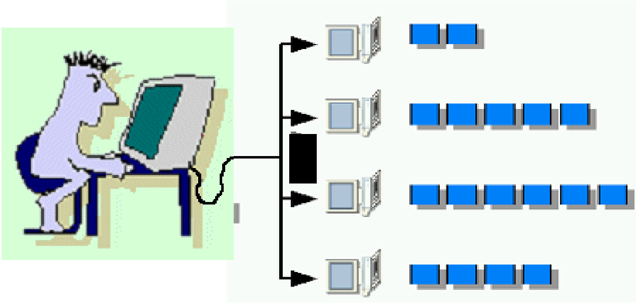
The direction of the primary particles has been sampled within an angle of semi-aperture:
$\theta_{max} = 2.5°$
more reasonable calculation time!



A fifteen Linux quadri-processors cluster was used to decrease the total calculation time

20 jobs of 1.5 10^8 events different seeds → clock CPU

Total number of events: $3 \cdot 10^9$

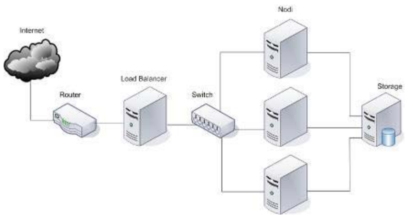


Clinical treatment simulation (multi-shots)

The GammaKnife simulation has been upgraded and now a real clinical treatment can be completely simulated!

*very long computation time needed to achieve a good statistics due to the **multi-shots** simulation*

Cluster used before is not enough!!!



***GRID** technology has been exploited*

(a possible solution in case of very long simulation)

- The large amount of required histories is divided into shorter simultaneous subtasks
- The subtasks are generated with different seeds to ensure that the histories are statistically independent
- The reduction time is related to the number of simultaneous subtasks

Calculation time decreased up to about 20 hours

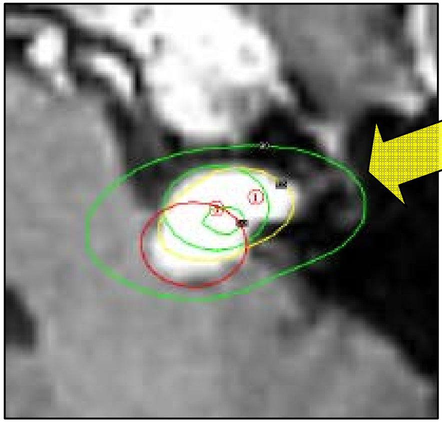
(~ 100 jobs simultaneously submitted)

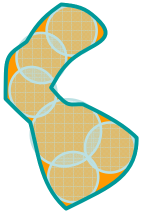
Clinical treatment simulation (multi-shots)

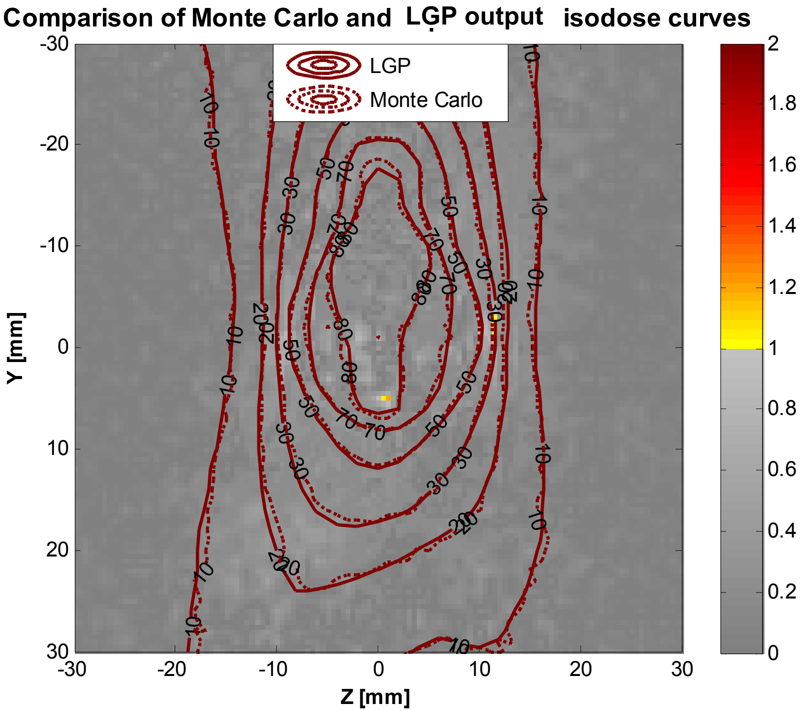
Geant4 vs *LGP*

- Homogeneous phantom
- Shot configuration from a ***real clinical treatment***
- ***Irregular shape*** of the target volume

7 shots { 1 with 18 mm collimator; 6 with 14 mm collimator }







LGP computes delivered dose for homogeneous phantom with accuracy also in case of a multi-shot clinical treatment!

Towards an advanced example…

We would like to propose the GammaKnife application as a Geant4 *advanced example*. For this aim, we want to consider some requirements which are *not mandatory* but at least *recommended*:

- Reasonable simulation time (not necessarily using clusters or GRID) → *phase-space*

- Good level of accuracy: to reproduce correctly the trends of the variables of interest concerning the specific simulated device → *extended benchmarks*

- Clearness of the code, wide-spread employment of messengers, as more as possible comments and simple macro files → *replacing long macro files*

Towards an advanced example...

old macro version ~ 1000 lines!!!

GKMacroRotation.mac

```
...
...

/run/initialize

## RING      A: 44 ROTATIONS AT FIXED THETA = 84°

# ANGLE 1 --> PHI = 3.8°
/calorimeter/DeleteSDAndRO Delete
/calorimeter/angleTheta 84 deg
/calorimeter/anglePhi 3.8 deg

/run/beamOn 5000


# # ANGLE 2 --> PHI = 11.4°
/calorimeter/DeleteSDAndRO Delete
/calorimeter/angleTheta 84 deg
/calorimeter/anglePhi 11.4 deg

/run/beamOn 5000

...
...

# # ANGLE 201 --> PHI = 350°
/calorimeter/DeleteSDAndRO Delete
/calorimeter/angleTheta 54 deg
/calorimeter/anglePhi 350 deg

/run/beamOn 5000
```

new macro version → 2 lines!!!

GKMacroRotation.mac

```
...
...
/detector/setMachine MachineAngle.in

/detector/EventsForAngle 5000

...
```

GammaKnife device version used →

MachineAngle.in

...	
...	
A1	**3.8 84**
A2	**11.4 84**
A3	**19 84**
A4	**26.6 84**
...	
...	

A function creates "on-flight" a tmp-file (a copy of the old macro) which is executed.
The user will define the events for each angle by using the command "**EventsForAngle**" only once

Conclusions and future developments

- The developed application correctly simulates the GammaKnife device used for Stereotactic Radiosurgery. The alternative rotation method has been demonstrated to give realistic results.
- An acceptable level of accuracy in deposited dose distribution has been achieved.
- The Treatment Planning System LGP has been successfully validated for homogeneus phantom, also in case of multi-shots treatment. Some limits have been found and studied in presence of different density materials.
- Last reviews have sensibly simplified the code and also made more independent of the particular device version used for the treatment.
- Total computation time is not yet satisfying, also in view of a possible inclusion among the Geant4 advanced examples. Further studies have to be carried out in order to find new and more efficient solutions.

Thanks for the attention