



Behaviors of the percentage depth dose curves along the beam axis of a phantom filled with different clinical PTO objects, a Monte Carlo Geant4 study

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HIGHLIGHTS

- Assessment of the capabilities of Geant4 code to reproduce the PDD curves in heterogeneities.
- Resolving artifacts due to the electron transport.
- Understanding in dose distribution differences in interfaces which include water, bone, and lung interfaces.

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ABSTRACT

The aim of this work is to assess the capabilities of Monte Carlo Geant4 code to reproduce the real percentage depth dose (PDD) curves generated in phantoms which mimic three important clinical treatment situations that include lung slab, bone slab, bone-lung slab geometries. It is hoped that this work will lead us to a better understanding of dose distributions in an inhomogeneous medium, and to identify any limitations of dose calculation algorithm implemented in the Geant4 code. For this purpose, the PDD dosimetric functions associated to the three clinical situations described above, were compared to one produced in a homogeneous water phantom. Our results show, firstly, that the Geant4 simulation shows potential mistakes on the shape of the calculated PDD curve of the first physical test object (PTO), and it is obviously not able to successfully predict dose values in regions near to the boundaries between two different materials. This is, surely due to the electron transport algorithm and it is well-known as the artifacts at interface phenomenon. To deal with this issue, we have added and optimized the StepMax parameter to the dose calculation program; consequently the artifacts due to the electron transport were quasi disappeared. However, the Geant4 simulation becomes painfully slow when we attempt to completely resolve the electron artifact problems by considering a smaller value of an electron StepMax parameter. After electron transport optimization, our results demonstrate the medium-level capabilities of the Geant4 code to modeling dose distribution in clinical PTO objects.

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1. Introduction

In our earlier paper (EL Bakkali et al., 2013) we have successfully adjusted and validated the Monte Carlo simulation parameters of our Geant4 model that has been addressed for calculating dose distributions in a homogeneous water phantom which was irradiated by a 12 MV photon beam that emerges from the

simulated Saturne 43 radiotherapy unit. The adjustment and the validation tasks have been carried out by comparing the calculated dosimetric functions with measured ones, thanks to the Gamma Index comparison method (Low and Dempsey, 2003). Due to our accurate Geant4 model, we were able to reproduce the dosimetric functions within 1.5%–1 mm accuracy. This accuracy is better than one proposed by AAMP (the American Association of Medical Physics) which is fixed at 2%–2 mm (Chetty et al., 2007). The success of our Geant4 model that was addressed for calculating dosimetric functions in a homogeneous water phantom has encouraged us to study more complicated situations, which are generated in the cases of introducing a sort of heterogeneities into

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a homogeneous water phantom. In the study, our main subject is to assess the capabilities of the Monte Carlo Geant4 code to accurately model the photons and electrons transport through heterogeneous mediums (which are filled with different materials and having different densities) and to identify any limitation of dose calculation algorithm implemented in Geant4 code. The reason for doing such study, is given as flows: In the clinical practice, the treatment planning systems (TPS) perform dose calculations in different tissues composed the human body (heterogeneous medium). The dose distributions are strongly modified by the presence of these tissues when the latest ones were irradiated by high-energy photon beams. The attenuation of these high-energy photon beams vary with respect to the properties of the traversed structure (Bone, lung, muscle, etc.) and this results essentially from the Compton scattering process. Such clinical Monte Carlo code must take into account the presence of this heterogeneities to achieve an exact calculations of dose through its. Building a clinical Geant4-based code requires two major challenges. The first one is the adaption of physics model, especially its particle transport algorithm for medium including a set of heterogeneities. Whereas, the second one is optimizing computing time spent by a given Geant4 simulation which is practically huge and enormous, the Monte Carlo code generates clinical plans in less than one hour in such manner.

