

A Geant4-based simulation of an accelerator's head used for Intensity Modulated Radiation Therapy

F. Foppiano, B. Mascialino, M.G. Pia, M. Piergentili.

Abstract— We present a Geant4-based simulation, this Monte Carlo program has been developed in order to simulate the absorbed dose distribution given by a medical linac used for intensity modulated radiation therapy (IMRT). The linac geometry was input into the Monte Carlo code using the accelerator's manufacturer's specifications. We made assumptions about some parameters such as the energy and the electron radial distributions that were assumed to be gaussian in shape. The capability of the program in evaluating dose distribution has been verified by comparison with measurements in water phantom; the comparisons were performed for percent depth dose (PDD) and for flatness at 15, 50 and 100 mm depth for various field size, for a 6 MV electron beam. The source-surface distance (SSD) was 100 cm. We show the comparisons between simulation results and experimental measurements and the software architecture.

Index Terms— IMRT, radiotherapy, Geant4.

I. INTRODUCTION

THE development of more advanced techniques in radiotherapy, such as intensity modulation, brings a need for more sophisticated and precise methods to calculate dose distributions.

In particular, Intensity Modulated Radiation Therapy (IMRT) involves a series of small fields, to obtain a specific treatment, with a complex dose distribution, for a single patient.

The most used treatment planning system are based on calculation algorithms those do not account for electron transport and therefore do not accurately predict dose in small fields where lateral electronic equilibrium is not achieved.

The aim of this project is to construct a dosimetric system, based on a Monte Carlo method, that accurately calculates dose distributions.

II. MATERIALS AND METHODS

A. Monte Carlo calculation

GEANT4 is an object-oriented toolkit developed to simulate the passage of particles through matter. It contains a large variety of physics models covering the interaction of electrons,

Manuscript received October 28, 2004.

F. Foppiano is with Istituto Nazionale per la Ricerca sul Cancro (IST), Largo Rosanna Benzi, 10 16132 Genova - Italy (e-mail: franca.foppiano@istge.it).

B. Mascialino is with the Italian Institute for Nuclear Research, via Dodecaneso 33, 16146 Genova - Italy (telephone: 0039 010 353 6420 - e-mail: Barbara.Mascialino@ge.infn.it).

M.G. Pia is with the Italian Institute for Nuclear Research, via Dodecaneso 33, 16146 Genova - Italy (telephone: 0039 010 353 6328 - e-mail: Maria-Grazia.Pia@ge.infn.it).

M. Piergentili is with the Italian Institute for Nuclear Research, via Dodecaneso 33, 16146 Genova - Italy (telephone: 0039 010 353 6420 - e-mail: Michela.Piergentili@ge.infn.it).

muons, hadrons and ions with matter from 250 eV up to several PeV. For these features and for its versatility, Geant4 applications are developed not only in particle physics, but also in many other fields where high accuracy and precision of simulations are needed, such as radiation physics, space science and radiotherapy. Specifically for our application, of particular interest is the LowEnergy package developed to extend electromagnetic interaction of particles with matter down to very low energy: 250 eV for electrons and photons.

We have developed a Geant4 application, which simulate the linear accelerator's head used at IST in Genova for the Intensity Modulated Radiation Therapy.

The components in the simulated linac head were the following: target, primary collimator, vacuum windows, flattening filter, ion chamber, mirror, jaws on the X and Y coordinates, multileaf collimator, with rounded leaf tips, and the phantom. Each pair of jaws can be rotated through an axis that is perpendicular to the beam axis. The user can select the position of each jaws and of every single leaf of the multileaf collimator

The phantom was divided in voxels in which we collect the energy deposit to calculate the relative dose absorbed. In the case of squared fields the phantom was made of water, in the case of the intensity modulated fields the phantom was made of plexiglass.

We have assumed Gaussian distribution for energy and momentum of the primary particles: the electrons.

B. Experimental measurements

The measurements, for the depth dose curves and lateral dose profiles for the squared fields, were made using an ion chamber (31002 Semiflex, PTW, Freiburg Germany) with an active volume of 0.125cm^3 and a cavity diameter of 0.55 cm. The ion chamber was mounted on a computer controlled scanning system (MP3-System, PTW, Freiburg Germany). The uncertainty of the position accuracy of the scanning system provided by the manufacturer was ± 0.1 mm. All the measurements were obtained at a SSD of 100 cm. The effective point of measurement for the ion chamber was taken to be $0.60r_{cav}$, where r_{cav} is the cavity radius of the chamber, consistent with the IAEA protocol [3]. The estimated total uncertainty of an ionization measurement at one depth was 0.5%, and it comes from the positioning repeatability of the ion chamber and short term fluctuations of the chamber, electrometer, air pressure and temperature, during the time frame of one scan. The estimated total uncertainty of a relative dose measurement was taken to be 1.8 %, this estimation take in account the relative uncertainty on the calibration of the dosimeter, on the

correction terms for influence quantities, on the beam quality correction, the long term stability of the dosimeter, on the dosimeter reading, the long term stability of user dosimeter and the establishment of reference conditions.

