

A GENERAL-PURPOSE DOSIMETRIC SYSTEM FOR BRACHYTHERAPY

F. Foppiano

IST, National Cancer Research Institute,
Largo Rosanna Benzi 10, 16132 Genova (Italy)
franca.foppiano@istge.it

S. Guatelli and M. G. Pia

INFN - Sezione di Genova
Via Dodecaneso 33, 16146 Genova (Italy)
Susanna.Guatelli@ge.infn.it, MariaGrazia.Pia@ge.infn.it

ABSTRACT

A general-purpose, object oriented software system has been developed for the simulation and dosimetric analysis of brachytherapy applications. The flexible object-oriented design makes this system very versatile, offering the possibility to configure it for different types of brachytherapy techniques (such as I-125 or Ir-192, for instance). The dosimetric system is based on the Geant4 Simulation Toolkit, allowing accurate geometry and material description and precise particle transport, down to low energies. These characteristics allow to simulate accurately effects such as the source anisotropy, and to calculate accurate dose distributions. The Geant4 Toolkit also gives access to various visualization systems, accessible through a variety of drivers, and, thanks to the object-oriented technology, allows an easy interface to powerful modern analysis system for dosimetric calculations. The accuracy of this Monte Carlo based dosimetric system has been verified through comparison with experimental data, concerning various brachytherapeutic sources and applicators: a selection of experimental validation results is presented. The dosimetric system is parallelized, to achieve fast computational results (dose distributions, isodose curves etc.), suitable to usage in clinical practice. The advanced technique adopted for parallelization allows transparent access either to a local computing farm, or to a geographically distributed computing GRID.

Key Words: Geant4, brachytherapy, accuracy, speed.

1 SOFTWARE SYSTEMS FOR RADIOTHERAPY

Radiotherapy is a widely used medical technology for cancer treatment; it exploits the biological effects of radiation on tissues to destroy tumour cells.

Two major techniques are distinguished in radiotherapy: external beam therapy and brachytherapy. In external radiotherapy a beam of ionising radiation is focused on the patient's target area, where the tumour is localised; in brachytherapy radioactive sources are positioned inside or close to the tumour to deposit therapeutic doses in the treatment target. According to the technique adopted for positioning the radioactive sources, one distinguishes endocavitary, interstitial and superficial brachytherapy.

Various commercial software systems are used in the clinical practice to plan the radiotherapy treatment. The clinical application requires the treatment planning software to

provide a fast response; this speed constraint is satisfied by the software codes adopting approximations at different levels. Dose distributions are calculated by means of approximated analytical methods; the experimental set-up is simplified, the patient's anatomy is approximated to water and, for instance, the radioactive sources used for brachytherapy are approximated to points, neglecting their real sizes.

No general-purpose commercial software system exists: for example, each brachytherapeutic technique and each type of source is handled by a specific software system. The absence of software systems of general applicability results in high costs to hospital, needing a variety of software equipment for the different applications of normal radiotherapeutic practice. Moreover, commercial software is not available at all for superficial brachytherapy to assist the medical treatment planning.

In the last forty years, Monte Carlo methods have been explored as an alternative to analytical methods for treatment planning, and various Monte Carlo based tools have been developed for radiotherapeutic studies. However, *de facto* Monte Carlo methods, even if widely recognised as more accurate than analytical approaches, are not used in clinical practice because of speed constraints.

Nowadays, the development of a general purpose dosimetric system, based on Monte Carlo methods, providing accurate dose calculation at speed adequate for clinical usage, represents a challenge, potentially capable of significant impact on the fight against cancer. A low cost solution would be desirable, to make the system accessible to a large number of hospitals, even small ones or in less wealthy countries. Openness to extension and evolution is an essential requirement too, to accommodate future improvements in the therapeutic techniques, as well as evolutions of the equipment.