In this work, we have developed a Geant4 model for calculating PDD dosimetric functions into phantoms filled by a lung-equivalent slab, bone-equivalent slab, and bone-equivalent-lung-equivalent slab, which mimic three important clinical sites. In our first attempt to calculate a PDD dosimetric function in phantom which includes a lung-equivalent slab, we have observed a nological predicted values of dose in regions near to the boundary between two distinct materials. This numerical phenomenon is known as artifacts at interfaces, and it was observed previously by many scientific researchers. Indeed, in their research paper (Poon and Verhaegen, 2005), when Poon and Verhaegen attempt to validate the photon and electron transport algorithms implemented in the Geant4 particle simulation toolkit for radiotherapy physics applications, they observed an electron step size artifacts that reflected many potential problems with the use of the condensed history algorithm in Geant4 code. To deal with this issue, they claimed that a careful selection of Geant4 physics processes and transport parameters must be applied indistinguishably. For well-explicating the artifacts at interfaces phenomenon, we considered the following example. It's well-known that in the Geant4 philosophy, the step has two distinct points, namely: the PreStepPoint point and the PostStepPoint point. Supposing, an electron is located near to the interface between two regions filled with different materials, the PreStepPoint and PostStepPoint can be located simultaneously in different materials. This consequently can conduct to obtaining a simulated electron trajectory more or less different to the real one depending on the electron step size. Due to the fact that, an accurate calculation of energy lost when electron traversing a given medium, exponents that, the Stopping Power along a given step must be constant, the accuracy related to the modeling of an electron transport in such case is primordial for assuring an exact calculation of dose distributions in a medium which includes a sort of heterogeneities. This accuracy will not be guaranteed until the step size becomes fine (passage from the condensed histories to the detailed histories algorithm); consequently an enormous CPU time is required to achieve this request.

2. Materials and methods

2.1. The Geant4 code description and verification

The Monte Carlo method is an accurate technique used in the simulation of the emerging of particles through the treatment head of a linear accelerator (LINAC) and also in accurately predicting the absorbed dose distributions. Today, we can find several general purpose Monte Carlo based-codes used for radiation transport simulation such Electron Gamma Shower Version 4 (EGS4), Monte Carlo N- particle (MCNP), PENELOPE and Geant4 (Agostinelli et al., 2003). The Monte Carlo Geant4 toolkit is a simulation C++ toolkit for the simulation of the passage of particles through matter. It is widely used in medical and space science, high energy and accelerator physics applications. It was developed primarily for high-energy physics discipline, meeting the efforts of the hundred of developers from CERN in Europe, KEK in Japan and SLAC in the United States. The Monte Carlo Geant4 code simulates a physical evolution of each particle using the step-by-step approach. It has well-developed components to model the geometry and materials, the particles of interest, the generation of primary particles, the tracking of particles through materials and also through external electromagnetic fields, the physics processes governing particle interactions and the visualization of the particle trajectories.

The Monte Carlo Geant4 has been successfully validated in medical area, its applications includes brachytherapy (Poon et al., 2006; Ababneh et al., 2014) and external radiotherapy (Arce et al., 2009; Andelson and Lilian, 2013).

2.2. The simulated PTO objects

The PTO objects are used generally to reproduce the majority of interfaces encountered during radiotherapy treatment, namely: water-bone, water-lung and water-bone-lung interfaces. Its utilization can verify the calculation of doses in heterogeneities and near to the boundary between different materials.

The lung-equivalent and bone-equivalent slab geometries have been used to verify dose calculation algorithms along the z-axis. The three modeled PTO objects are:

- Object A (water-bone-water)
- Object B (water-lung-water)
- Object C (water-bone-lung-water)

The materials data (chemical compositions and densities) related to the bone-equivalent and lung-equivalent slabs which define the three above PTO objects are shown in the Table 1.

The three heterogeneous phantom geometries studied in this work are shown in Fig. 1. Regarding the objects A and C, the lung-equivalent slab has a dimension of $30 \times 30 \times 10 \text{ cm}^3$, whereas objects B and C including a bone-equivalent slab are of $30 \times 30 \times 2 \text{ cm}^3$ dimension.

2.3. Monte Carlo simulation of the PTO objects

Our Geant4-based user-friendly code has been demonstrated to accurately simulate the dose distributions in a homogeneous water phantom. This code generates the full phase-space data of all particles for the 12 MV photon beam that emerge from the simulated Saturne 43 treatment unit. The phase-space containing about 4×10^6 of 12 MV bremsstrahlung photons and was previously calculated during the electron beam adjustment phase, has been used as radiations source for the calculation of dose distributions in the three PTO objects considered in this study. Sufficient events were simulated to ensure that the statistical uncertainty on the

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