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Geant4 used in medical physics and hadrontherapy technique

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Abstract This article mainly presents the application of Geant4 package (Geant4.7.0, 2005), developed by CERN (the Center of European Research of Nucleus), in medical physics and a novel technique, namely, hadrontherapy. The distribution of energy deposition in a water model by different radiation beams was also given. The results show that the distributions for proton beams are completely different from those for other radiation beams. Charged particles like protons exhibit little scattering when they penetrate the matter and give the highest energy deposition near the end of their range just before they reach the resting state. These characteristics permit very precise control of the shape of the energy distribution inside the patient's body.

Key words Geant4, Hadrontherapy, Radiation energy distribution, Energy deposition

CLC numbers TN25, O571.33

1 Introduction

In recent years, Geant4, a toolkit designed initially for simulating nuclear and high-energy physics experiments, has been widely used in several analysis including radiation analysis, space and cosmic ray analysis and, more recently, medical oncology analysis and evaluations [1]. The toolkit is based on the object-oriented technology. It provides transparency for implementation of various physics parameters.

Geant4 includes a complete range of functionality including tracking, geometry, physics models and hits. The physical processes cover a comprehensive range, including electromagnetic, hadronic and optical processes, a large set of particles with long half-life, materials and elements, over a wide-energy range starting, in some cases, from 250 eV and extending, in others, to TeV energy range. It has been designed and constructed to describe the physics models utilized, to handle complex geometries, and to enable its easy adaptation for optimal use in different sets of applications [2]. A low-energy limit for particle interaction corresponding to the minimal energy within the validity range of the models is not possible. A higher threshold for any specific application can be alternatively defined by the user.

Geant4 is supported under various operating systems. In the simulation described by the authors of this study, the simulation under Linux (Redhat 8) has been used. The simulation was run on Pentium-IV personal computers.

2 Geant4 used in medical physics

The development of Geant4 medical physics applications originated from the collaboration between Geant4 Developers and Medical Physics Groups [1]. The applications of Geant4 in medical physics included the following three aspects: material and geometry modeling, detector modeling, and physics modeling.

2.1 Materials and geometry modeling

It is not necessary to approximate human tissues to water for dosimetry. Geant4 provides accurate description of homogeneous and heterogeneous materi-

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als of human tissues. Example: how to define "bone":

density = 1.85 g/cm^3;

bone = new G4Material ("bone", density, Elements = 8);

bone -> Addelement (elH, 0.063984);

bone -> Addelement (elC, 0.278);

bone -> Addelement (elN, 0.0274);

bone -> Addelement (elO, 0.410016);

bone -> Addelement (elMg, 0.002);

bone -> Addelement (elP, 0.07);

bone -> Addelement (elS, 0.002);

bone -> Addelement (elCa, 0.147); [3]

It is necessary to define all the elements before the description. Geant4 also offers volume parameterization, which is used to model complex geometries with variable volume characteristics depending on one or more parameters, and to geometrically model the anatomy.

2.2 Modeling of phantom

How to define a phantom geometry? A detector geometry in Geant4 is made of a number of volumes. The largest volume is called "World" volume. It must contain, with some margin, all other volumes in the detector geometry. The other volumes are created and placed inside previous volumes, including in the "World" volume. Each volume is created by describing its shape and its physical characteristics, and then placing it inside a containing volume [4].

Then how to retrieve the energy deposit in a phantom? First, define a phantom such as a water box and then set it as a sensitive detector. Now it is possible to retrieve the energy deposit of primary particles and all the secondary particles generated in the detector.

2.3 Physics models

Geant4 offers alternative and complementary physics models both in electromagnetic and hadronic physics. The physics processes are available for photons, e-, e+, hadrons, and ions. To avoid infrared divergence in Geant4, some electromagnetic processes require a threshold below which no secondary particles will be generated. The range threshold should be defined in the initialization phase using the SetCuts() method of G4VUserPhysicaList.

