

Monte Carlo Simulations of mini-Tissue Equivalent Proportional Counter : comparison between Geant4, MCNP6, and PHITS

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1. Introduction

The well-known dosimetric device tissue equivalent proportional counter (TEPC) is a master detector that can measure the microdosimetric spectra and estimate the quantified radiation dose level for the mixed radiation fields [1]. Based on the fact that low pressure tissue equivalent gas can be used to demonstrate radiation damage and effect of infinitesimal, microscopic tissue volumes, the TEPC able to observe single energy deposition event which can be converted into spatial dose distribution and microdosimetric quantities such as frequency mean lineal energy ($\overline{y_F}$) and dose mean lineal energy ($\overline{y_D}$).

Since the first innovative design of spherical TEPC by Rossi and Zaider [1], depending on the purpose and radiation environment of concern, several shapes of TEPC in various sizes have been developed over the past two decades. For instance, Justin *et al* utilized a Benjamin-type spherical TEPC to investigate the performance of TEPC in photon and neutron field, and Monte Carlo simulations using Geant4 showed good agreement with actual experiment data [2]. Also, a slim cylindrical mini TEPC fabricated by De Nardo *et al* showed high precision (3% of the calculated accuracy of proton edge based on ICRU 49 tables) and promising plans to be used in therapeutic practice [3].

In here, by employing three different Monte Carlo simulations, a comparative analysis of mini cylindrical TEPC for photon field was represented in the form of microdosimetric spectra (dose distribution) and microdosimetric quantities ($\overline{y_F}$, $\overline{y_D}$). Subsequently, our simulation results were also compared with some experimental results to validate our results and to be set as a benchmark prior to its actual implementation.

2. Material and Methods

In the first part of this section, configuration of mini cylindrical TEPC and calculation steps to obtain lineal energy distribution for predicting the relative biological effectiveness (RBE) are described. In succession, overall setup for each Monte Carlo simulation is represented ahead of result figures and tables including experimental data from prior researches.

2.1 Detector configuration and dose distribution

To simulate the microscopic tissue within the radiation field, it is required that the kinetic energy deposited by recoil proton nucleus both in the infinitesimal tissue site and low-pressure gas cavity of TEPC should be the same. As the density of microscopic tissue replaced by density of water and diameter of both the simulate tissue size and gas cavity can be set to a fixed value, we could determine the exact simulated tissue size of interest by adjusting the density of gas and expressed in equation (1).

$$\rho_g = \frac{\rho_t \times d_t}{d_g} \quad (1)$$

In this study, the diameter and height of the gas cavity were set as 1 mm and this compartment was surrounded 0.1 mm thickness of A-150 Tissue Equivalent plastic wall, and the simulated tissue sizes were varying from 1.0 to 2.66 μm . The isotropic photon source of Cs-137 was placed 0.55 mm away from the center of its side surface.

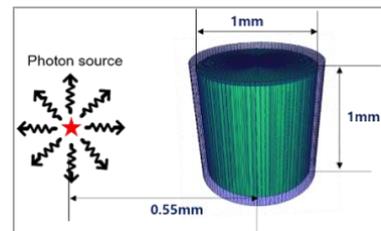


Figure 1. Configuration of mini right cylindrical TEPC (Diameter=Height=1 mm) with photon source. (Green area: Methane based Tissue Equivalent gas, Transparent area: A-150 Tissue Equivalent plastic)

Since TEPC allows to observe deposited energy per single event (i.e. the deposited energy per event, ε), which represent total deposited energy amount contributed by primary particle and its secondaries in a single event, we can obtain lineal energy (y) by deviding with mean chord length (\overline{l}). Here, the mean chord length is defined as the average length of randomly oriented chords within a specific volume [4]. Besides, for a spherical or right cylindrical volume of diameter d with isotropic radiation source, the mean chord length can be expressed as equation (3).

$$y = \frac{\varepsilon}{\overline{l}} \quad (2)$$

$$\bar{l} = \frac{2}{3} \times d \quad (3)$$

equation (3).

