

## DISTRIBUTED PROCESSING, MONTECARLO AND CT INTERFACE FOR MEDICAL TREATMENT PLANNING

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We show how nowadays it is possible to achieve the goal of accuracy and fast computation response in radiotherapeutic dosimetry using MonteCarlo methods, together with a grid computing model. We present a complete, fully functional prototype system for brachytherapy, integrating a Geant4-based simulation, an AIDA-based dosimetric analysis, a web-based user interface, and distributed processing either on a local computing farm or on geographically spread nodes. Thanks to the object-oriented approach adopted for the architecture, the work presented can be easily extended to become a general purpose dosimetric system, capable to address all radiotherapeutic techniques.

## 1. Introduction

Radiotherapy is a widely used medical technology for cancer treatment; it exploits the biological effects of radiation on tissues to destroy tumour cells. Two different major techniques are distinguished in radiotherapy: external beam therapy and brachytherapy; their difference consists in how radiation is delivered to the patient. In the case of external radiotherapy, a beam of ionising radiation is focused on the patient's target area, where the tumour is localised. In the case of brachytherapy radioactive sources are positioned inside or close to the tumour to deposit therapeutic doses in treatment target, while preserving surrounding healthy tissues. According to the technique adopted for positioning the radioactive sources, one distinguishes endocavitary brachytherapy (exploiting natural body cavities to position the sources, for instance for lungs, vagina and uterus treatment), interstitial brachytherapy (for prostate carcinoma) and superficial brachytherapy (for skin tumors).

Various commercial software systems are available in clinical practice to plan the radiotherapeutic treatment. They adopt approximations at different levels, because of the speed constraints imposed by clinical practice. 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 the radioactive sources used for the therapy are approximated to points, ignoring their real sizes.

No general-purpose commercial software system exists: each brachytherapeutic technique and type of source is handled by a specific software system; this 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 challenge consists to develop a Monte Carlo application for brachytherapy - and, more in general, for radiotherapy - providing accurate dose calculation at speed adequate for clinical usage. Ideally, such a dosimetric system should be able to address all brachytherapy techniques, reproducing the experimental set-up in any

clinical case realistically, and it should be managed through a friendly user interface. 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. Architecture of the dosimetric system

A novel prototype system for dosimetry in the context of brachytherapy has been developed, entirely based on software tools originally meant for high energy physics experiments. The system adopts the object oriented technology.

The dosimetric system 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 <sup>1</sup> Toolkit. The dosimetric information resulting from the simulation is elaborated and visualised by means of AIDA-compliant <sup>2</sup> 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 <sup>11</sup>) 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.

The code is implemented in C++; at the present time the development platform is Linux, but porting to other platforms is foreseen.

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.

The Geant4 dosimetric system has been developed following a rigorous software process: this is an essential quality for the reliability of a product addressed to radiotherapeutic treatment.

### 3. The simulation for radiotherapeutic dosimetry

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 ample set of independent, alternative physics models for any type of particles available in Geant4 allows to develop a general purpose dosimetric system, capable to handle any radiotherapeutic technique. The Geant4 Low Energy Electromagnetic package<sup>3</sup> 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 manufacturers' data. While commercial software systems treat the radioactive sources as point-like, the dosimetric system developed models them realistically, taking into account the real sizes, 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<sup>5</sup> 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<sup>8</sup> 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.

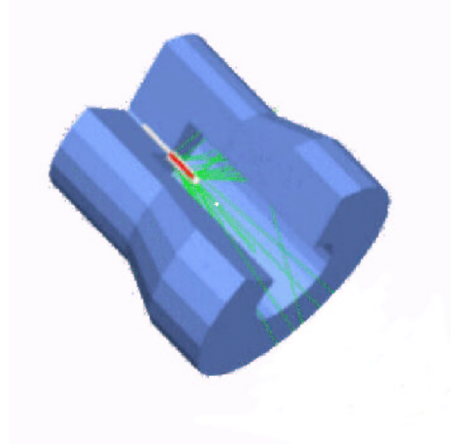


Figure 1. The geometrical model of a Leipzig applicator, enclosing a Ir-192 radioactive source, used for superficial brachytherapy.

### **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 model of the patient is especially useful for simple dosimetric studies, such as the characterization of the radioactive source or comparisons with experimental data for the purpose of software validation. 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 <sup>6</sup> 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 parameterization function; it allows to model a realistic description of the patient by importing the image data into a Geant4 geometry model defined in terms parameterised volumes (voxels); the parameterization 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 <sup>4</sup>.

Direct validation of the dosimetric application has been performed by comparing it to experimental dosimetric measurements <sup>5, 7</sup> for an Ir-192 radioactive source Microselectron (used in superficial and endocavitary brachytherapy) and for a Bebig Ioseed I-125 (used in interstitial brachytherapy).

