

Investigation of Electron Beam Depth-dose Curve Using EGSnrc

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Abstract. As a matter of fact, electron beam therapy is fundamental in cancer treatment, with advantage of precise dose deposition and shallow penetration, making it ideal for targeting superficial tumors in recent years. Accurate modelling of electron beam characteristics is important for safe and effective radiation therapy. On this basis, this research looks at the electron beam depth dose curve, and its behaviour under different field size using EGSnrc (Electron Gamma Shower National Research Council) as well as discusses its validity by compare simulation results with other researchers' work. According to the analysis, this study has proved the validity of DOSXYZnrc since the simulation data is consistent with the agreed data despite some other unmentioned parameters should be rechosen at the same time. To ensure the safe and effective delivery of radiation therapy, accurate electron beam information and dosimetry are indispensable for radiation oncologists and medical physicists. These results shed light on guiding further exploration of electron beam therapy.

Keywords: Electron beam therapy; dose-depth curve; different field size.

1. Introduction

The intersection of advanced technology and medical physics has led to significant breakthroughs in revolutionizing diagnosis, treatment, and data analysis. Monte Carlo method was firstly invented by John von Neumann and Stanislaw Ulam to estimate the probability of winning solitaire and calculation of neutron transport [1]. It describes particle-particle interactions and stochastic processes in a microscopic level and provides a final macroscopic result. As the complexity of the problem increase, time to obtain analytical solution increases exponentially [2]. Due to the impracticality and impossibility of the analytical simulations and solutions, Monte Carlo simulation which could provide a numerical solution has been put into use due to its flexibility and ability to address non-linear problems. Nowadays, it has been applied in nuclear medicine, source modelling, radiation dose distribution and other areas in medical physics. In biological systems, randomness plays a significant role in many processes, such as the scattering of photons or the random distribution of particles in a tissue. Analytical methods often cannot capture these inherent fluctuations accurately. Monte Carlo methods are preferred over analytical techniques in situations involving highly diverse tissues or intricate systems because they offer a more versatile, adaptable, and accurate approach [3]. Accompanied by advantages of Monte Carlo methods are its drawbacks, it requires a larger time of simulated events and longer time to obtain a good solution. The accuracy of physical models, the soundness of underlying assumptions, and reasonable parameters are equally crucial for achieving accurate outcomes.

There are even different developed Monte Carlo packages arising in past decades, e.g., Geant4, Fluka, MCNP, EGS to simulate different particle transportation and interaction [4]. However, efforts are still needed to optimize the Monte Carlo codes considering prolonged computational durations and insufficiency of data to calibrating models [5], and in this context, a CPU fast Monte Carlo engine, MonteRay, been invented for helium ion beam dose calculation with enhancement in speed and accuracy compared with FLUKA [6]. Monte Carlo techniques also play a crucial role in the field of particle therapy, particularly in the treatment planning process. These techniques enable precise and accurate modelling of the interaction between therapeutic particles, such as protons or carbon ions, and the patient's tissues [7,8]. This level of detail allows for the calculation of dose distributions with high precision, ensuring that the radiation is precisely delivered to the tumour while sparing

surrounding healthy tissues. It also verifies treatment plans and optimizes beam delivery techniques, contributes to the effectiveness and safety of particle therapy in cancer treatment. Size-specific does estimate developed from Monte Carlo simulation was put into application recently for different parts of the body [9, 10]. It gives a more personalized estimation of radiation dose by considering patient size. Ongoing research efforts also involve the validation and benchmarking of Monte Carlo simulations against experimental data or reference standards to ensure their accuracy and reliability [11, 12]. This practice is essential for quality assurance, treatment plan optimization, and advancing research and development in medical physics applications.

Electron beam's applications in radiation therapy had a very long history. It employs high-energy electrons generated by a linear accelerator to target area and irradiate cancerous tumours with precision. This therapy is particularly effective for treating superficial tumours located near the body's surface, for example, skin cancers and breast cancers. However, as beam energies exceeds around 20 MeV, depth-dose curves are smoother and penumbrae broaden with depth, which has little application [13].