2.4 A simple example

A simulation is done for a phantom of water box by Geant4. The geometry in our simulations can be described by Fig.1. Four different radiotherapeutic sources: 10 MeV electrons, 5 MeV X-ray beam, 14 MeV neutrons, and monochromatic 200 MeV proton beams, are used in the Geant4 simulations. The phantom has 200 slices of water, and the slices are 0.5-cm thick cylinders with 1 cm radius, along the beam's central axis. The SSD (Source to Surface Distance) for the source of 5-MeV X-Ray beam and 14-MeV neutrons is set to be 100 cm. For the Geant4 simulations, a total of 5×10^6 primary events are simulated for all the energies. The production threshold is set to 10 μm for all particles. We give the relative contribution in the result; therefore, we have the energy deposition divided by the maximum value, respectively.

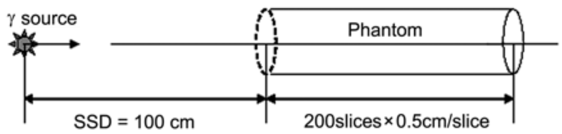

Fig.1 Sketch map of the geometrical structure of the model.

Fig.2 presents the comparison of the relative energy deposition in water for different radiotherapeutic sources. We will analyze the results in the following sections and will also show that Geant4 can be a credible toolkit for medical physics.

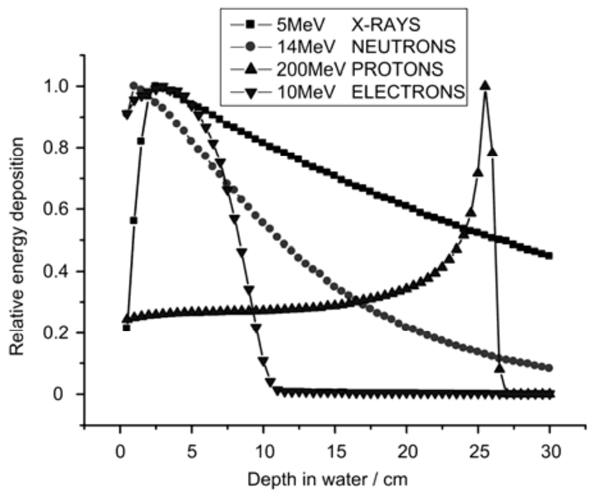

Fig.2 Relative energy depositions in water for different radiotherapeutic sources.

3 Hadrontherapy technique

The technique is based on the same fundamental facts that when any form of ionizing radiation is used for radiotherapy, it causes changes in the atoms of diseased cells, which lead to changes in those cells and cause them to die or stop functioning. It offers an excellent means of noninvasively treating patients with localized cancers, and, owing to fewer side effects, patients usually experience better quality of life after proton/ion treatments than after other forms of radiation. The twin goals of controlling disease and minimizing side effects are the classic aims of radiation treatment; hadrontherapy enhances the opportunity for both. In the recent years, many Monte Carlo applications with regard to proton/ion therapy and based on the Geant4 toolkit have been developed [5].

The main advantage of the use of protons and ions in radiotherapy relies on the energy distribution curve obtained when the particles traverse tissues, which can be seen clearly from Fig.2. The depth – energy curve for proton beam is completely different from those of other radiation beams, i.e. photons and electrons, used in radiotherapy. Charged particles like protons exhibit little scattering when they penetrate the matter and give the highest energy near the end of their range just before reaching the resting state. This is the well-known “Bragg Peak”. These characteristics permit the precise control of the shape of the distribution of energy deposition inside the patient’s body.

Figs.3 and 4 show the energy deposition in water for different incident energies of proton source. It can be seen that proton beams of different energies have a low “entrance energy” (the energy deposition in the front of the phantom), a high-energy “Bragg Peak” region, and no “exit energy” beyond the phantom, while X-ray or electron beams may deposit most of their energy in the front of the phantom. It can also be seen that the position of the “Bragg Peak” is changed with the incident energy, which allows control of the deposition of radiation energy with modulated beam. For example, a 15cm-depth tumor can be treated using a 40-MeV proton source roughly according to Fig.4. All these characteristics are in accordance with previous work [6,7]. Fig.5 shows the energy deposition in water with simple continuous energy of proton beams.

