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MONTE CARLO SIMULATION OF ELECTRON BEAM IN PHANTOM WATER FOR RADIOTHERAPY APPLICATION

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Abstract

Radiotherapy (RT) is an effective treatment that can control the growth of cancer cells. There is a hypothesis suggests that secondary electrons with an energy of a few eV produced from RT play an important role on cancer's DNA strand break. In this study, the Monte Carlo simulation of electron beam irradiation in phantom water is performed to investigate the production of low-energy electrons. Electron beams produced from an radio-frequency linear accelerator (RF linac) are used in this study. The accelerator can generate the electron beam with adjustable energy of up to 4 MeV and adjustable repetition rate of up to 200 Hz. With these properties, the electron dose can be varied. We used ASTRA software to simulate the electron beam dynamics in the accelerator and GEANT4 toolkit for studying interactions of electrons in water. The energy of electrons decreases from MeV scale to keV-eV scale as they travel in the water. From simulations, the dose distribution and depth in phantom water were obtained for the electron dose of 3, 5, 10, 25, and 50 Gy. Further study on effect of low-energy electron beam with these dose values on cancer DNAs will be performed with GEANT4-DNA simulation.

INTRODUCTION

The main propose of radiotherapy (RT) technique is to kill tumour cell by inducing the damages on the DNA while sparing normal cells [1]. The particle irradiating onto the cells would lead to two actions on DNAs, which are direct and indirect actions. In direct action the ionized electrons directly deposit their energy to the DNA strand while OH radicals are generated then give the damages to the DNA strand in indirect action. Theses damages can be occurred in the form of single strand breaks (SSBs) and double strand breaks (DSBs). The DSBs are more complex than the SSBs, which lead to less opportunity for the cell to repair itself and result in cell death [2].

To investigate the effect of electron irradiation on the cell samples, the RF linac at the PBP-CMU electron Linac laboratory (PCELL) is used to generate the electron beam for this experiment. This linac can produce electron beam with energy in a range of 0.5 - 4 MeV with adjustable repetition rate of up to 200 Hz [3].

To estimate the electron absorbed dose in liquid sample, GEANT4 Monte Carlo toolkit [4] is used. From the simulation results, we can design the experimental setup to detect some interesting parameters, for example; number of electrons after passing through the material or the electron absorbed dose in material. To generate input electrons for GEANT4 simulation, we use the ASTRA software [5] and to track electron in 3D magnetic field obtained from CST simulation [6]. Since phantom water can offer the excellent agreement with irradiation experiment on human anatomy, it therefore widely used to estimate the absorbed dose in human tissue [7]. In this work, the phantom water (soft tissue [8]) is considered as the representation of the cell sample. The aim of this work is to find the most appropriate position for electron beam irradiation as well as the irradiation time that can provide the electron absorbed dose of 3, 5, 10, 25, and 50 Gy in the sample.

Table 1: The Percentage of Phantom Water Components Used in GEANT4 Simulation [8]

Material	**Component**	**Percentage**
Phantom water(soft tissue)	Hydrogen	10.4472
	Carbon	23.2190
	Nitrogen	2.4880
	Oxygen	63.0238
	Sodium	0.1130
	Magnesium	0.0114
	Phosphorus	0.1130
	Sulfur	0.1990
	Chlorine	0.1340
	Potassium	0.1990
	Calcium	0.0230
	Iron	0.005
	Zinc	0.0030

SIMULATION METHOD

The simulation in this work was divided into two sections for acceleration and irradiation. The simulation layout and details of components in simulation setup are demonstrated in Fig. 1.