The motivation for this paper stems from the necessity to verify the accuracy and validity of Monte Carlo simulation in EGSnrc (Electron Gamma Shower National Research Council) package, especially DOSXYZnrc in the application of electron beams behaviours in different depth of water with different beam energies and field sizes. While modern radiation therapy techniques have improved the targeting of tumours, uncertainties and variations in patient anatomy and setup can still impact treatment outcomes. Thus, this paper aims to use several different parameters in the Monte Carlo code. The compare these results with agreed results from others and discuss the validity of the Monte Carlo codes.

The research framework is structured into several key components. Firstly, the method and parameters used are describe. Secondly, results for different beam energies generated from the DOSXYZnrc package were presented. experimental data from other researchers were provided to testify the accuracy of simulated ones considering uncertainties. Finally, simulated data for different field size were presented and compared, validity of the DOSXYZnrc then discussed.

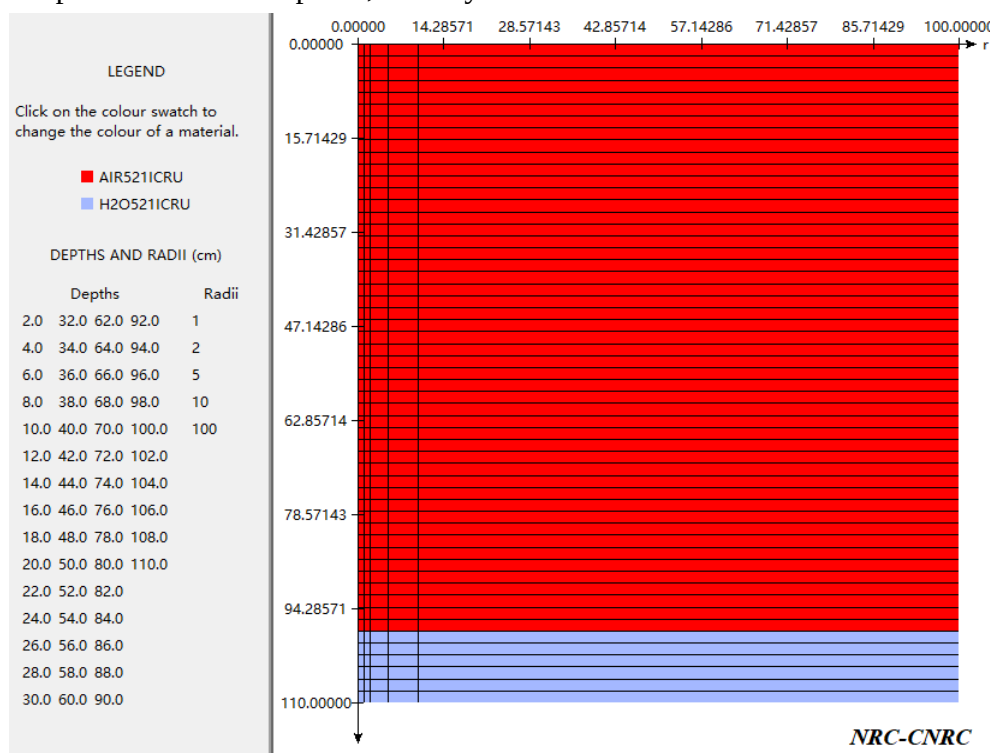


Fig. 1 The setting used for depth dose curve where the TSD (target source distance) is set to be 100 cm ensuring consistency with clinical conditions and the field size of water phantom is $10 \times 10 \text{ cm}^2$.

2. Methodology and Parameter Setup

DOSXYZnrc 2023 version of EGSnrc is utilized in this paper. The Monte Carlo approach is used by EGSnrc to model particle transportation. Individual electrons, photons, or other charged particles are tracked as they move through matter. The code determines the likelihood that different types of interaction activities will take place at every stage of the particle's journey. EGSnrc considers a variety of physical processes, such as multiple scattering, photon interactions, and electron interactions [14]. It has multiple applications like BEAMnrc, DOSXYZnrc and DOSRXnrc with different functions like linear accelerator, dose calculations and kerma calculations [15]. The total phantom dimensions were set to be in agreement with research by Meyer [16] and Loevinger [17], and they all replicated the typical size used in clinical scenarios. Water is used as a majority of the medium phantom here as it is similar with tissue, both with low atomic number. A 100 cm of air with density 0.00125g/cm^3 was also set as a medium at the start of the electron radiation to simulate the actual situation where the electron beam machine is not in direct contact with the patient. A monoenergetic electron source with a Gaussian energy spectrum for each energy level was used. The source type is $\text{isource} = 0$. The phantom was positioned at the isocenter, and the beam axis was aligned perpendicular to the phantom's surface.