2 A DOSIMETRIC SYSTEM FOR BRACHYTHERAPY

A novel prototype software system for dosimetry in brachytherapy has been developed, entirely based on software tools originally developed for high energy physics experiments. This prototype is part of a project of wider scope, aiming at developing a general-purpose simulation and analysis framework for medical dosimetry. The system adopts the object-oriented technology and has been developed following a rigorous software process, which contributes to software quality and reliability.

The system addresses various fundamental requirements: the capability to handle all brachytherapy techniques, an accurate model of the experimental set-up, a high precision in the dosimetric calculations, fast execution compatible with clinical practice, and a friendly user interface.

Its architectural design encompasses a simulation component, responsible for modeling the experimental set-up and the interaction of radiation with the biological tissues; the simulation is based on the Geant4 [1] Toolkit. The dosimetric information resulting from the simulation is elaborated and visualised by means of AIDA-compliant [2] analysis tools. The analysis component is responsible to produce and elaborate the quantities of clinical interest, such as dose distributions and isodose curves. The application is controlled through a simple web-based interface.

The execution can take place either sequentially on a single machine, or in parallel on different nodes. The system exploits an intermediate layer (DIANE [12]) to perform sequential

execution, parallel execution on a local computing farm or with distributed computing resources on a grid transparently. The parallelisation allows to achieve the execution speed adequate for clinical usage.

Thanks to the adoption of the object oriented technology, the dosimetric system can handle different brachytherapeutic techniques within the same software environment: this achievement represents a progress with respect to commercially available software products for treatment planning, that are specialised for a given therapeutic application. The extension to other radiotherapeutic techniques, such as conventional radiotherapy with extracted beams or hadrontherapy, is straightforward and currently in progress.

3 THE SIMULATION COMPONENT

The simulation component of the dosimetric system is based on the Geant4 Toolkit. Geant4 has been chosen as the basic tool for the dosimetric simulation, because it offers both accurate and powerful physics models and geometry modeling capabilities.

The Geant4 Low Energy Electromagnetic package [3] is especially relevant to medical applications: by extending the coverage of electromagnetic interactions below 1 keV, it allows to perform precise dosimetric studies. A variety of Geant4 capabilities, allowing to model the geometry and materials of the radiotherapeutic equipment as well as the patient in detail and realistically, makes it possible to describe the experimental set-up accurately in terms of biological tissues and geometrical structures. Last but not least, the transparency of physics implementation, clearly exposed in Geant4 through the design, allows to understand how the simulation results are produced, hence improving the validation of the physics results: this feature is especially relevant in sensitive applications, such as medical ones.

3.1 Modeling the radioactive sources

The brachytherapeutic sources are modeled in terms of their geometry (materials and volume shapes involved) and of the energy spectrum of the photons delivered by the radioactive core.

The characteristics of the radioactive sources are defined from manufacturer's data. While commercial software systems treat the radioactive sources as point-like, the dosimetric system developed models them realistically, taking into account the real size, geometrical shapes and materials both of the sources themselves and of the structures encapsulating them. The energy spectra of the emitted particles are also generated accurately.

The precise modeling of the brachytherapeutic source allows to reproduce the effects of the source anisotropy [6] in the simulation, and consequently in the dose distribution. Commercial software systems, make crude approximations about the source anisotropy; therefore they lack the capability to account for such effects.

The dosimetric system adopts an Abstract Factory design pattern [9] to treat any type of brachytherapeutic source in a completely general way. The system handles any source transparently through two abstract interfaces, responsible for the geometrical description and for the generation of the primary spectrum respectively; the Abstract Factory pattern allows the user to configure the application by instantiating the appropriate pair of concrete geometry and spectrum corresponding to a given therapeutic source.

