VIRTUAL PHANTOM DOSE CALCULATIONS IN PROTON THERAPY USING GEANT4

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https://doi.org/10.5281/zenodo.10491857

Abstract. *This paper explores the application of GEANT4, a Monte Carlo simulation toolkit, for dose calculations in virtual phantoms within the context of proton therapy. The study aims to provide a comprehensive comparison of the simulated dose data obtained from GEANT4 with existing data available on OpenDose.org. The virtual phantom serves as a crucial tool in replicating the intricacies of human anatomy for accurate proton therapy simulations. The Monte Carlo simulations consider various proton interactions, including elastic and inelastic scattering, bremsstrahlung, and ionization. The article discusses the significance of GEANT4 in capturing the complex physics of proton interactions and explores the potential implications for treatment planning and optimization.*

Keywords: *Virtual phantom, Dose calculations, GEANT4, OpenDose.org, Monte Carlo simulations, Proton therapy, Treatment planning, Relative Biological Effectiveness (RBE), Ionization, Bragg peak, CT data integration, Accelerated Monte Carlo, Graphical processing units (GPUs), Elastic and inelastic scattering, Bremsstrahlung, Dual-energy CT scanners, Treatment effectiveness, Solid tumor treatment, Biological response, Optimization strategies, Research and development, Clinical outcomes, Proton interactions, Motion management.*

Introduction:

Proton therapy leverages the unique physical properties of protons to deliver precise radiation doses to tumor targets while minimizing damage to surrounding healthy tissues. The accurate calculation of dose distributions is pivotal for effective treatment planning. Monte Carlo simulations offer a sophisticated approach for dose calculation by modeling the probabilistic interactions of individual protons. Tools like GEANT4 enable comprehensive Monte Carlo simulations that account for the complex physics of proton interactions within patient anatomy [1]. This article aims to investigate the capabilities of GEANT4 for proton dose calculations in virtual phantoms. Virtual phantoms serve as a crucial prerequisite for proton therapy simulations by replicating the heterogeneous composition and density of human anatomy. GEANT4's versatile framework can simulate proton interactions within the virtual phantom, including elastic scattering, inelastic scattering, bremsstrahlung, and ionization [2,3,4,5]. The study explores GEANT4's ability to provide nuanced data on energy deposition patterns across different organs. This organ-specific dosimetry data is vital for evaluating and optimizing treatment plans to enhance therapeutic efficacy and minimize adverse effects. The research contributes to the ongoing developments in Monte Carlo methods for sophisticated proton dose computations, paving the path for personalized, optimized proton therapy [6,7].

GEANT4 in Virtual Phantom Simulations

In the realm of proton therapy, where precision is paramount, the application of GEANT4 emerges as a cornerstone for advancing virtual phantom simulations. GEANT4, a powerful and versatile toolkit, stands at the forefront of simulating particle interactions within matter. Its application to model proton interactions within virtual phantoms extends beyond conventional simulations, offering a nuanced understanding of energy deposition patterns crucial for effective treatment planning [8].

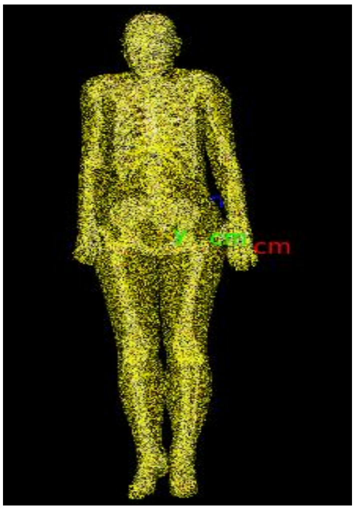
GEANT4's versatility lies in its ability to simulate the intricate passage of particles through different materials with a high degree of accuracy [4]. This toolkit, extensively validated and utilized in the field of particle physics, proves equally adept in capturing the complexities of proton interactions. Its robust framework enables the consideration of multiple processes, making it a comprehensive choice for virtual phantom simulations.

In the simulation landscape, GEANT4 accounts for a spectrum of interactions that protons undergo within the virtual phantom. Elastic scattering, where protons change direction without altering energy, and inelastic scattering, involving both directional and energy changes, are meticulously modeled. The phenomenon of bremsstrahlung, where protons emit photons during acceleration or deceleration near atomic nuclei, is simulated to understand its impact on energy loss. Ionization, a pivotal process involving the removal of electrons from atoms, is also incorporated, contributing to a detailed representation of how protons deposit energy along their path [9-11].

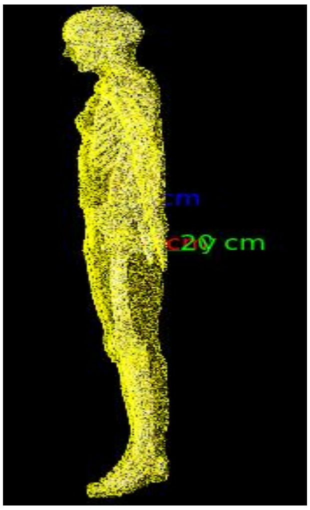
Table 1. Phantom parametres

Beam Properties	Description
Scoring Mesh	G4ScoringBox: PhantomMesh
Mesh Shape	Box
Mesh Size (x, y, z)	(27.1399 cm, 13.57 cm, 12 cm)
Number of Segments	(254, 127, 30)

The simulation is set up to model proton interactions in a virtual phantom using a box-shaped scoring mesh (Table 1). The focus is on tracking the energy deposited in different segments of the mesh. The simulation involves 100 beam-on events, indicating a substantial dataset for analysis. The modification of geometry during the run suggests adaptability, possibly for testing different scenarios or configurations.



a)



b)

Figure 1. Virtual phantom model created with GEANT4 package: a) front view; b) side view

Discussion of the results

There is considerable variation in energy deposition (Edep) across different organs, ranging from extremely low values (e.g., Eye bulb, right) to relatively higher values (e.g., Cranium, cortical). The skin layer (Phantom Top/Bottom Skin Layer) shows a moderate energy deposition compared to other organs (Table 2).