Electrons experience both inelastic and elastic collisions with atomic electrons and nuclei. In this case, ionization is a dominant source of energy loss from electrons. In terms of electron beam parameters, different energies of the electron beam were set, from 7 to 18 MeV, the range most frequently used in practice. The 7 MeV beam is typically used for surface treatments, whereas the 18 MeV beam is often utilized for deeper-seated targets. To investigate how different field size affect the depth-dose curve, 2×2 , 3×3 , 4×4 and $6 \times 6\text{ cm}^2$ were simulated for 18 MeV electron beam. The setting is also shown in Fig. 1. For every set of data points, 5×10^6 electron histories were simulated to guarantee statistical validity of the findings. To determine the dosage distribution, the electron histories were tracked through the phantom.

3. Results and Discussion

3.1. Depth-dose Curve

When electrons pass through materials, a series of interactions can be caused, including multiple scattering, energy loss, bremsstrahlung radiation and absorption. There are wavefunctions to simulate these processes. This causes series of superpositions which makes absorption and transmission being complex and hard to model. So experimental results are of great significance, due to unperfect theory and complex Schrodinger equation. DOSXYZnrc somehow avoids the complexity. Since electrons are quantised, flux only reduces the number of electrons but not lower the energy of each electron. The depth dose curve can give a detailed explanation of how the energy from an electron beam is deposited in tissue and their characteristic at different depths. In the simulation using DOSXYZnrc, one sets TSD to 100 cm, field size to $10 \times 10\text{ cm}^2$ and ran for 6, 7, 10, 12, 15 and 18 MeV. The results obtained are shown in Fig. 2.

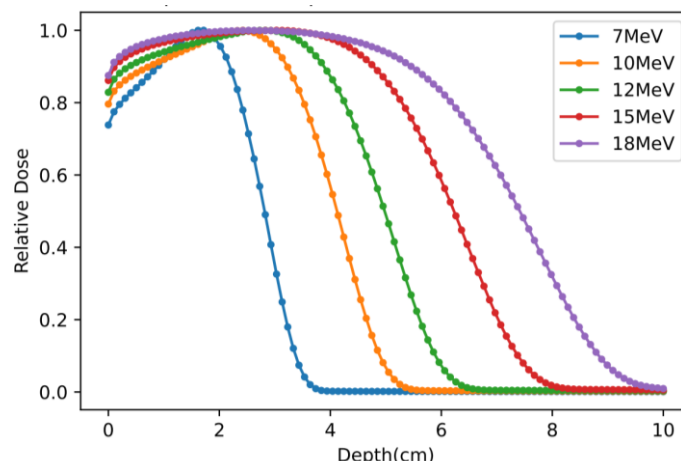


Fig. 2 The depth dose curve for different electron beam energy. The simulated data points were connected to show their trends. Uncertainties were not shown on graph because they are minuscule compared with the data points, to the scale of 0.1 or smaller.

Table 1. The peak and depth for 0.8 relative dose data points for depth dose curve with their relative uncertainties. They are compared with accepted values by Meyer et. al. [16].

Electron beam energy (MeV)	Depth at maximum dose d_m (cm)	Depth at 0.8 relative dose $d_{0.8}$ (cm)	Depth at 0.8 relative dose $d_{0.8,M}$ (cm) by Meyer	Difference (%)
7	$1.8 \pm 1.0e^{-3}\%$	$2.8 \pm 1.3e^{-3}\%$	2.3	+22
10	$2.5 \pm 4.4e^{-4}\%$	$4.0 \pm 2.3e^{-4}\%$	3.4	+18
12	$2.8 \pm 4.1e^{-4}\%$	$4.8 \pm 3.3e^{-2}\%$	4.1	+15
15	$3.1 \pm 3.8e^{-4}\%$	$5.6 \pm 1.5e^{-3}\%$	5.0	+12
18	$3.2 \pm 3.0e^{-4}\%$	$6.4 \pm 4.9e^{-4}\%$	6.0	+6