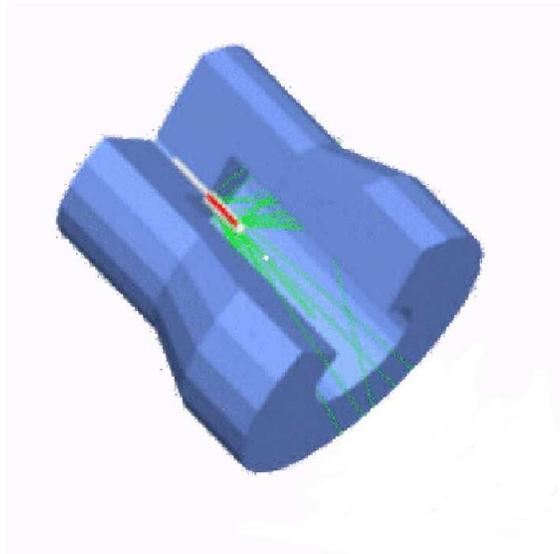


Figure 1: The geometrical model of a Leipzig applicator, enclosing a Ir-192 radioactive source, used for superficial brachytherapy.

3.2 Modeling the patient's target

The patient's target can be modeled either as a phantom or deriving the real-life geometry and material composition from a computerized tomography image.

The phantom is defined as a simple box volume; its size and associated material can be specified by the user. The material may be chosen among water, soft tissue, bone and muscle; the material composition is defined through the constituent elements, according to the chemical formula of the compound. The list of available pre-defined materials can be easily extended to include other compositions of medical interest.

An interface [7] to the Digital Imaging and Communication in Medicine (DICOM) standard, commonly adopted to code computerized tomography images, is available together with the public distribution of the Geant4 Toolkit. The DICOM interface exploits a feature of the Geant4 Geometry package, allowing to associate a material composition to a geometrical volume via a parameterisation function; the parameterisation encodes a relationship between a grey tone in the image and a corresponding material density.

3.3 Validation of the simulation

The validation of the simulation has been performed both at the microscopic and macroscopic level.

The microscopic validation consists in the verification of how Geant4 physics models compare to reference experimental data or well established databases, for the particle types and energy ranges involved in brachytherapy. A series of tests have been performed involving electrons, photons, positrons in order to guarantee the reliability of the physics models applied in the brachytherapy dosimetric system. A summary of relevant results is available in [4]; as an example, figure 2 shows the comparison of two Geant4 electromagnetic models with respect to

NIST protocol reference data for the photon mass attenuation coefficient in water. Direct

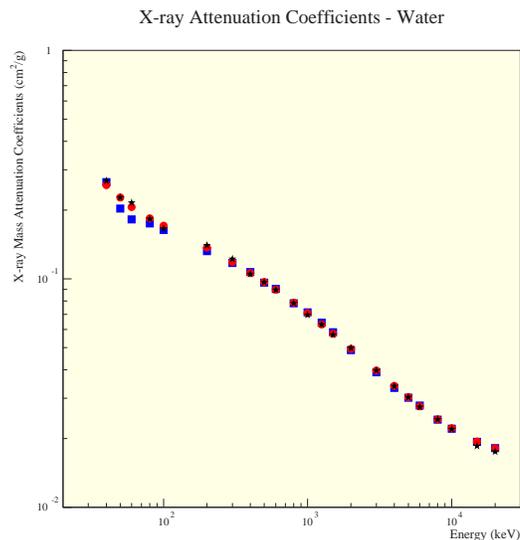


Figure 2: Photon mass attenuation coefficient in water: black star marks represent NIST protocol reference data, blue square marks are the results of Geant4 Standard Electromagnetic package, red circle marks are the results of Geant4 Low Energy Electromagnetic package.

validation of the dosimetric application has been performed by comparing it to experimental dosimetric measurements [6], [8] for an Ir-192 radioactive source Microselectron (used in superficial and endocavitary brachytherapy) and for a Bebig Iseed I-125 (used in interstitial brachytherapy). The comparison of simulation versus experimental data for a I-125 source are shown in figure 3.

4 DOSIMETRIC ANALYSIS

The results of the simulation relevant to dosimetric studies are stored in analysis objects like a two-dimensional histogram of the energy deposit in the plane containing the source, or a ntuple associating spatial coordinates and energy deposits. The relevant output of the simulation is stored in xml format. The dosimetric analysis elaborates the information produced by the simulation, as the energy deposited in the phantom, to produce distributions of interest in the clinical practice, such as 2-dimensional, colour-coded histograms of the dose in planes at various distances from the source, and isodose curves.