The measurements of absorbed dose in a plane, for the fields obtained with the multileaf collimator, were made using Kodak X-Omat V films and the film dosimetry system RIT113 with the scanner VXR-16 DosimetryPRO.

C. Normalization and comparison of data

For the depth-dose curves, all data were normalized to the maximum value. Lateral profile obtained from the experimental measurements are normalized to the dose value on the beam axis. Lateral profile obtained with the dosimetric system are normalized to the mean value in the flat zone. For the lateral profiles, in the central flat region we have made a rebinning, to reduce the statistical fluctuations.

Comparisons between experimental measurements and Geant4 simulations have been performed with a Goodness-of-Fit statistical toolkit [4], specialized in the comparison of data distributions. In particular, we have used the Kolmogorov-Smirnov test to evaluate the agreement between the two distribution.

III. RESULTS

In all the simulations we have made, we have reproduced with the dosimetric system the real experimental set-up, such as the position of the jaws and of every single leaf of the multileaf collimator, the energy of the beam, the source-surface distance and the material of the phantom.

A. Field 10x10 cm

We start this study from the 10x10 cm field, that is often used as a reference field to calculate relevant dosimetric quantities.

In figure 1 we show the lateral dose profiles at 15 mm depth, for the 10x10 cm field, with the 6 MV beam (SSD=100 cm).

We have divided the curves in five regions: the central flat zone, the high gradient regions and the tails, and we have used the Kolmogorov-Smirnov test in each of these regions. The test states that there is a good agreement between the two distributions, in each region.

TABLE I

RESULTS OF THE KOLMOGOROV-SMIRNOV TEST FOR THE LATERAL DOSE PROFILES AT 15 MM DEPTH, FOR THE 10X10 CM FIELD, WITH THE 6 MV BEAM.

range	distance	p-value
-84, -64mm	0.296	0.23
-63, -46 mm	0.389	0.21
-47, 45 mm	0.2	0.5
46, 56 mm	0.5	0.53
57, 84 mm	0.281	0.31

In figure 2 we show the lateral dose profiles at 50 mm depth, for the 10x10 cm field, with the 6 MV beam (SSD=100 cm).

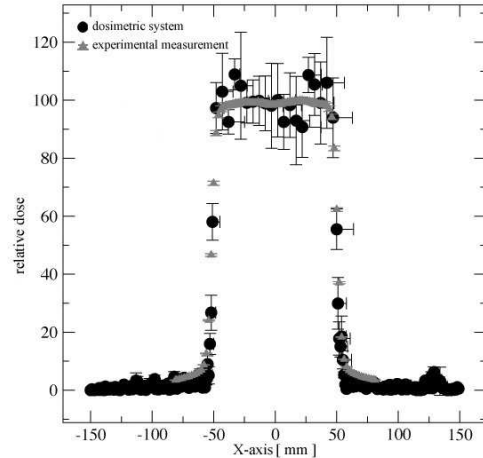


Fig. 1. Lateral dose profiles at 15 mm depth, for the 10x10 cm field, with the 6 MV beam. The grey symbol corresponds to the experimental measurements, the dark symbol corresponds to the Geant4 simulation.

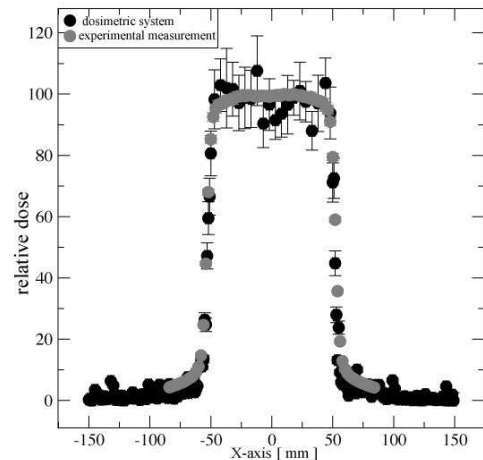


Fig. 2. Lateral dose profiles at 50 mm depth, for the 10x10 cm field, with the 6 MV beam. The grey symbol corresponds to the experimental measurements, the dark symbol corresponds to the Geant4 simulation.