There is Bragg's peak appearing for electron beam, indicating adjusting electron beam energy for tumours at different depth. There is more radiation absorbed by tissue closer to the radiation source compared with those on the back of the tumour. For low electron beam energy, the peak is sharp, suggests great treatment outcomes for superficial cancerous tissue. As the energy grows, the curve is smoother and wider, and maximum depth reaches at larger depth (seen from Table 1). This means that larger energy penetrates deeper inside the water phantom, suitable for cancerous tissue deeper inside the body but it also threatens the healthy tissue. Since the shape of curve cannot be greatly modified, in terms of deep tumours, it is difficult to obtain great treatment outcomes without harming healthy tissues nearby. This agrees with the theory [17]. The uncertainties for all the data points are small due to large number of simulations which leads to precise statistical estimation and convergence of values. Comparing the simulated depth at 0.8 relative dose $d_{0.8}$ with accepted values $d_{0.8,M}$ by Meyer, the simulated data were generally larger than accepted values. Better parameters apart from the ones mentioned above could be chosen to match the radiation source equipment used by Meyer.

3.2. Effects Under Different Field Size for 18 MeV Beam

For treatment planning, the field size influence on the depth-dose curve is essential, especially when working with targets of irregular form. TSD is 100 cm, and the energy of the electron beam is 18 MeV. Four field sizes were chosen, 2×2 , 3×3 , 4×4 and $6 \times 6 \text{ cm}^2$. The data points are shown in Fig. 3 and Table 2. Energy of the electron beam was chosen to be 18 MeV. Because the uncertainties are so minor compared to the data points, to a scale of 0.1 or smaller, they were not displayed on the graph.

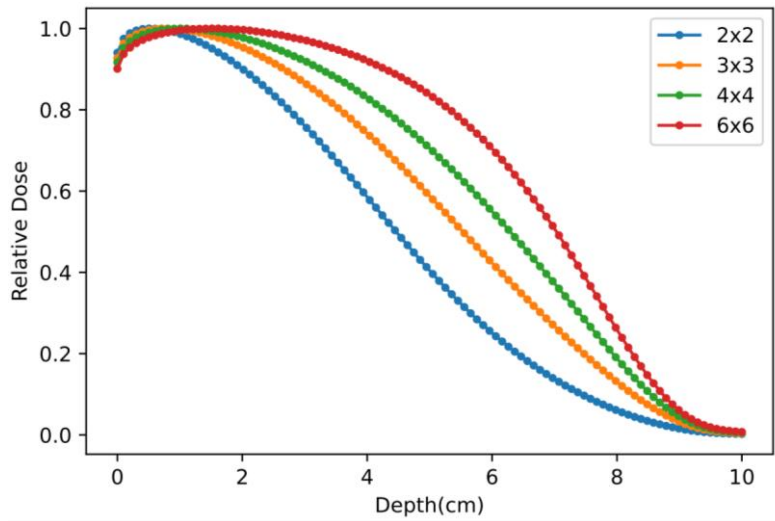


Fig. 3 Depth-dose curve for different field sizes

Table 2. Depth at maximum dose $d_{m,field}$ for different field sizes.

Field size	$2 \times 2 \text{ cm}^2$	$3 \times 3 \text{ cm}^2$	$4 \times 4 \text{ cm}^2$	$6 \times 6 \text{ cm}^2$
Depth at maximum dose $d_{m,field}$ (cm)	0.6	0.9	1.1	1.6

When the electron beam reaches the water phantom, a larger field size would give a relatively low dose due to the spreading of beam. In low field size, the fall-off in dose beyond maximum dose is more abrupt, suggests prevention of high dose radiation received by other tissue. As the field size increases, the curve becomes linear and then swelled at $6 \times 6 \text{ cm}^2$, the fall-off is more gradual, and the dose remains relatively higher at greater depths. This means poor treatment outcome at larger field size, thus it is better to avoid large field size if unnecessary. As the field size increases, the depth at maximum dose also increases. Larger field size is more suitable for larger tumours deeper inside the body. This agrees with the accepted data produced by Meyer. Larger field sizes have larger radiation because there are more electrons scatter to places perpendicular to direction of beam and there is more absorption of electrons. In actual practice, tissue heterogeneity must be taken into account as this might affect the effectiveness of the electron beam therapy and tissue beyond the PTV. The target volume's dosage homogeneity may be reduced by smaller field sizes. This is due to the possibility that a small area may experience dramatically different doses, which might result in under- or overdose in some areas. More uniform dosage distributions within the target volume are frequently achieved with larger field sizes.