The adoption of the AIDA abstracts interfaces for data analysis allows to avoid the dependency on any specific external analysis system, and provides the system the flexibility to use different AIDA implementations interchangeably, simply loading shared libraries. The plot shown in Fig. 4 has been obtained using the AIDA-compliant Anaphe [10] analysis system, originally developed for the analysis of experiments at the Large Hadron Collider at CERN, to elaborate and visualise the dose distributions resulting from the simulation.

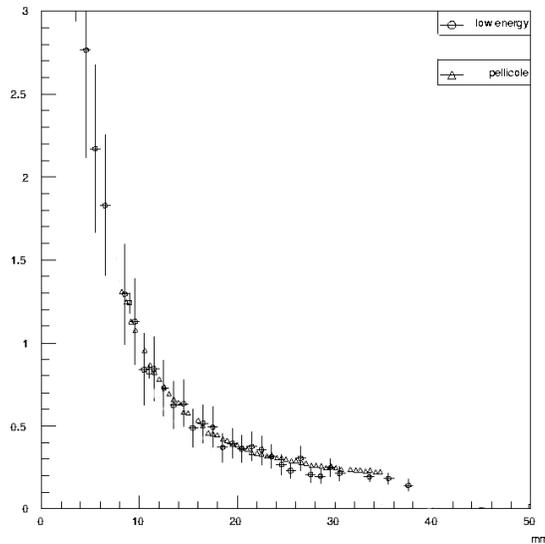


Figure 3: Dose as a function of distance: comparison of experimental data (triangle) and Geant4 simulation (circle) for a I-125 source used for prostate brachytherapy.

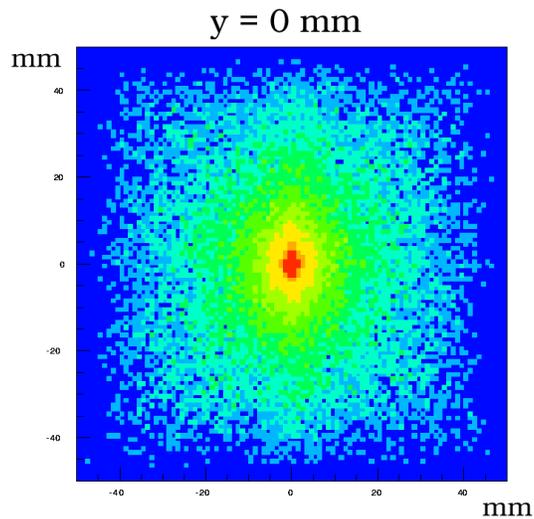


Figure 4: Dose distribution in a plane perpendicular to the radioactive source, elaborated with AIDA and Anaphe.

5 USER INTERFACE

A simple, user-friendly interface is especially important for a software system to be used in daily clinical practice in hospitals.

A simple command-line interface is available, through which the user can configure the

simulation application, choosing interactively the radioactive source to simulate, the absorber material of the phantom, the number of photons delivered by the radioactive core. The user may select alternative visualisation drivers to visualise the experimental set-up and particle tracks.

It is also possible to run the dosimetric system through a web interface and to retrieve a two-dimensional histogram with the dose distribution in the plane containing the source. Through the web interface the user can define the configuration of the application, specifying the type of the source, the phantom absorber material, the number of photons delivered by the radioactive core, and can submit the job. The user may select various modes to run the application: in a *demo* version, in parallel on a cluster, or on the GRID (currently under development). The result of the simulation will then appear on the screen.

6 PERFORMANCE STUDIES

Monte Carlo methods have never been used in clinical practice because, even if they are more accurate than available commercial software, the calculation time needed to accumulate sufficient statistics is too long for a realistic use in radiotherapeutic treatment.

The performance of the dosimetric system has been studied in three execution modes: sequential on a single dedicated machine, parallel on a dedicated computing farm, parallel on a Grid [11] test-bed. An intermediate software layer, the DIANE [12] system, makes the three execution modes completely transparent to the user, allowing to use the same code in any of the three configurations.