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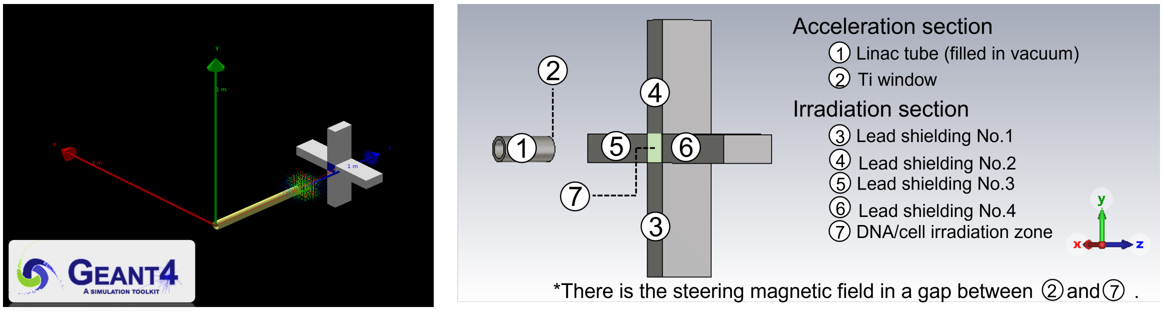

*There is the steering magnetic field in a gap between ② and ⑦ .

Figure 1: GEANT4 simulation setup for acceleration and irradiation section.

Acceleration Section

In this section, the 2 MeV electron beam distribution from ASTRA simulation is used as the input electron beam for GEANT4 simulation. This electron beam is injected inside the linac tube filled with vacuum. After that, the beam travels through the 50 μm titanium (Ti) window (used to separated the vacuum and ambient air region) before irradiating onto the cell sample. When the beam traveling through Ti window, it would generate photons in forms of X-ray or gamma ray. Therefore, the steering magnet is used to bend the beam from the direction of photons. The 3D magnetic field from CST EM studio simulation was included in our GEANT4 setup. The number of generated electrons and photons per 300k incident electrons at position 10, 15, 20, and 25 cm down stream the Ti window was collected and considered in order to find the appropriate position for the irradiation section, where has the lowest number of photons. The simulation results show that all positions give the same percentage of electrons (99.3 %), while the lowest number of photons is obtained at the position 25 cm down stream the Ti window. The number of generated electrons and photons per 300 k incident electrons at this position (25 cm) is shown in Fig. 2. At this position, the number of generated photons inside the selected zone (green area in Fig. 2) is 799 particles per 300 k incident electrons.

Irradiation Section

In order to decrease the effect of unwanted photons in the sample, the lead shielding is used. The shielding aperture of 5×5 cm^2 is considered match to the size of the sample dish (round shape with diameter of 5 cm). Based on simulation result, the sample is placed 25 cm away from the Ti window with 2.5 cm shift in the +x direction. The phantom water, which represents the soft tissue, is used as the cell sample in the simulation. The phantom water's components are listed in Table 1. The longitudinal and transverse absorbed dose in phantom water are shown in Fig. 3 and Fig. 4, respectively. From the longitudinal absorbed dose distribution, we considered the R-optimise depth (the depth where the absorbed dose equals the absorbed dose at surface) to be the depth of our sample. The R-optimise depth is 0.56 cm for the selected irradiation position. The transverse absorbed dose distributions imply that the sample receives much higher absorbed dose from electrons than photons. The electron distribution confirms that the sample would get the irradiation dose through out the considered area, enveloped by red circle. Using the information from both longitudinal and transverse distributions, we get 10.1 cm^3 (calculated from 5 cm in diameter of sample dish and 0.56 cm of R-optimum depth) of irradiated sample volume per one injection.

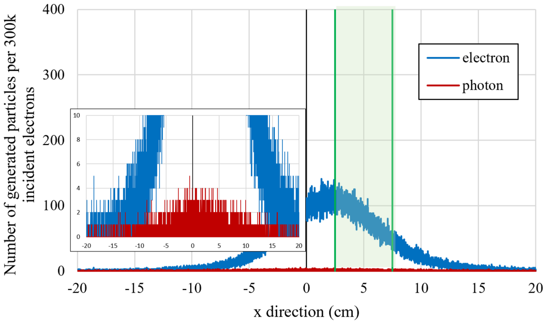

Figure 2: The number of generated electrons and photons per 300 k incident electrons at the position 25 cm down stream the Ti window after being bent by steering magnet. The selected zone for irradiating sample is shown in green area.