We have divided the curves in five regions: the central flat zone, the high gradient regions and the tails, and we have used the Kolmogorov-Smirnov test in each of these regions. The test states that there is a good agreement between the two distributions, in each region.

In figure 3 we show the lateral dose profiles at 100 mm depth, for the 10x10 cm field, with the 6 MV beam (SSD=100 cm).

We have divided the curves in five regions: the central flat zone, the high gradient regions and the tails, and we have used the Kolmogorov-Smirnov test in each of these regions. The test states that there is a good agreement between the two distributions, in each region.

TABLE II

RESULTS OF THE KOLMOGOROV-SMIRNOV TEST FOR THE LATERAL DOSE PROFILES AT OF 50 MM DEPTH, FOR THE 10X10 CM FIELD, WITH THE 6 MV BEAM.

range	distance	p-value
-84, -60mm	0.385	0.23
-59, -48 mm	0.27	0.90
-47, 47 mm	0.43	0.19
48, 59 mm	0.3	0.82
60, 84 mm	0.4	0.10

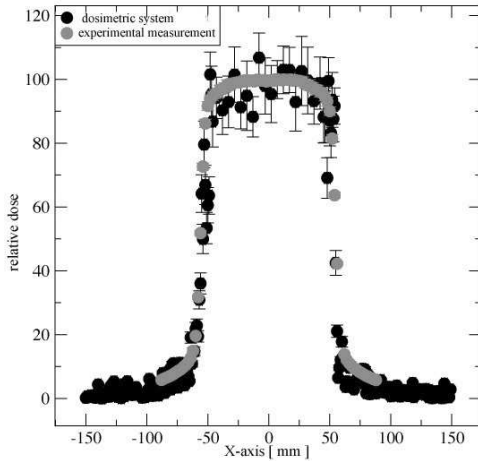


Fig. 3. Lateral dose profiles at 100 mm depth, for the 10x10 cm field, with the 6 MV beam. The grey symbol corresponds to the experimental measurements, the dark symbol corresponds to the Geant4 simulation.

TABLE III

RESULTS OF THE KOLMOGOROV-SMIRNOV TEST FOR THE LATERAL DOSE PROFILES AT 100 MM DEPTH, FOR THE 10X10 CM FIELD, WITH THE 6 MV BEAM.

range	distance	p-value
-84, -64 mm	0.425	0.25
-63, -46 mm	0.325	0.60
-45, 50 mm	0.52	0.17
51, 56 mm	0.52	0.65
57, 84 mm	0.381	0.40

B. Field 5x5 cm

After the 10x10 cm field, we have studied the 5x5 cm field, that have dimensions similar to the fields used in IMRT.

In figure 4 we show the lateral dose profiles at 15 mm depth, for the 5x5 cm field, with the 6 MV beam (SSD=100 cm).

We have divided the curves in five regions: the central flat zone, the high gradient regions and the tails, and we have

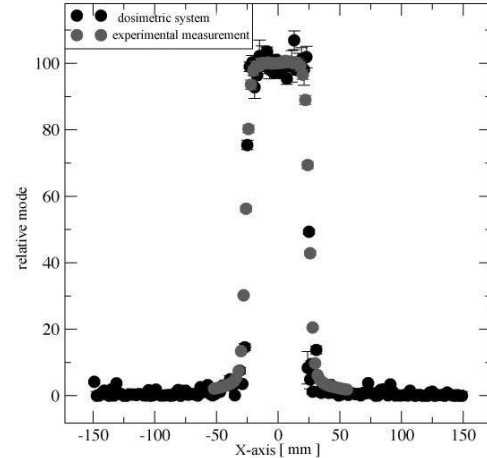


Fig. 4. Lateral dose profiles at 15 mm depth, for the 5x5 cm field, with the 6 MV beam. The grey symbol corresponds to the experimental measurements, the dark symbol corresponds to the Geant4 simulation.

used the Kolmogorov-Smirnov test in each of these regions. The test states that there is a good agreement between the two distributions, in each region.

TABLE IV

RESULTS OF THE KOLMOGOROV-SMIRNOV TEST FOR THE LATERAL DOSE PROFILES AT 15 MM DEPTH, FOR THE 5X5 CM FIELD, WITH THE 6 MV BEAM.

range	distance	p-value
-56, -35 mm	0.26	0.89
-34, -22 mm	0.43	0.42
-21, 21 mm	0.38	0.08
22, 32 mm	0.26	0.98
33, 56 mm	0.57	0.13

In figure 5 we show the lateral dose profiles at 100 mm depth, for the 5x5 cm field, with the 6 MV beam (SSD=100 cm).