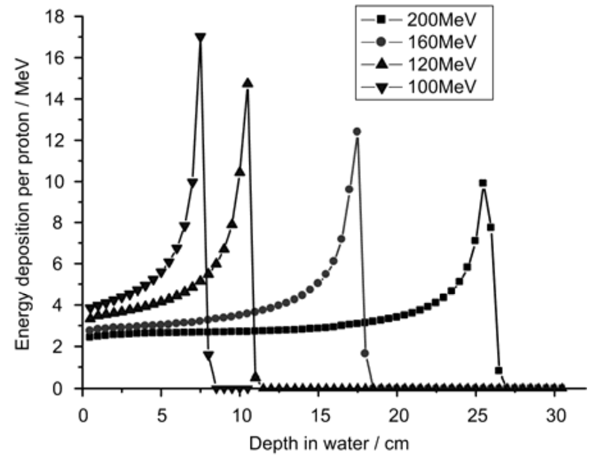

Fig.3 Energy deposition in water for different incident energies of proton source (1).

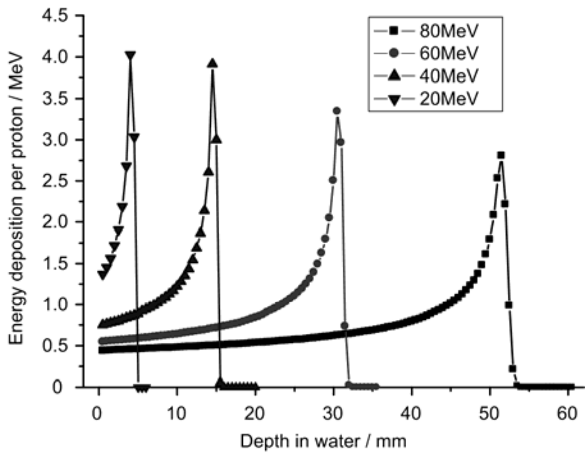

Fig.4 Energy deposition in water for different incident energies of proton source (2).

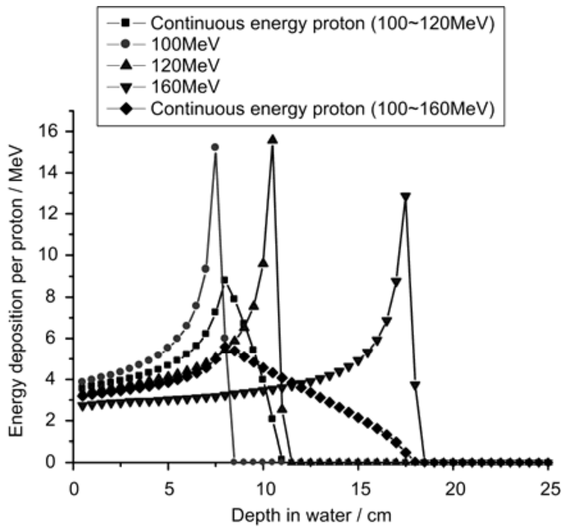

Fig.5 Energy deposition in water for simple continuous energy of proton source.

4 Conclusions

Geant4 enables to model accurately human anatomies, beam lines, radioactive sources, phantoms, detectors and the electromagnetic, hadronic physics for photons, e-, e+, p, n, alpha particles, and heavy ions. Geant4 is used as a MC toolkit in a wide set of medical physics applications, both in radiotherapy and in diagnostics. An elementary simulation for medical physics is done and it can be found that the deposition of radiation energy by protons is very different from that by X-ray or electron beams. A proton beam has a high-energy "Bragg Peak" region, which permits the precise control of the shape of the distribution of the energy deposition inside the patient's body.

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