When the energy bin is placed on logarithmic scale, using mid-point value of each energy bin and its counts can be convert into the lineal energy distribution (the dose distribution) as described in equation (4).

$$yd(y)|_i = \left(\frac{y_i f_i}{\sum_{i=1}^n y_i f_i} \right) \times \frac{1}{C} \quad (4)$$

Consequently, from this microdosimetric spectra, we can obtain two important quantities the frequency mean lineal energy and the dose mean lineal energy which will be used to predict the RBE of certain radiation environment.

$$\bar{y}_F = \frac{\sum_{i=1}^n y_i f_i}{\sum_{i=1}^n f_i} \quad (5)$$

$$\bar{y}_D = \frac{\sum_{i=1}^n y_i^2 f_i}{\sum_{i=1}^n y_i f_i} \quad (6)$$

In equation (5) and (6), y_i and f_i is indicating the mid-point value of i^{th} lineal energy bin (unit: keV/ μ m) and the counts in the i^{th} lineal energy bin.

2.2 Monte Carlo simulation

Three different Monte Carlo (MC) simulations were implemented with same geometry described in previous section but utilized different transport physics model and nuclear cross section library which are one of major cause of discrepancies between MC simulations.

In the first MC simulation code, Geant4.10.05, the *G4EmLivermorePhysics* (one of the low energy electromagnetic physics) was used for the physics to transport photon and secondary electrons [2].

Furthermore, in MCNP6.2 and PHITS3.02, the pulse height F8 tally and [T-deposit] tally were implemented to record the deposited energy per single event. To proceed electron transport as accurate as possible, the ESTEP option was revised from default value 3 to 5000 as suggested by Hanna Koivunoro *et al* [5]. Unlike the MCNP6.2 which utilized the default physics model, changing of transport option was required in PHITS3.02 to proceed secondary electrons transportation within microscopic region. Since the transportation of electron and positron is time consuming job, the default transport algorithm in PHITS only able to transport photon. Therefore, by changing the value "negs" into 1 ([parameter] section), transport of electrons, positrons and photons was able to proceed based on EGS5 algorithm.

To achieve good counting statistics, all the MC simulations were performed for a total 1E10 histories, and six mini TEPCs were placed together but not contacted with Cs-137 source at the center. At this step, lineal energy events below 1 keV/ μ m were disregarded for all simulation results as such low lineal energy region can be disturbed by noise and show low accurate data in actual experiments [2].

3. Results and Discussions

3.1 Dose distribution with three MC simulations

In accordance with increased simulated microscopic tissue size, some conspicuous features such as aggravated energy straggling and broadening and shifting of distribution are expected to appear.

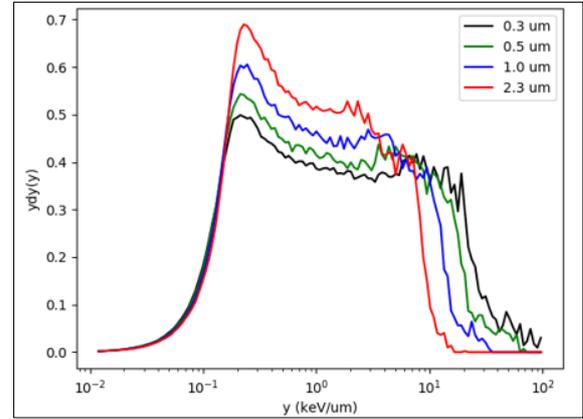
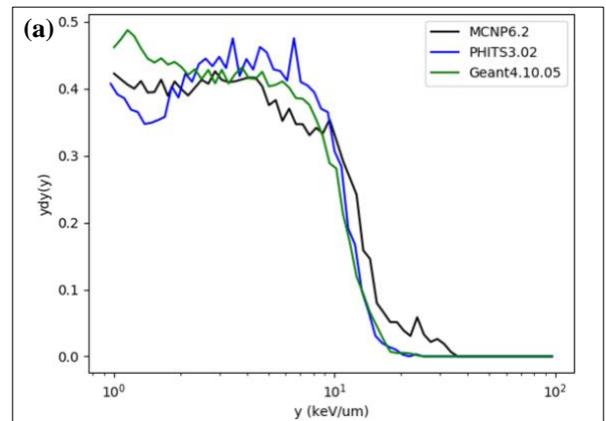


Figure 2. Dose distribution of Cs-137 with increased simulated tissue size from 0.3 to 2.3 μ m using MCNP6.2.

To check the tendency on the dose distribution by increasing the tissue size, four additional simulation data (0.3 ~ 2.3 μ m of tissue size) using MCNP6.2 were enumerated in figure 2. As described in equation (1), the gas density of gas cavity is proportional to the simulated tissue size. As such, when the range of secondary electrons that traverse the gas cavity exceeds the diameter of gas cavity, aggravated energy straggling may appear on the dose distribution. Not only that, but larger mean chord length derived from larger tissue size will also make smaller lineal energy values, so does the microscopic spectra shift to smaller lineal energy values. In figure 2, the abovementioned impacts are demonstrated along with increased simulated tissue size.