Also in this case, we have divided the curves in five regions: the central flat zone, the high gradient regions and the tails, and we have used the Kolmogorov-Smirnov test in each of these regions. The test states that there is a good agreement between the two distributions, in each region.

C. Field 40x40 cm

We have started to study the 40x40 cm field, that can help us to determine if we have used the correct parameters characterizing the initial electron beam.

In figure 6 we show the depth dose curves at 100 mm depth, for the 40x40 cm field, with the 6 MV beam (SSD=100 cm).

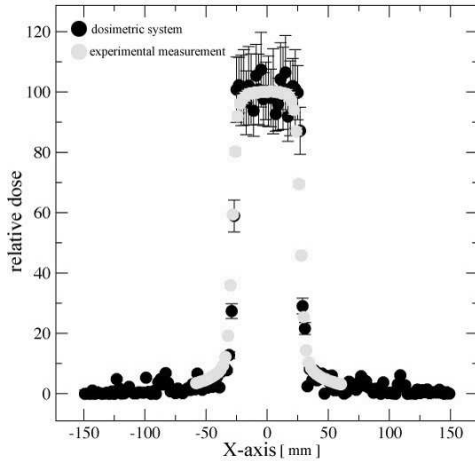


Fig. 5. Lateral dose profiles at 100 mm depth, for the 5x5 cm field, with the 6 MV beam. The grey symbol corresponds to the experimental measurements, the dark symbol corresponds to the Geant4 simulation.

TABLE V

RESULTS OF THE KOLMOGOROV-SMIRNOV TEST FOR THE LATERAL DOSE PROFILES AT 100 MM DEPTH, FOR THE 5X5 CM FIELD, WITH THE 6 MV BEAM.

range	distance	p-value
-61, -35 mm	0.33	0.5
-34, -26 mm	0.40	0.75
-25, 21 mm	0.32	0.24
22, 32 mm	0.27	0.75
33, 61 mm	0.21	0.91

Table VI contain the result of the Kolmogorov-Smirnov test, the test demonstrate that the dosimetric system can simulate with great accuracy the experimental measurements.

TABLE VI

RESULTS OF THE KOLMOGOROV-SMIRNOV TEST FOR THE DEPTH-DOSE CURVES, FOR THE 40X40 CM FIELD, WITH THE 6 MV BEAM.

range	distance	p-value
0, 300 mm	0.005	1

D. Field obtained with intensity modulated beams

We have studied an intensity modulated field used to treat a patient with prostate cancer. This field was obtained superimposing two fields shaped with the multileaf collimator, the first field was shown in figures 7 and 8, the first one represents a radiographic film exposed to the beam and the second one represents the dose distribution in a plane, at the same depth we have put the film in the phantom, given by the modulated beam; this distribution was obtained with the dosimetric system; the dimensions of the symbols in the picture are proportional to the absorbed dose.

Figures 9 and 10 show the whole intensity modulated field, the first figure represents the film exposed, the second one

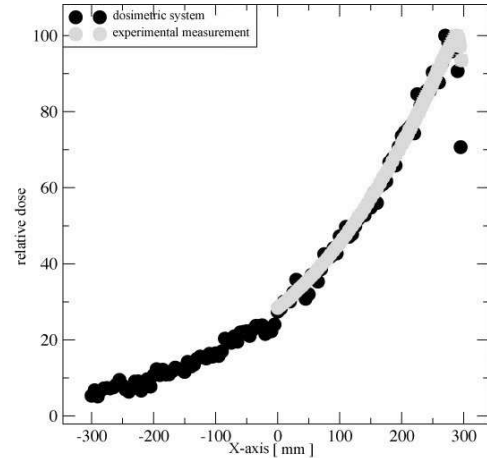


Fig. 6. Depth dose distribution, for the 40x40 cm field, with the 6 MV beam. The grey symbol corresponds to the experimental measurements, the dark symbol corresponds to the Geant4 simulation.

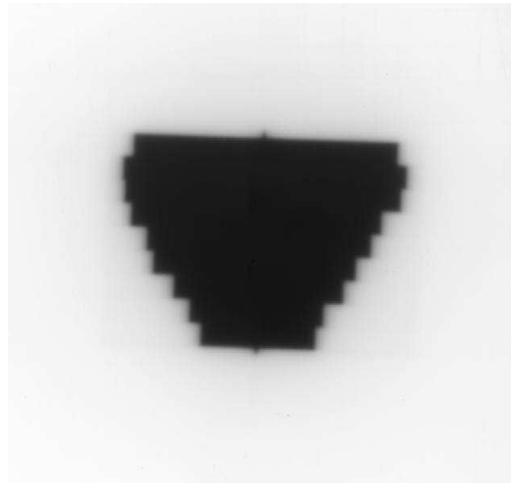


Fig. 7. Film exposed to a modulated beam.

