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Assessment of Monte Carlo Geant4 capabilities in prediction of photon beam dose distribution in a heterogeneous medium

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ABSTRACT

The aim of this study is the assessment of the Geant4 capabilities in accurately modeling of dose distribution in a heterogeneous water phantom. In this purpose, a Geant4 user code has been designed and developed to enable an accurate modeling of cross beam profiles in a heterogeneous water phantom deposited by a 12 MV photon beam emitted by a Saturne 43 Linac head and configuring a 10 × 10 cm^2 radiation field. The calculated cross beam profiles at two distinct depths (22 cm and 25 cm), were compared to the ones obtained with MCNPX code. Our findings show that the shapes of dosimetric curves at two distinct depths calculated with Geant4 code and the ones obtained by MCNPX code are in a very good agreement. However, the Geant4 code seems painfully slow when calculating those dosimetric curves and its associated statistical uncertainties don't seem to reach 1% after two weeks of calculations. To deal with this issue, we suggest that a new variance reduction technique specially addressed for dose calculation in a heterogeneous medium must be developed by the Geant4 collaboration, in order to decrease the required computing time and to improve the statistical of calculations.

1. Introduction

For many years, there are many manufacturers around the worlds which intent to fabricate radiotherapy treatment machines that accelerate electron beams at high velocity called medical linear accelerators or Linacs. The medical device used in this work is a Saturne 43 Linac which uses photon beam that has a quality of 12 MV and configuring 10 × 10 cm^2 radiation field.

Geant4 Monte Carlo code [1] is one of powerful Monte Carlo codes applied nowadays in physics by many scientific researchers to accurately simulate complex geometry in order to study the radiation interaction with matter as well as particle transport. The application of this code has been largely achieved in a wide range of physics areas, one of them is a medical physics area, especially the radiotherapy field. The most of research papers [2–4] intent to validate the Geant4 Monte Carlo code for a variety types of medical linear accelerators used in radiotherapy, thereby comparing dose distribution curves with ones measured in a homogeneous water phantom by using the Gamma Index comparison method [5]. However, the heterogeneous water phantom by a megavoltage photon beam is seems as forsaken research subject. To our knowledge, this feasibility study is the first one assesses the capabilities of Monte Carlo Geant4 in the prediction of dose distribution in a heterogeneous medium.

The aim of this work is to evaluate the accuracy of Geant4 in simulating dose distribution in a heterogeneous water phantom. The heterogeneous medium considered in this study is mediastinal localization. In order to establish this goal, The Monte Carlo MCNPX v. 2.5 code [6] has been taken as reference code for our study, which is considered as the most potential Monte Carlo code and has the ability to handle complex geometries used in many physics applications. The code is an extended version of MCNP4C developed and continuously updated by Los Alamos National Laboratory in USA. It can track about thirty four types of particles, including photons, electrons, neutrons and protons with energy from KeV to GeV. The calculated dosimetric curves for two distinct depths have been compared to the ones obtained with MCNPX code and extracted from unpublished works of Zoubair thesis [7].

2. Material and methods

In our previous work [3] we have successfully performing an accurate Geant4 model of a 12 MV photon beam in a homogeneous water phantom. The megavoltage photon beam is emitted by a Saturne 43 Linac treatment head configuring a 10 × 10 cm^2 radiation field. The simulation of this medical device was done according to the manufacturer's specifications, taking into account the following elements:

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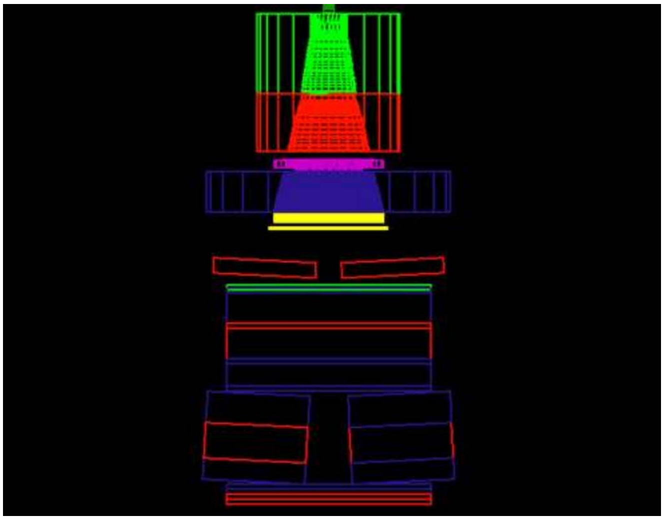

Fig. 1. Visualization of Linac Saturne 43 treatment head geometry by means of HeppRep visualization system.

invariant elements (Titanium window, primary collimator, secondary collimator, ionization chamber and aluminum plaque), elements which strongly depend on the selected irradiation energy (target and flattening filter) and others that depend on the shape of the beam (removable jaws). Fig. 1 shows our Geant4 model of the accelerator treatment head.

