Simulation of the image-based 3D dose distribution by Geant4: Application to liver cancer treatment with ^{90}Y

Authors: Phan Viet Cuong, Le Tuan Anh, Nguyen Hong Ha, Ho Thi Thao

Corresponding author: pvcuong@iop.vast.ac.vn

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Abstract

The Yttrium-90 is a type of therapeutic isotope which have maximum beta energy of 2.23 MeV, the penetration in tissues about 1.1 cm and its half-life of 64.1 hours. Therefore, it is widely used in brachytherapy, especially in the hepatocellular carcinoma and other liver cancers. The quality of the treatment depends largely on the dose calculation in regimen planning. There are some dose calculation methods: (I) Body Surface Area method (BSA), (II) Empiric method, (III) Partition method and (IV) MIRD method. All of these method are analytic or empiric methods. There have been some studies showing the limitations in accuracy of these methods. This study would present an approach to calculate dose and activity in treatment planning by Monte Carlo simulation method. By using anatomical segmentation techniques to define geometry of liver and tumor for construct the simulation geometry. Besides, the distribution of ^{90}Y in the liver also determined by this method based on SPECT images. The material of liver/tumor is determined via CT number-densities based on Hounsfield scale. We are developing several semi-empirical models and implement to the Geant4 toolkit to simulate the interaction of the electron with matter and deposited dose distribution in the patient liver.

Mô phỏng phân bố liều 3D dựa trên hình ảnh bằng công cụ Geant4: Áp dụng cho điều trị ung thư gan sử dụng dụng đồng vị ^{90}Y

Từ khóa: Geant4, mô phỏng Monte Carlo, DICOM, xạ trị tắc mạch phóng xạ.

Tóm tắt

Yttrium-90 là một loại đồng vị phát bức xạ beta với năng lượng cực đại 2.23 MeV, độ đâm xuyên trong mô khoảng 1.1 cm và nó có chu kỳ bán rã là

64.1 giờ. Vì vậy nó được sử dụng rộng rãi trong xạ trị tắc mạch, đặc biệt là điều trị ung thư biểu mô tế bào gan và một số loại ung thư gan khác. Chất lượng của việc điều trị phụ thuộc chủ yếu và việc tính hoạt độ dược chất cần cung cấp cho bệnh nhân. Một số phương pháp hiện nay được sử dụng đó là: (I) Diện tích bề mặt cơ thể (BSA), (II) Phương pháp kinh nghiệm, (III) Phương pháp phân đoạn và (IV) Phương pháp MIRD. Đó đều là những phương pháp giải tích hoặc dựa trên kinh nghiệm. Đã có một số nghiên cứu chỉ ra những giới hạn về độ chính xác của các phương pháp này. Nghiên cứu này sẽ trình bày cách tiếp cận để xác định liều và hoạt độ cần cung cấp cho bệnh nhân bằng phương pháp mô phỏng Monte Carlo. Bằng việc sử dụng kỹ thuật phân mảnh y tế để xác định hình học của lá gan và khối u, phục vụ cho việc xây dựng hình học mô phỏng. Bên cạnh đó, sự phân bố của ^{90}Y trong gan cũng được xác định bằng phương pháp này dựa trên hình ảnh SPECT của bệnh nhân. Vật liệu của lá gan/khối u được xác định thông qua bộ chuyển đổi CT number-densities trên thang Hounsfield. Chúng tôi đang phát triển một số mô hình bán thực nghiệm và đưa vào công cụ mô phỏng Geant4 để mô phỏng quá trình tương tác của electron với vật chất và xác định sự phân bố liều trong gan của bệnh nhân.

1. Introduction

Radioembolization with yttrium-90 (^{90}Y) microspheres is becoming a preferred treatment for primary and secondary hepatic malignancies. Selection of the proper treatment activity is paramount to providing a high degree of safety and efficacy with ^{90}Y radioembolization. However, calculation of treatment activity has largely remained empiric, based on fractional hepatic involvement and body surface area (BSA) to estimate safely acceptable doses. [1] The partition model (PM) incorporates tissue masses and a measurement of the tumour-to-normal tissue (TN) ratio. It requires separation of the organ system into compartments (normal liver, lungs and tumour), and setting prescribed safe radiation doses whereby the maximum administered activity does not exceed these dose limits (80 Gy to normal functioning liver) [2]. Via MIRD calculations, the target organ dose is calculated as the product of the cumulated activity in the organ and the corresponding organ S-value, and the total target dose is the summation of all source organ contributions. However the use of organ level S-values inherently assuming uniform activity distribution in the organ, and the use of standardized anatomical models are the major limitations to the technique. [2] Therefore, we tend to develop a new method to determine radioactivity of ^{90}Y need to delivery for patient by the Monte Carlo simulation based on anatomical image of patient and using the Geant4 toolkit.

