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Monte Carlo Simulations of Human Phantom for Hadron Therapy Applications

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Monte Carlo simulations Geant4 plays a key role in simulating the artificial human phantoms for hadron therapy application. In this work, two human phantoms, MIRD and ICRP110, are simulated using Geant4 simulations. The energy loss as a function of organ ID is also simulated and analyzed using ROOT analysis. A proton beam's radiation dose in the ICRP110 human phantom is simulated as a Bragg curve.

Keywords: Monte Carlo simulations, Human Phantom, MIRD, Energy loss.

1. Introduction

The Geant4 applications of MIRD Phantom and ICRP110_HumanPhantom [1] has recently been implemented as an advanced example in version 10.7 of the Geant4 Monte Carlo Toolkit [2]. The Geant4 is a platform for "simulating the passage of particles through matter" using Monte Carlo methods. It is the successor of the GEANT series of software toolkits developed by The Geant4 Collaboration, and the first to use object-oriented programming. The advanced example implements the adult male and adult female voxelised phantoms published in the ICRP110 [3]. It allows the estimation of radiation doses to single voxels and phantom organs from any radiation field incident on the phantom. In this study, the MIRD phantom and ICRP110_HumanPhantom are simulated and estimate the phantoms' voxel, energy loss, and radiation doses in each organ of human phantom.

2. Geant4 Simulation of Human Phantom

In this section, a systematic construction of MIRD human phantom and ICRP110 human phantom using Geant4 simulations are discussed in detail.

2.1 Geometry Construction of MIRD Human Phantom

Building a human phantom in Geant4 simulation is handled through the builder design pattern. The creation of coherent models of the human phantom is handled through an Abstract Factory design pattern. The organs of the MIRD phantom [4] are implemented in hard code. The organs of the ORNL phantom [5] are handled through GDML (Geometry Description Markup Language) [6]. The materials of the MIRD model are defined in the class G4HumanPhantomMaterial. The materials of the ORNL model are defined in the GDML files.

2.2 Primary Particle Generation and Physics List

The G4 General Particle Source is used to generate the primary radiation field. The primary radiation field is defined in macro files. In simulation, particles such as charged particles, gamma, and geantino are used. Further, the Physics list, for example, electromagnetic processes, are modeled. The threshold of production of secondary particles is set to 1mm.

3. Results

3.1 Simulated MIRD Human Phantom

The figure 1 shows the complete simulated MIRD female human phantom without beam on (left) and with beam on (right)

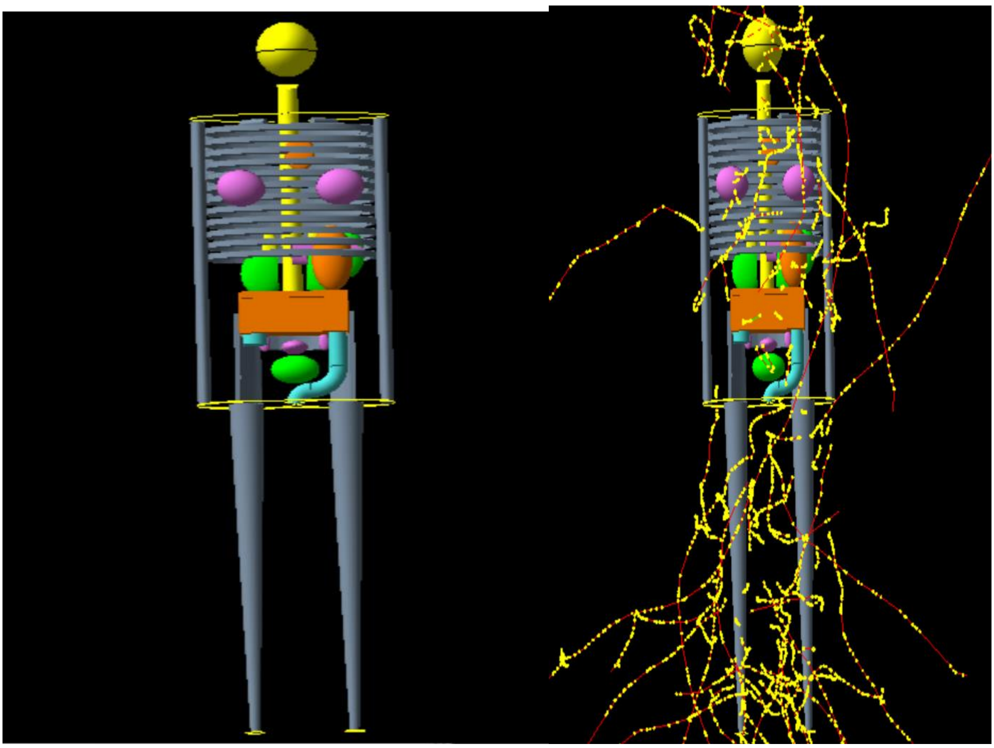

Figure 1 (MIRD Human Phantom (left) without beam On (right) with beam On in Geant4 simulation.

3.2 Energy Deposited

The energy deposit is calculated in the organs of the phantom. At the end of the simulation execution, a summary of the total energy deposit in each organ is obtained. The physics analysis of energy loss is carried out using ROOT software [7], where Energy deposited in each body part is stored in Ntuple.

The radiation dose is calculated by dividing the energy loss by organ body mass through which radiation dose is calculated. The results of energy loss as a function of organ ID inside human body is shown in figure 2.