The validation of Monte Carlo Geant4 code for Linac Saturne 43 has been successfully done by performing three main steps. The first step was the design and development of Geant4 user code addressed specially for creating an accurate Geant4 model of a megavoltage photon beam emitted by Linac treatment head, assuring a high precision model of all relevant components of a Linac treatment head. For this purpose, a number of C++ classes have been developed from scratch in aim to implement the adequate physics, material properties, geometry specifications, source characteristics and all routines required for generating phase-space data. The second step was the design and development of another Geant4 user code for calculating dosimetric curves in a homogeneous water phantom. Also, a number of C++ classes have been developed for performing this task and representing all simulation components for characterizing the physics, geometry and materials of phantom, and for reading phase-space data. The two user codes developed in the two above steps were coupled to perform a part job of the third step. Thus, the Monte Carlo simulation was split into two stages, in the first one we store the simulation outline in a phase-space file recorded just after jaws components. The phase-space files generated during the beam characterization have been used as input data to finally calculate the dose distributions in homogeneous water phantom with dimensions of $40 \times 40 \times 40$ cm^3. The third step aimed to design a new methodology for adjusting all parameters related to the source characteristics for a 12 MV photon beam by comparing calculated dosimetric curves with measured the ones.

In the present work we attempt to replace the homogeneous water phantom with one containing a sort of heterogeneity. The Phantom configuration with inclusion of lung heterogeneity has been specifically defined. In Fig. 2 we show the geometry of a heterogeneous water phantom considered in this study; it is about mediastinal localization. In aim to perform this study, the program which calculates dose delivered in phantom has been changed to take into account the heterogeneity of the medium, and it capable to enable an accurate modelization of 12 MV cross beam profiles. The accuracy of the calculated dosimetric beam data is highly dependent on the hardness of the Geant4 model, including the physics, material properties, geometry specifications, source characteristics. The electron source characteristics have been adjusted during our previous study by following our

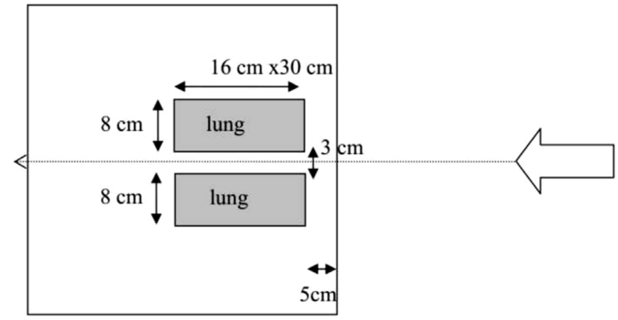

Fig. 2. Heterogeneous water phantom geometry [9].

own methodology. The heterogeneous medium is irradiated by a megavoltage photon beam emitted by Linac treatment head, where the optimized electron source parameters are: mean energy, sigma and its full width at half maximum, are 11.5 MeV, 0.4 MeV and 1.177 mm, these optimized parameters are founded during the adjustment phase. The modelization of photons and electrons transports through heterogeneity has been done by considering the following interaction processes: Compton Scattering, Gamma Conversion, Photo-Electric Effect for photons, Multiple Scattering, Ionization and Bremsstrahlung for electrons and positrons. The Geant4 code provides several physics models, including emstandard_opt0, emstandard_opt1, emstandard_opt2, emstandard_opt3, emlivermore and empenelope. The emstandard_opt2 model has been optimized to model the transport of photons and charged particles for radiotherapy applications. This model has been chosen to model the physical phenomenon involved by radiation interaction in a heterogeneous water phantom. Concerning the cut production, its value was set to 10 µm for photons as well as for electrons/positrons, according to the recommendation of Perrot [8].

The phantom was irradiated with a field size of 10 cm $\times$ 10 cm, maintaining the source-to-surface distance (SSD) equal to 100 cm. The upper surface of this heterogeneity was placed at 5 cm depth from the water surface. The calculation of cross beam profiles have been performed under the same detecting conditions as the ones involved with MCNPX code in the work conducted by Zoubair [7]. Indeed, we used a detection volume assembling a uniform scoring voxels of $0.1 \times 0.1 \times 0.1$ cm^3 dimensions. The voxelized phantom size were 9.1 cm, 0.1 cm, 0.1 cm, along x, y and z respectively. The number of voxels were 91, 1, 1 along x, y and z respectively. The reference data are obtained from unpublished work of Zoubair [7], which investigated the feasibility of MCNPX code in the calculation of cross beam profiles (at two distinct depths) in a heterogeneous water phantom irradiated by 12 MV photon beam emitted by Saturne 43 Linac treatment head. These dosimetric curves were obtained after simulating 12.10 10 particles stored in phase-space file containing 30 million of particles representing the 12 MV beam data relative to an electron beam hitting the X-ray target with the following parameters: a mean energy, sigma and its full width at half maximum of 11.4 MeV, 0.5 MeV and 1.7 mm, respectively. The global photon cut-off energy was set as 60 KeV. This energy was used as the bremsstrahlung creation threshold and photon transport cut-off. The global electron cut-off energy was set to 120 KeV. This energy was used as the ionization creation threshold and the electron transport cut-off. The calculated beam data with MCNPX code have been achieved within a global statistical uncertainty less to 1%.

3. Results and discussion

After four days of computation on a computer cluster consisting of 8 CPUs, we obtained the calculated dose profiles in a heterogeneous medium at two distinct depths: 22 cm and 25 cm. The phase-space was recycled 24 times and the number of simulated events was 2.5 10^7, in total 6 10^8 particles have been simulated. Figs. 3 and 4 give