2. Materials and methods

2.1. Geometry construct

The DICOM images is used to construct simulation geometry, define material of patient liver and determine the ^{90}Y distribution via ^{99m}Tc-MAA scan in pre-treatment phase. Based on the CT images, we construct the liver geometry by use several image segmentation techniques, such as Canny to detect egde of liver/tumor. The Canny edge detection algorithm is widely used for image segmentation based on a set of criteria, which include finding the most edges by minimizing the error rate, localization, and noise robustness. Also, the result detected by Canny edge detection algorithm reduce the loss of edge component and the error between the detected edge and the real gradient on the original image. [3] Canny is implemented as a multi-step method. It includes Gaussian smoothing to remove noise, calculation of gradient magnitudes of the boundaries that have been smoothed, removing the points is not the maximum, and finally, removing the values below the threshold. The average magnitude is calculated following: [3]

$$M(x,y) = \frac{1}{M}\sum_{1}^{m}\sqrt{M_x(x,y)^2 + M_y(x,y)^2}$$

Where M_x and M_y are the average magnitudes of the horizontal and vertical gradient, respectively. Based on predefined thresholds, we will decide which points will be boundary and which points are not boundary. [3]

To generate the 3D geometry, we apply the 3D reconstruction algorithms of ITK (the Insight Segmentation and Registration Toolkit), the volume of the liver will be constructed. To achive the distribution of ^{90}Y in patient liver, we assumed the distribution of ^{90}Y is equivalent with ^{99m}Tc-MAA in the pre-treatment phase. We also used the same segmentation techniques to determined this distribution.

The Fig.1 is the constructed geometry achived from patient by using DICOM image, display on the OpenGL Qt.

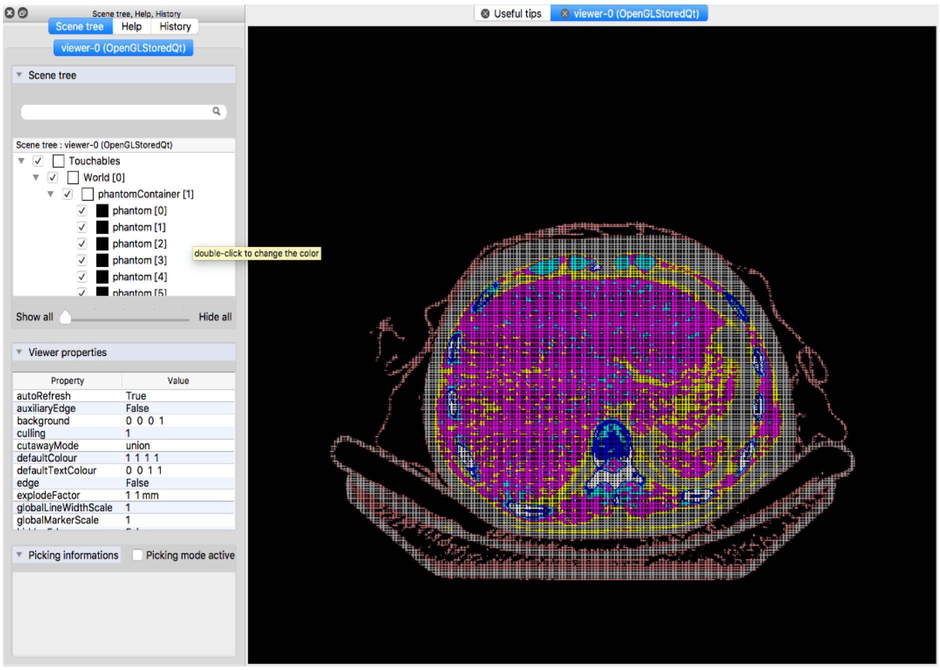

Fig 1: Constructed geometry of a liver cancer patient in the 108 Military Hospital – Vietnam.

