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G4DARI: Geant4/GATE based Monte Carlo simulation interface for dosimetry calculation in radiotherapy

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ABSTRACT

Monte Carlo (MC) simulation is widely recognized as an important technique to study the physics of particle interactions in nuclear medicine and radiation therapy. There are different codes dedicated to dosimetry applications and widely used today in research or in clinical application, such as MCNP, EGSnrc and Geant4. However, such codes made the physics easier but the programming remains a tedious task even for physicists familiar with computer programming. In this paper we report the development of a new interface GEANT4 Dose And Radiation Interactions (G4DARI) based on GEANT4 for absorbed dose calculation and for particle tracking in humans, small animals and complex phantoms. The calculation of the absorbed dose is performed based on 3D CT human or animal images in DICOM format, from images of phantoms or from solid volumes which can be made from any pure or composite material to be specified by its molecular formula. G4DARI offers menus to the user and tabs to be filled with values or chemical formulas. The interface is described and as application, we show results obtained in a lung tumor in a digital mouse irradiated with seven energy beams, and in a patient with glioblastoma irradiated with five photon beams. In conclusion, G4DARI can be easily used by any researcher without the need to be familiar with computer programming, and it will be freely available as an application package.

1. Introduction

External beam radiation therapy is the most commonly used in the treatment of various types of tumors. Radiation beams are aimed at covering the target volume while minimizing the probability of damage to normal tissues, especially organs at risk. It exploits the biological effects of high energy X-rays on tissues to target tumor cells in the treated area. The target volume delineating the tumor for radiation therapy is described in the International Commission on Radiation Units (ICRU) (ICRU, 2010; Gregoire and Mackie, 2011; Segedin and Petric, 2016).

Regarding radiation therapy, the spatial distribution of the calculated absorbed dose plays a crucial role in the treatment planning. Efficiency of the radiotherapy largely depends upon the accuracy of the dose delivered to the tumor, and usually high doses are to be delivered with increased accuracy.

Many clinical treatment planning perform analytical methods for dose calculation and this has often some limitation (Chen et al., 2014). Alternatively, Monte Carlo (MC) methods are the preferred for dosimetry calculation in clinical situation. Thus, there is an interest in the use of such methods for accurate dosimetry.

Different MC codes, such as GEANT4 (Agostinelli et al., 2003; Allison et al., 2006), PENELOPE (Baró et al., 1995; Sempau et al., 1997), and MCNP (Briesmeister, 2000), which use different radiation physical interaction models and radiation transport algorithms, have been used and the comparison of MC codes for dosimetry were previously discussed by several authors (Love et al., 1998; Faddegon et al., 2009). Accurate MC calculations require a long computing CPU time, which makes it prohibitive for routinely clinical use. Nevertheless, there have been rapid developments in computer technology (increase in processor speed and multithreading) as well as improvements in software optimization (Gardner et al., 2012; Rannou et al., 2013).

GEANT4 is a Monte Carlo particle physics simulation toolkit implemented in object-oriented C++. At a high level, the toolkit allows users to construct complex geometries and track particles (e.g. photons or electrons) passing through and interacting with materials. The physics processes implemented for photons are mainly Compton scattering, photoelectric effect, and pair production, and for electrons are ionization, bremsstrahlung, and multiple scattering. Transportation is also treated as a physics process and is responsible for tracking particle

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location in the geometry. The toolkit offers additional precision considering physics modeling and it has been extensively validated on simple and realistic geometries (Santin et al., 2002; Agostinelli et al., 2003). With its great flexibility, the code provides good promise for radiotherapy applications and a high level of accuracy for dose calculations (Spiga et al., 2007; Sardari et al., 2010; Hamdi et al., 2017). The counterpart of its flexibility is its complexity in developing algorithms by researchers (e.g. physicists, biologists and clinicians).

In this paper, we designed an intuitive and user-friendly Graphical User Interface (GUI) based on GEANT4 able to parameterize and simulate dose calculations without the need to write any programming code. The GUI also provides a map of all particle interactions and subtypes of interactions. All the information relevant to the simulation can be exported to a text file in the form of a report. The GUI, Geant4 Dose And Radiation Interactions (G4DARI), written in C++, was based on GEANT4 classes for the configuration of the source, the target and particle tracking, on GATE simulation toolkit for the dosimetry (Sarrut et al., 2014), and on the framework QT for interactive graphical display (https://www.qt.io/ide/). Another tool, ROOT, which might be used in result analysis as it has the ability to manage large data files (Brun and Rademakers, 1997; Antcheva et al., 2009).