4. Limitation and Prospects

Despite the vast applications of Monte Carlo method in different fields, even in industry 4.0 nowadays [18], there are some future challenges about it waiting to be addressed. They include computational efficiency, integration with machine learning, advancements in fast Monte Carlo codes and development of models with detailed biological information [19, 20]. Ongoing research in nuclear and particle physics will lead to more accurate cross-section data and physics models. These improvements will increase the reliability and precision of Monte Carlo simulations. Similar to many Monte Carlo simulation tools, EGSnrc, can be complex and resource-intensive, requiring a high level of expertise and computational resources. One limitation of EGSnrc is the complexity of some of the models which could require accessing to high-performance computing clusters, especially those involving high-energy particles or complex geometries. For the results of the code to be trusted, thorough validation and verification, including benchmarking against experimental data, are vital. The user's proficiency in the physics of particle interactions and the actual application of the software are crucial for the accurate usage of EGSnrc. Human error might lead to incorrect settings or outcomes.

However, its outlook remains promising, with opportunities for incorporation with machine learning and artificial intelligence techniques to help optimize EGSnrc simulations and integration with imaging software and treatment planning systems [21, 22]. As increasingly powerful computer resources become accessible, processing times are shortened and larger and more complicated simulations can be run, the variety of prospective research area will expand. The increase usage of EGSnrc in radiation therapy also implies its growing recognition. One important material that could be introduced to the system is bone, lung and other human tissues and organs because electron beam is very sensitive to tissue heterogeneities. Replicate typical human anatomical structures can greatly increase the accuracy of DOSXYZnrc.

Considering electron beam therapy, because of their restricted range in materials, electrons can only be used to treat surface cancers. However, mixture of radiation source, e.g., electron beam and X-ray could penetrate deeper in body and is a future possible customized treatment strategy. Electron beams display a penumbra effect which causes a steady dosage drop towards the field edge [23]. To reduce adverse effects on healthy tissues, precise dosage distribution and planning are essential. Dynamic electron arc treatment is one example of a technique and technology that works to maximize the tumour dosage while minimizing the penumbra effect on healthy tissues [24, 25]. Thus, development and remaining in the forefront of scientific progress of Monte Carlo method, EGSnrc and electron beam therapy requires the advancements in interdisciplinary work involving computing, dosimetry, medical physics and machine learning.

5. Conclusion

In conclusion, the analysis of electron beam depth using the DOSXYZnrc Monte Carlo simulation code is a critical and highly valuable area of research within the field of medical physics and radiation therapy. This research modelled the behaviour of electron beams as they traverse through different materials and interact with human tissues and compare simulated results with other researcher's work. Through a series of simulations, the impact of various factors, including beam energy and field size on the depth dose were investigated. It aimed to testify the validity of Monte Carlo model of electron beam in EGSnrc. Simulated data is compared with accepted data from Meyer and Loevinger. The results show that the EGSnrc can be a reliable source for modelling electron beam taking into account the uncertainties with reasonable parameters. However, it is important to acknowledge the limitations of this approach, especially the complexity and requirements for professionalism in operator and computation resources. Looking ahead, the future electron beam analysis with EGSnrc holds great potential with more accessible and efficient Monte Carlo simulations. Many of the present restrictions are anticipated to be addressed by developments in computing technology, machine learning, and interdisciplinary collaboration.

The findings of this study hold considerable significance for the field of electron beam therapy. To design optimal treatment plans that target cancerous tissues while preserving healthy surrounding structures, it is crucial to understand the depth of electron beams within the patient's body. Moreover, the validation of Monte Carlo simulations against experimental data enhances the confidence of EGSnrc in clinical use, potentially leading to improved treatment outcome for patients.

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