## **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.

2 has been obtained using the AIDA-compliant Anaphe<sup>9</sup> 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; isodose curves are shown in Fig. 3.

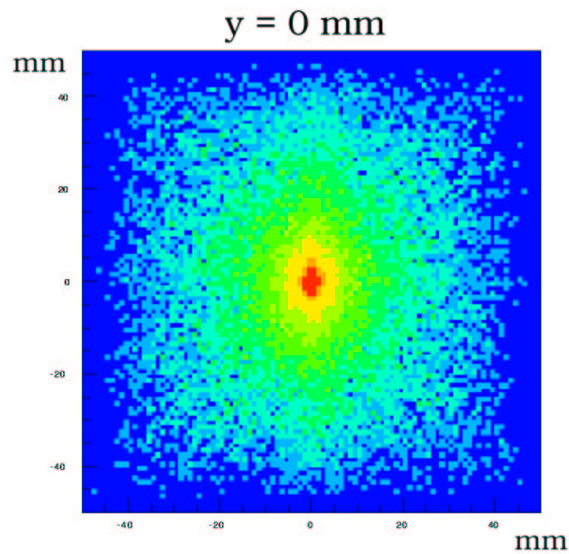


Figure 2. Dose distribution in a plane perpendicular to the radioactive source, elaborated with AIDA and Anaphe.

## 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

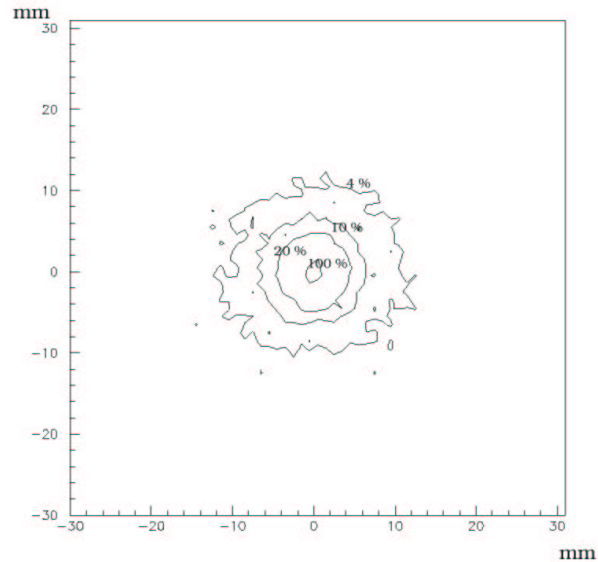


Figure 3. Isodose curves, resulting from the analysis of the dose distribution produced by the simulation.

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 Pentium III (1000 MHz) PC, parallel on a dedicated computing farm of 50 Pentium III PCs (500-1000 MHz), parallel on a Grid<sup>10</sup> test-bed. An intermediate software layer, the DIANE<sup>11</sup> system, makes the three execution modes completely transparent to the user, allowing to use the same code in any of the three configurations. The results in sequential and parallel execution modes are summarised in



tables 1 and 2.

Table 1. Performance times for different brachytherapeutic techniques in sequential mode, on a Pentium III PC.

Technique	Number of events generated	Execution time
Endocavitary brachytherapy	1 million	61 minutes
Superficial brachytherapy	1 million	65 minutes
Interstitial brachytherapy	5 millions	67 minutes

Table 2. Performance times for different brachytherapeutic techniques in sequential mode, on a farm of 50 Pentium III PCs, 500-1000 MHz each.

Technique	Number of events generated	Execution time
Endocavitary brachytherapy	1 million	4 minutes, 34 seconds
Superficial brachytherapy	1 million	4 minutes, 25 seconds
Interstitial brachytherapy	5 millions	4 minutes, 36 seconds

While the execution time in sequential mode is prohibitive for clinical usage, the results in parallel mode on a dedicated farm of PCs are 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 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

Thanks to the Object Oriented technique, it is possible to extend the dosimetric system to all radiotherapy techniques thanks to a plug-ins system.

In this way it is possible to offer a single tool which defines treatment plannings for all raditherapy devices.

Thanks to a modular design of physics processes, it is possible to choose interactively physics models more suitable for each specific radiotherapeutic treatment.

Such general tool is revolutionary in the medical physics context and it is under development in the Geant4 Medical Physics Group.

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. It is characterised by high accuracy in the simulation of physics processes, as well as in the geometrical and material modeling. 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 parallelization of the execution, trasparently through an intermediate layer either on a local computing farm or accessing distributed computing resources over the Grid, allows a Monte Carlo approach to deliver 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 dosimetric system is open-source, and based on open-source software systems.

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