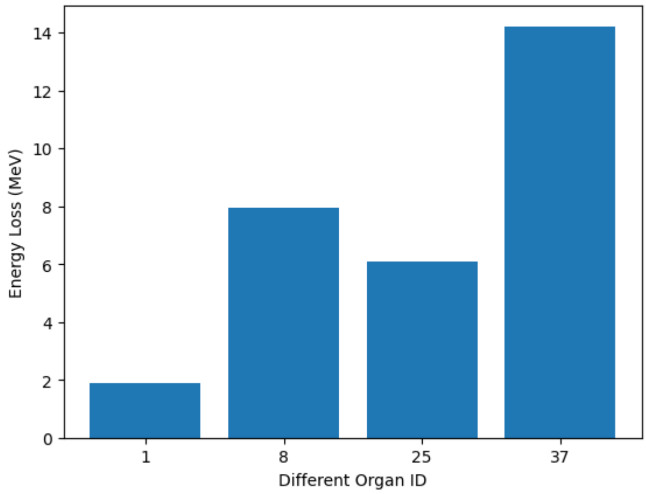

Figure 2: Energy Loss vs different organ ID.

3.3 Simulated ICRP 110 Human Phantom

The 3D model of the ICRP Reference Female voxel phantoms in Geant4 simulation via the G4ICRP110 Phantoms application is shown in figure 3. From figure we can clearly see different components of body parts such as the stomach, bladder, heart, lungs of female phantom. A pencil beam of proton of the kinetic energy of 125MeV is simulated and passed through the ICRP110 phantom's left breast, directed along the sagittal axis of the chest phantom, and then passed through the lungs and heart. The pencil beam of the proton travels from the front to the back side of the phantom along the positive direction (Y axis). The simulated setup of the ICRP110 phantom nicely demonstrated the dose retrieval capability of the ICRP110P phantoms for hadron therapy applications.

The resulting in Bragg peak is determined by the dose calculated from the energy deposited by the proton beam in the chest phantom at various depths, which is recorded via the scoring mesh of the ICRP110 phantom in Geant4 simulations.

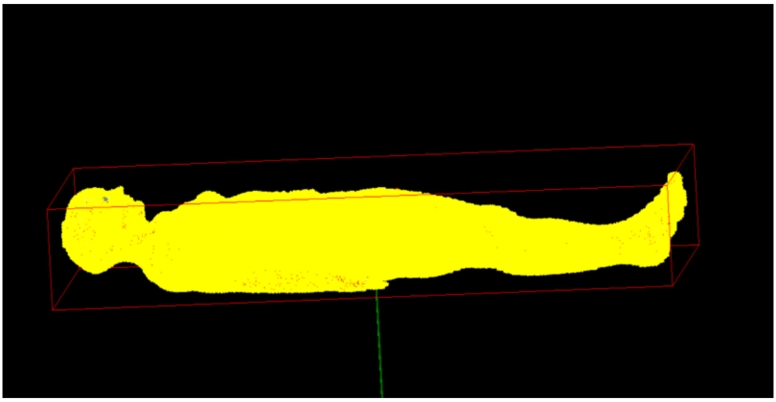

Figure 3: Simulated ICRP 110 human phantom with Geant4 simulation.

3.4 Bragg Peak from Bethe Bloch mechanism

When the charged particles, for example, protons, alpha particles, and heavy ions, interact with detector material, they lose their energy, while passing through material through the process of ionization. This energy loss is described by the Bethe-Bloch equation (1) [8].

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right], \quad ....(1)$$

The Bragg Curve represents a graph of the energy loss rate, or Linear Energy Transfer (LET), as a function of the distance through the material. The energy loss is characterized primarily by the square of the nuclear charge, Z, and the inverse square of the projectile velocity, β. This gives the Bragg Curve its familiar shape, peaking at very low energies just before the projectile stops. This Bragg Peak give makes ion therapy advantageous over X-ray treatment for cancer. The bragg curve for proton beam is shown in figure 4.

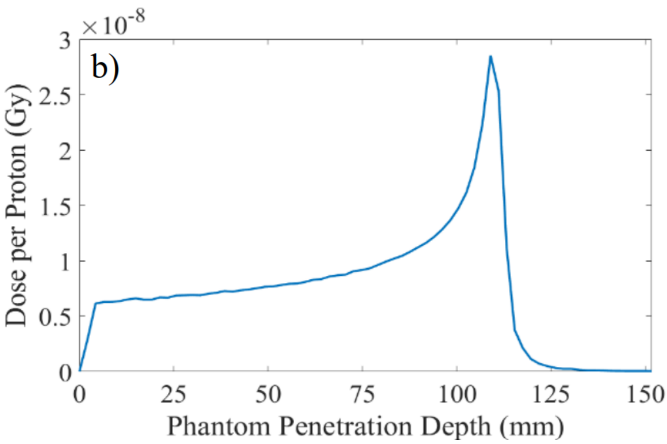

Figure 4: Dose per proton as a function of phantom penetration depth.

4. Summary and Conclusions

Using Monte Carlo simulations Geant4, the MIRD human female phantom is simulated in a Geant4 environment. The energy loss as function of organ ID is also simulated and analyzed using ROOT analysis. Further, the ICRP human phantom is also simulated. The radiation dose by a proton beam is simulated and interpreted as a Bragg curve. This study is useful for treatment of hadron therapy applications.

Acknowledgments

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