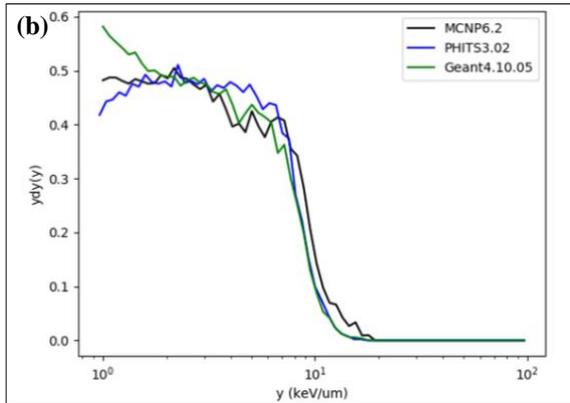


Figure 3. Dose distribution of Cs-137 using three MC simulations with simulated tissue size of 1.0 μm (a) and 2.0 μm (b).

In figure 3, the dose distributions with tissue size of 1.0 and 2.0 μm show that MC simulations with three different codes have a good agreement. Still, some discrepancies exist especially at lower lineal energy region (near 1 $\text{keV}/\mu\text{m}$), and MCNP results show slightly higher lineal energy values than Geant4 and PHITS. Therefore, additional works including ESTEP value adjustment and understanding of transport algorithm in each MC simulation are required to obtain higher consistency.

3.2 Comparison with prior researches

Some prior researches data which possess similar setup such as shape and size of TEPC and same photon source (Cs-137) were selected to compare our MC simulation results. The representative microdosimetric quantities are arranged in table 2, and the dose distribution when simulated tissue size set as 2.66 μm is shown in figure 4.

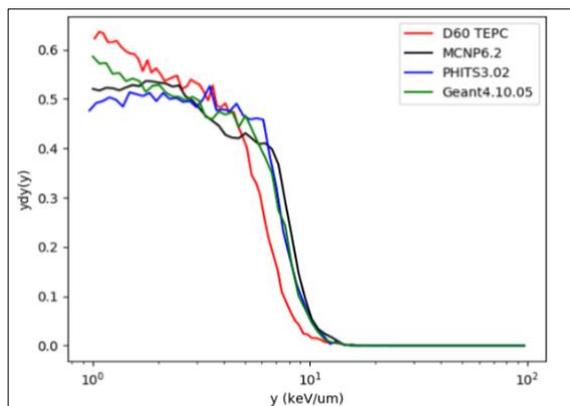


Figure 4. Dose distribution of MC simulations and D60 TEPC experiment data performed by Justin *et al.* (Using Cs-137 source and simulated tissue size of 2.66 μm)

Dose mean lineal energy	1.0 μm	2.0 μm	2.66 μm
Geant4	2.41	1.91	1.74
MCNP6	2.69	1.95	1.84
PHITS	2.32	1.91	1.76
Literature	-	-	1.72
Frequency mean lineal energy	1.0 μm	2.0 μm	2.66 μm
Geant4	0.41	0.41	0.40
MCNP6	0.41	0.40	0.40
PHITS	0.38	0.37	0.37
Literature	-	-	0.67

Table 1. Dose mean lineal energy and frequency mean lineal energy of MC simulation data and D60 TEPC experiment result.

It should be noted that D60 TEPC is a spherical type TEPC with TE gas cavity filled with pure propane and 60 mm in diameter, and developed by Korea Astronomy and Space Science Institute (KASI). They show quite a good agreement, yet some discrepancies are occurred due to differences on environmental setup such as TEPC geometry (TE gas material, shape and size of TEPC) and the natural limitation of MC simulation.

4. Conclusions

Monte Carlo simulation of mini cylindrical TEPC using Geant4, MCNP6, and PHITS were performed to investigate how photon field effect the microscopic tissue site. Between MC simulation results, overall microscopic spectra showed a good agreement. Furthermore, the fair agreement of our MC simulation results with published prior researches suggest that these MC simulation codes can be utilized as a benchmark work prior to its actual implementation. Following the photon field simulation, the neutron field simulation to confirm the validation of our TEPC design is on progress.

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