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Enhancing Precision in Radiotherapy Delivery: Validating Monte Carlo Simulation Models for 6 MV Elekta Synergy Agility LINAC Photon Beam Using Two Models of the GAMOS Code

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Abstract

The most crucial requirement in radiation therapy treatment planning is a fast and accurate treatment planning system that minimizes damage to healthy tissues surrounding cancer cells. The use of Monte Carlo toolkits has become indispensable for research aimed at precisely determining the dose in radiotherapy. Among the numerous algorithms developed in recent years, the GAMOS code, which utilizes the Geant4 toolkit for Monte Carlo simulations, incorporates various electromagnetic physics models and multiple scattering models for simulating particle interactions with matter. This makes it a valuable tool for dose calculations in medical applications and throughout the patient's volume. The aim of this present work aims to validate the GAMOS code for the simulation of a 6 MV photon-beam output from the Elekta Synergy Agility linear accelerator. The simulation involves modeling the major components of the accelerator head and the interactions of the radiation beam with a homogeneous water phantom and particle information was collected following the modeling of the phase space. This space was positioned under the X and Y jaws, utilizing three electromagnetic physics models of the GAMOS code: Standard, Penelope, and Low-Energy, along with three multiple scattering models: Goudsmit-Saunderson, Urban, and Wentzel-VI. The obtained phase space file was used as a particle source to simulate dose distributions (depth-dose and dose profile) for field sizes of 5 × 5 cm^2 and 10 × 10 cm^2 at depths of 10 cm and 20 cm in a water phantom, with a source-surface distance (SSD) of 90 cm from the target. We compared the three electromagnetic physics models and the three multiple scattering models of the GAMOS code to experimental results. Validation of our results was performed using the gamma index, with an acceptability criterion of 3% for the dose difference (DD) and 3 mm for the distance-to-agreement (DTA). We achieved agreements of 94% and 96%, respectively, between simulation and experimentation for the three electromagnetic physics models and three multiple scattering models, for field sizes of 5 × 5 cm^2 and 10 × 10 cm^2 for depth-dose curves. For dose profile curves, a good agreement of 100% was found between simulation and experimentation for the three electromagnetic physics models, as well as for the three multiple scattering models for a field size of 5 × 5 cm^2 at 10 cm and 20 cm depths. For a field size of 10 × 10 cm^2, the Penelope model dominated with 98% for 10 cm, along with the three multiple scattering models. The Penelope model and the Standard model, along with the three multiple scattering models, dominated with 100% for 20 cm. Our study, which compared these different GAMOS code models, can be crucial for enhancing the accuracy and quality of radiotherapy, contributing to more effective patient treatment. Our research compares various electromagnetic physics models and multiple scattering models with experimental measurements, enabling us to choose the models that produce the most reliable results, thereby directly impacting the quality of simulations. This enhances confidence in using these models for treatment planning. Our research consistently contributes to the progress of Monte Carlo simulation techniques in radiation therapy, enriching the scientific literature.

Keywords

GAMOS, Monte Carlo, LINAC, Radiotherapy, Dose Distribution, Phase Space, Gamma Index, 6 MV Photon Beam

1. Introduction

The current battle against cancer relies on three major pillars of treatment: radiotherapy, chemotherapy, and surgery. In this context, radiotherapy aims to deliver a precise dose to the tumor volume while preserving the surrounding healthy tissues. X-rays beams, in the ranges 4 - 25 MeV produce by linear accelerators (LINACS), are most often used in radiotherapy to the patient irradiation for local cancer treatment. Among all the numerous algorithms developed in recent years for dose distribution in radiotherapy planning, the GAMOS code based on Geant4 Monte Carlo has proven to be the most accurate method. For dosimetry calculations in medical physics, the Monte Carlo method is universally recognized as the gold standard. For dosimetry calculations in medical physics, the Monte Carlo method is universally recognized as the gold standard. Several studies [1] [2] [3] [4] have demonstrated that Monte Carlo-based codes are the most accurate tools for dose calculations in radiotherapy. Among the early research using Geant4 for simulating a linear accelerator in radiotherapy, noteworthy are the works of [2] [5] [6]. Several studies where the Monte Carlo method is used in modeling the linear accelerator head are cited [7]-[13], while the GAMOS code is predominantly identified in research studies such as [14]. These studies validate the geometry module and the different physics lists, which have been optimized to model the transport of photons and charged particles for radiotherapy applications. Additionally, [15] compares the three Geant4 electromagnetic physics sets of models (Standard, Livermore, and Penelope) to experimental data, testing the four different models of angular bremsstrahlung distributions as well as the three available multiple-scattering models, and optimizing the most relevant Geant4 electromagnetic physics parameters. Before the fitting, comprehensive CPU time optimization has been conducted using several Geant4 efficiency improvement techniques, along with a few more developed in GAMOS. Furthermore, [16] utilizes Gnome Builder, Python, and GTK to create a program named GamosLinacGUI for the design interface. With this program, users can input numbers, choose parameters, and rapidly construct geometry and physics files if they wish to study the fundamentals of GAMOS and simulate a linear accelerator.