The execution time in sequential mode, requiring about one hour of CPU time on a Pentium III (1000 MHz) PC to simulate an adequate number of events, is prohibitive for clinical usage. The time needed to simulate the same statistics on a dedicated computing farm of 50 Pentium III PCs (500-1000 MHz) goes down to the order of 4 to 5 minutes: this demonstrates that the results in parallel mode on a dedicated farm of PCs may be compatible with clinical practice. The system requirements to achieve such performance are relatively modest, if compared to the financial investment required by commercial software (especially considering that the dosimetric system described is completely general, while commercial software is specialised for a single application).

As a further step, the dosimetric system has been run on a Grid testbed, thus collecting the necessary computing resources from geographically distributed sites. Further tests are still necessary for a quantitative evaluation of the performance in this mode, considering that the Grid is still under development; however, the feasibility of the approach has been demonstrated, and the generality of DIANE layer to shield the user from the complexity of parallel execution - either on a local farm or on geographically distributed resources - has been verified.

Thanks to the integration in the GRID, any hospital provided with web access can run the dosimetric application through a web portal, accessing distributed computing resources, shared with other hospitals and institutes belonging to the same virtual organization.

7 CONCLUSIONS AND OUTLOOK

A prototype of a general purpose dosimetric system has been developed, addressed initially to brachytherapy, but easily extensible to all the radiotherapeutic techniques, which achieves calculation accuracy and quick response. The functionality of the system derives entirely from

software originally developed for high energy physics experiments, demonstrating how different fields can profit of technologies originating from particle physics: the Geant4 simulation Toolkit, the AIDA analysis interfaces and their concrete implementation systems, the Web, the DIANE system for parallelisation and transparent access to distributed computing resources, the Grid.

The system is characterised by high accuracy in the simulation of physics processes, as well as in the geometrical and material modeling. The parallelisation of the execution, that the intermediate DIANE layer allows transparently either on a local computing farm or on distributed computing resources over the Grid, makes it possible to achieve precise results within the time constraints imposed by the clinical practice in hospitals. The integration in a Grid environment allows even small hospitals, or developing countries, to profit of advanced technologies and tools for radiotherapy, without needing any significant financial investment.

The Object Oriented technique makes it possible to extend the dosimetric system easily to all radiotherapy techniques. A set of of plug-in modules, to model the geometry and primary particle spectra specific to various medical dosimetry applications, is under development: an example of such modules is shown in figure 5, showing the geometry of a treatment head for IMRT (Intensity Modulated RadioTherapy) [13].



Figure 5: The geometry of a treatment head for Intensity Modulated Radio-Therapy (IMRT).

8 REFERENCES

1. S. Agostinelli et al., *Nucl. Instr. Meth., A* 506, 250 (2003).
2. G. Barrand et al., *CERN-IT-2001-013*.
3. S. Chauvie et al., Proceedings of CHEP 2001, Beijing, (2001).
4. G.A.P. Cirrone et al., “Validation of Geant4 electromagnetic physics”, *Proceeding of IEEE NSS 2003 Conference*, Portland Oregon, October 2003, (2003).

5. <http://www.nist.gov>.
6. M. Tropeano, Thesis, Univ. of Genova (2001).
7. J.L. Archambault, L. Beaulieu, J.F. Carrier, V.H. Tremblay, “Geant4 User Guide for Application Developers”, Version 6.2, (2004).
8. S. Guatelli, Thesis, Univ. of Genov (2002).
9. E. Gamma et al., “Design Patterns”, Addison-Wesley (2003).
10. O. Couet et al., *CERN-IT-2001-012*, (2001).
11. I. Foster and C. Kesselman, “The Grid”, Morgan Kaufmann, (2003).
12. J. T. Moscicki, *Nucl. Instr. Meth. A* 502, 426 (2003).
13. M. Piergentili, Thesis, Univ. of Genova (2004).