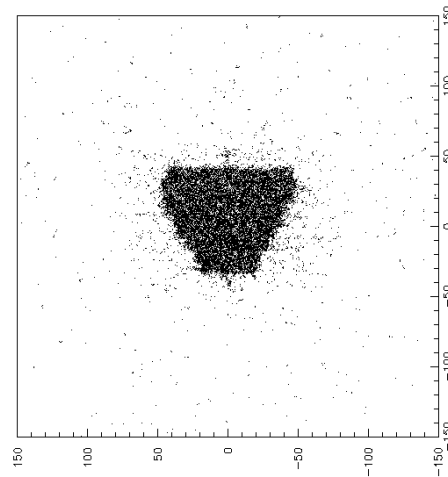


Fig. 8. Dose distribution in a plane given by the modulated beam, this distribution was obtained with the dosimetric system; the dimensions of the symbols in the picture are proportional to the absorbed dose.

represents the dose distribution in a plane, at the same depth we have put the film in the phantom, given by the modulated beam, this distribution was obtained with the dosimetric system.

In both these figure we can appreciate the regions with different dose intensity, and we can see that the dosimetric system is able to reproduce the dose distribution and in particular the dose interleaf transmission due to the rounded leaf tips.

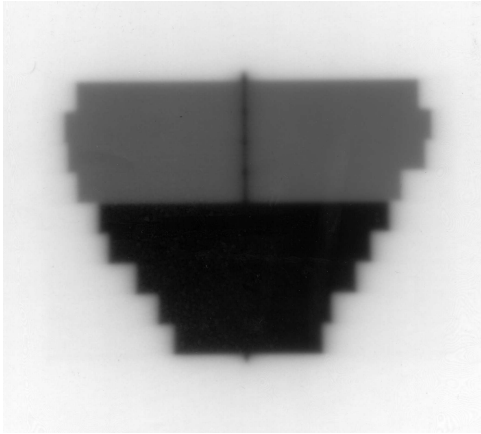


Fig. 9. Film exposed to a modulated beam.

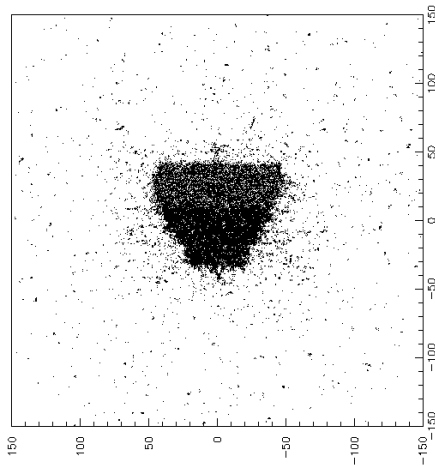


Fig. 10. Dose distribution in a plane given by the modulated beam, this distribution was obtained with the dosimetric system; the dimensions of the symbols in the picture are proportional to the absorbed dose.

IV. CONCLUSIONS

Results obtained from Geant4 simulation for the fields in homogeneous phantoms show a satisfactory agreement with measured dose data. All the statistical comparisons state that there is not a statistical difference between the experimental measurements and the data obtained with the Geant4 simulation.

This method of dose calculation can be a dosimetry tool in addition to the traditional analytical treatment planning systems that do not account for the loss of electronic equilibrium.

This simulation can be used, after some changes in the modelization of the geometry, to study also others medical linac's heads. This tools is publicly available with the public release of Geant4 as an Advanced Example.

REFERENCES

- [1] Geant4 Collaboration, *Geant4 - a simulation toolkit*, NIM A 506 (2003) 250-303
- [2] S. Chauvie, G. Depaola, V. Ivanchenko, F. Longo, P. Nieminen, M.G. Pia, *Geant4 Low Energy Electromagnetic Physics* Proceedings of CHEP 2001, Beijing (China), 337-340.
- [3] International Atomic Energy Agency, *Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water*, Technical Reports Series No.398, IAEA, Vienna (2000)
- [4] G.A.P. Cirrone, S. Donadio, S. Guatelli, A. Mantero, B. Mascialino, S. Parlati M.G. Pia, A. Pfeiffer, A. Ribon, P. Viarengo *A Goodness-of-Fit Statistical Toolkit* Transactions on Nuclear Science, 2004 in press.