After obtaining the appropriate volume of sample irradiation, the calculated of irradiation time was performed. From simulation results, the absorbed dose in 10.1 cm^3 of sample is 0.65 Gy per an electron bunch. The expected electron beam produced from the linac has a pulse current of 50 mA operating at 5 Hz of repetition rate [9]. By using this information to calculate the irradiation time, we found that to receive the electron absorbed dose of 3, 5, 10, 25, and 50 Gy in the sample, it requires the irradiation time of 1.84, 3.07, 6.13, 15.34, and 30.67 second, respectively.

CONCLUSION

This simulation is performed in order to find the most appropriate position for the cell irradiation section.The steering magnet is used to bend the 2 MeV electron beam away from the generated photons after the primary electron beam

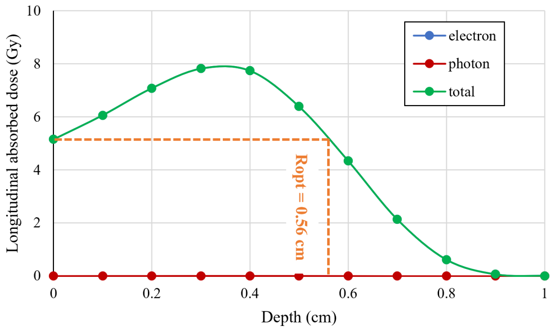

Figure 3: The longitudinal absorbed dose distribution in phantom water.

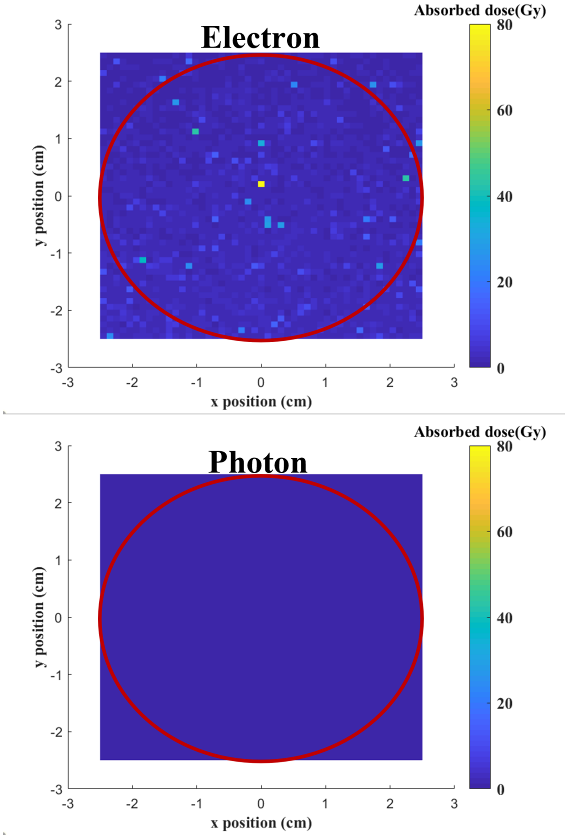

Figure 4: The transverse absorbed dose distribution of generated electrons and photons in phantom water. The sample dish size of 5 cm in diameter is displayed by a red circle.

passing through Ti window in order to reduce the effect from generated photons. The simulation results show that the best position for irradiation section is at 25 cm down stream the Ti window with 2.5 cm shifted in +x direction. At this position the sample will receive electrons 99.3 % from total number of generated electron and photons, with the lowest number of photons. The selected zone is considered to fit with the size of sample dish (5 cm in diameter). Inside the selected zone of 5×5 cm^2, there is the phantom water representing the cell sample.

The simulation results provide the longitudinal and transverse absorbed dose distributions in phantom water, which were used to calculate the optimum volume of irradiated sample per single injection. This results in the optimal volume of 10.1 cm^3. For the irradiation time estimation, we found that to receive the absorbed dose of 3, 5, 10, 25, and 50 Gy in samples, it requires 1.84, 3.07, 6.13, 15.34, and 30.67 second of irradiation time, respectively. Further study will be proceeded with GEANT4-DNA simulation to study the interaction of the absorbed electrons in DNA.

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