2. Overview of Monte Carlo, GEANT4 and GATE

2.1. Basics in radiotherapy

In radiotherapy, the calculation of the dose to the patient undergoing treatment is crucial and mandatory. In order to avoid irradiation of normal tissues by the beams targeting the tumor, several (4–10) beams are proposed, and the total radiation dose to the target tumor has to be pre-determined. In Intensity-Modulated Radiation Therapy (IMRT), in addition to the tumor precise localization, the tumor is partitioned in several segments where each segment should receive the appropriate dose (Bakiu et al., 2013; Craft et al., 2014). This treatment planning is accomplished by means of Monte Carlo calculations in patient 3D images usually obtained with computed tomography (CT). Some clinics have the opportunity to perform PET imaging with 18 F-fluorodeoxyglucose (18 F-FDG) to assess tumor metabolism which adds more accuracy to target the metabolically active tumor. Recent research tend to locate the tumor region lacking oxygen (hypoxic), which is hard to treat, to receive a higher radiation dose.

The delineation of the tumor is usually performed depending on imaging, and the images also serve to spare the organs at risk neighboring the tumor or on beam trajectory. In brief, the gross tumor volume (GTV) represents the extent of the tumor as seen on images but it is not always used as a target for radiation. The clinical target volume (CTV) is the volume expected to be irradiated and depends on the microscopic tumor infiltration and the surrounding normal tissues. The planning target volume (PTV) is the volume including CTV and surrounding tumor margins with clinically acceptable probabilities, especially in moving organs, to ensure that the dose is absorbed in the CTV (ICRU, 2010).

In clinical radiotherapy, dose calibration is usually assessed in a water phantom prior to patient treatment (Ahnesjo and Aspradakis, 1999; Gibbons et al., 2014; Vamvakas et al., 2017). For a given X-ray energy, the maximum absorbed dose in the water phantom is localized by means of an ionization chamber at a reference distance together with several doses at different depths along the axis of the X-ray beam (Fig. 1a). This dose related to depth is normalized to its maximum which accounts for 100% and the curve is termed percentage depth dose (PDD) (Fig. 1b). From these measurements, the absorbed dose to the tumor at any depth is established by taking into account beam geometry and photon scattering and with the help of a calibration table of the accelerator.

Recent clinical accelerators deliver the dose to the tumor in a continuous rotating fashion with an automatic adjustment of the beam intensity, energy and cross section to cover the PTV (Helical tomotherapy) (Zhu and Fu, 2015).

2.2. Monte Carlo simulations

It has been demonstrated that Monte Carlo simulations are very appropriate to calculate dose distribution in radiotherapy clinics (Chetty et al., 2007; Chen et al., 2014). Basically, the beam photons are directed towards a tumor segment with a predefined energy, fluence, angle and cross section. The same scheme can be valid for other particles but with appropriate probabilities of interactions. The first parameter to evaluate is the depth of penetration of the photon, and this depends on the photon energy, on the medium density and atomic constitution which is mainly related as the total attenuation coefficient μ, and on a random number generated from the distribution of the photon attenuation in this medium with this energy. Once the position of the interaction is calculated, the type of interaction is calculated based on the partial attenuation coefficients of this photon in the medium, which can be Rayleigh, Compton, photoelectric or pair creation. If the photon emerges with a remaining energy in a determined angle, the calculation restarts with this new energy in the medium. In case where an electron is set in motion by the photon, similar tracking of the electron are performed starting with the free path of the electron, its probability of interaction by collisions with atomic electrons or its interactions by bremsstrahlung with atomic nuclei. All interactions of each photon including the bremsstrahlung and the electrons set in motion are registered with x, y and z positions, the type of interaction and the transferred energy during the interaction. The interactions described here are the top level and classical interactions. Toolkits such as GEANT4 track particles and their interactions beyond those enumerated above. GEANT4 handles other processes such as muons interactions, optical photons, crystal scintillations, reflection of scintillations etc… (Agostinelli et al., 2003).

2.3. GEANT4 toolkit

GEANT4 was designed to include more than the physics aspects. GEANT4 also manages the emitting source and its geometry, the geometry of the particle emission, the geometry of the target, the tracking of the particles, the display and result saving and retrieval (Agostinelli et al., 2003). Above all, GEANT4 is written in C++ and is grouped in classes which makes it easy to implement in newly developed programs by users.

In short and for a simple simulation, the user has to fill a script file with commands grouped in blocs, starting with the bloc of the geometry definition where the simulation has to be executed. Several commands are available for position specification, material composition, orientation etc…. The bloc of the physics list specifies the types of interactions and the particles of interest, their energy and position to be returned…. The bloc of the emitting source where the user specifies the geometry of the source, the emitted particles, their angle of emission, localization, and energy. The output file where the results are grouped by events and by hits depending on the types of interactions. Finally, this script file has to be called from a batch or a macro file for the execution of the simulation. It is a hard task to understand all the classes to be used for a given simulation, their commands, and their inputs to the commands.

2.4. GATE platform

A priori one can assume the energy deposit as calculated with GEANT4 in a volume of known mass from which the absorbed dose can be calculated. Obviously, this task is already incorporated in the Geant4 Application for Tomographic Emission (GATE) toolkit (Santin et al., 2002; Jan et al., 2004). Although GATE was primarily designed for tomographic imaging, it was recently completed with tools for dosimetry calculation (Visvikis et al., 2006; Jan et al., 2011; Perrot et al.,