2.2. Determine liver/tumor material

The material of liver/tumor is determined using the CT images. Based on the gray-scale of each CT image, we converted it into the ASCII format and using the CT number-densities to determine the kind of material and its density.

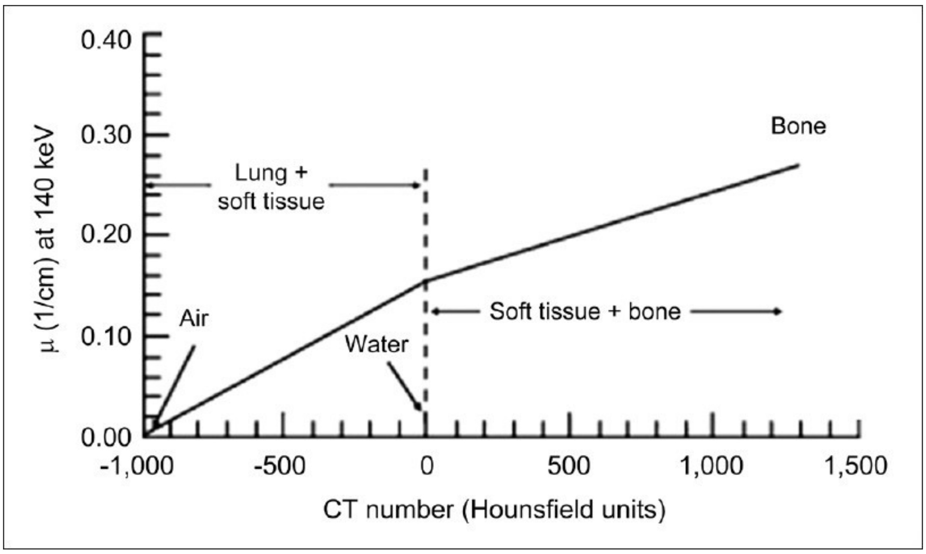

Fig. 2: The CT number-densities converter. [4]

2.3. Physics model

To simulate the behavior of ^{90}Y in patient liver, we need to present the decay process and the interaction of electron with matter. By using the Geant4 toolkit, we can simulate these process based on the Monte Carlo method. The Geant4 is a open source platform for simulation the passage of particles through matter, it is widely use in high energy physics, space physics and medical physics. Geant4 contains dozens of class to illustrates the interaction of radiation with matter.

With the decay process, we used the *G4RadioactiveDecay()* class. The simulation model depends on data taken from the Evaluated Nuclear Structure Data File (ENSDF), its provides information on: [5]

- Half-lives
- Nuclear level structure for the parent or daughter nuclide
- Decay branching ratios
- Energy of the decay process

With the interaction process, by consider several built-in model in Geant4 such as Livermore, Penelope, we found that there were high deviation on electron mean energy lost between them and with experimental data, especially in the energy range around 100 eV. Therefore, we tend to develop new semi-empirical model based on experiment data to apply for this simulation.

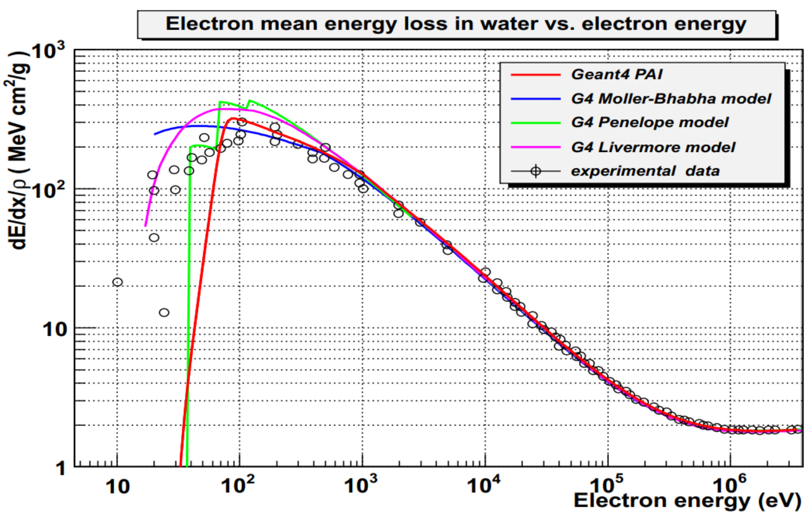

Fig. 3: Electron mean energy loss in water of several built-in model in the Geant4 versus experiment data.

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