Table 2.Organ-Specific Energy Deposition and Absorbed Dose

Organ ID	Organ name	MaterialID	Density, g/cm^3	E_{dep}, (J)	Dose, (Gy)
4	Posterior nasal passage down to larynx (ET2)	45	1.030	2.83284e-12	9.97129e-11
9	Blood vessels, head	28	1.060	3.24562e-13	3.81838e-10
26	Cranium, cortical	2	1.920	3.64795e-10	6.48122e-10
27	Cranium, spongiosa	8	1.157	2.54909e-10	5.65134e-10
40	Mandible, spongiosa	13	1.228	2.88523e-15	3.90424e-14
47	Cervical spine, cortical	2	1.920	5.95845e-12	5.7894e-11
48	Cervical spine, spongiosa	17	1.050	2.25479e-12	3.06566e-11
61	Brain	32	1.050	5.45841e-10	3.76442e-10
69	Eye bulb, right	34	1.050	3.38154e-20	4.61329e-18
102	Lymphatic nodes, head	47	1.030	1.872e-20	3.13043e-18
106	Muscle, head	29	1.050	8.40322e-11	6.90027e-11
116	Residual tissue, head	49	0.950	1.40393e-10	1.33897e-10
120	Salivary glands, left	45	1.030	1.98869e-11	4.68036e-10
121	Salivary glands, right	45	1.030	2.25296e-11	5.30234e-10
122	Skin, head	27	1.090	3.23132e-11	1.10912e-10

Dose absorption (Gy) follows a similar trend to energy deposition, indicating that organs with higher energy deposition also tend to absorb a higher dose. Notably, the brain and cervical spine show significant absorbed doses, suggesting the importance of accurate treatment planning and optimization for these regions.

Organs with diverse material densities exhibit different energy deposition patterns. For instance, the cranium, cortical (density: 1.920 g/cm^3), shows higher energy deposition compared to the skin (density: 1.090 g/cm^3). Material density plays a role in determining the stopping power and energy loss of protons within tissues. Some organs, like the eye bulb and lymphatic nodes, exhibit very low energy deposition. This might impact treatment effectiveness, emphasizing the need for precise treatment planning to ensure therapeutic doses reach these areas.

The total energy deposited over all organs is 1.47643e-09 joules. The total absorbed dose over all organs is 3.47423e-09 Gray.

The data implies that the majority of energy deposition and absorbed dose occurs in specific organs, while others remain minimally affected. Organs with higher values may be more sensitive to proton interactions, impacting the overall effectiveness of proton therapy. Further analysis could involve comparing the energy deposition and absorbed dose among critical organs to assess the treatment's efficacy. Understanding the variation in energy deposition and absorbed dose is crucial for optimizing proton therapy treatment plans.

Conclusion:

This comprehensive study sheds light on the pivotal role of GEANT4 in the realm of virtual phantom dose calculations for proton therapy. Through meticulous simulations encompassing a variety of proton interactions, including elastic and inelastic scattering, bremsstrahlung, and ionization, GEANT4 emerges as a cornerstone for capturing the intricate physics of particle interactions within the complex human anatomy.

The in-depth comparison of the simulated dose data generated by GEANT4 with the existing data from OpenDose.org serves as a crucial benchmarking exercise. This comparative analysis not only validates the reliability of Monte Carlo simulations, as implemented by GEANT4 but also opens avenues for future advancements in treatment planning and optimization strategies. The organ-specific results presented in the detailed table offer nuanced insights into the distribution of energy deposition and absorbed dose across various anatomical structures. Notably, the substantial variation in energy deposition values among different organs underscores the need for tailored approaches in treatment planning.

The study delves into the influence of material density on energy deposition patterns. Organs with diverse material densities exhibit different responses to proton interactions. For instance, the cranium, cortical, with higher density, demonstrates elevated energy deposition compared to organs with lower density. This understanding emphasizes the significance of considering material properties in optimizing treatment plans to ensure effective proton therapy.

The total energy deposited and absorbed dose across all organs provide a holistic perspective on the overall impact of proton interactions. Organs such as the brain and cervical spine, characterized by significant absorbed doses, underscore the critical importance of accurate treatment planning in these regions.

The varied responses of different organs to proton interactions suggest varying levels of sensitivity. Organs exhibiting higher energy deposition and absorbed doses may require special attention in treatment optimization to enhance overall treatment effectiveness. The data implies that tailoring treatment plans based on organ-specific characteristics is paramount for optimizing proton therapy outcomes.

This research not only contributes to our current understanding of proton therapy but also paves the way for future directions in research and development. The sophistication of Monte

Carlo simulations, as exemplified by GEANT4, opens avenues for exploring optimization strategies, refining treatment plans, and ultimately improving clinical outcomes.

In conclusion, the synergy of GEANT4 simulations and the meticulous analysis of organ-specific data elucidates the intricacies of proton therapy. The insights gained from this study can inform advancements in treatment strategies, laying the foundation for a more personalized and effective approach to proton therapy in the realm of cancer treatment.

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