However, up to now, most studies conducted with Geant4 have not explored the three electromagnetic physics models available in the GAMOS code: the Standard, Penelope, and Low-Energy models [17] [18]. An exception is the work of [15], which investigated the three sets of Geant4 electromagnetic physics models (Standard, Livermore, and Penelope), the three multiple scattering models, and the four angular distribution models of bremsstrahlung.

This simulation is carried out using the GAMOS platform that extends Geant4 [5] to provide an environment specifically tailored for medical applications. GAMOS enables simulations without the need for C++ programming, offering flexibility in modifying Geant4's physical parameters [18] through a scripting language. Among the Monte Carlo simulation tools mentioned are Electron Gamma Shower (EGS) for simulating the transport of photons and electrons in various mediums [19] [20], ETRAN (Electron TRANsport) for photon/electron coupled transport [21], Monte Carlo N-Particle transport code (MCNP) to simulate the transport of photons, electrons, neutrons, and other particles in complex geometries [22], PENELOPE (PENetration and Energy LOss of Positrons and Electrons) particularly designed for simulating the transport of photons, positrons, and electrons in matter [23], Phoebe (PHOton and Electron Beams) specifically for applications that require a detailed understanding of the transport and interactions of photons and low-energy electrons in matter, and GEANT (GEometry ANd Tracking) used to simulate how particles pass through matter [5], with the latest version, GEANT4, being the first tool in this domain to use C++ programming language and an object-oriented programming methodology. Although recent, GEANT4 requires substantial memory resources. Within Geant4, there is the GATE code (Geant4 Application for Tomographic Emission) [24] and the GAMOS code, which is used in our simulation (version 6.2.0). GAMOS provides easily accessible libraries, components such as geometry, visualization, physics, primary particles, user actions, signal processing, scoring, histogramming, etc., as well as tutorials (Compton Camera, DICOM, Gamma Spectrometry, Histograms and Scorers, PET, SPECT, Plug-in, Protontherapy, Radiotherapy, Shielding, and X-rays) that offer detailed information on calculations [25]. In this study, we validated simulations concerning the Elekta Synergy Agility linear accelerator at the International Cancer Center of Dakar (ICCD) in Senegal, comparing depth-dose and dose profiles obtained from the three electromagnetic physics models and the three multiple scattering models with experimentally determined values.

2. Materials and Methods

2.1. Modeling the LINAC Head with GAMOS Code

The modeling of the Elekta Synergy Agility linear accelerator head using the GAMOS code was conducted to simulate a 6 MV photon beam. This Monte Carlo simulation platform, dedicated to various medical applications such as radiotherapy, gamma spectrometry, shielding, Compton camera, proton therapy, and positron emission tomography (PET), is built upon Geant4. The modeling encompasses the three electromagnetic physics models and the three multiple scattering models of the GAMOS code. The modeled components of the accelerator head include the target, primary collimator, flattening filter (considered crucial for beam flattening at the exit of the primary collimator), ionization chamber, and X and Y jaws. All technical data required for modeling were provided by the manufacturer, covering dimensions, chemical composition, and density of different structures. However, adjustments were made to certain parameters such as energy and flattening filter. The visual representation of the LINAC irradiation head **Figure 1** in combination with the water phantom was created using the VRML2FILE function of the GAMOS code with view3dscene. Data analysis was performed using the Python language and the Visual Studio Code (VSC) development environment. All obtained results were compared to experimental data from the International Cancer Center of Dakar in Senegal. This systematic approach and the use of GAMOS to model the accelerator head demonstrates our commitment to simulation accuracy, reinforced by systematic comparison with experimental data from ICCD.

2.2. Phase Space Simulation

Following the modeling of the linear accelerator components (target, primary collimator, flattening filter, ionization chamber, and X and Y jaws), we generated a phase space file following the format of the International Atomic Energy Agency (IAEA) [26], aiming to become a Monte Carlo simulation standard. Positioned between the jaws and the water phantom, this file generated 3×10^8 events using the following electromagnetic physics models: Standard, Low-Energy, and Penelope, along with the three multiple scattering models: Goudsmit-Saunderson, Urban, and Wentzel-VI. These simulations were conducted for field sizes of $5 \times 5\ \text{cm}^2$ and $10 \times 10\ \text{cm}^2$ at depths of 10 cm and 20 cm.

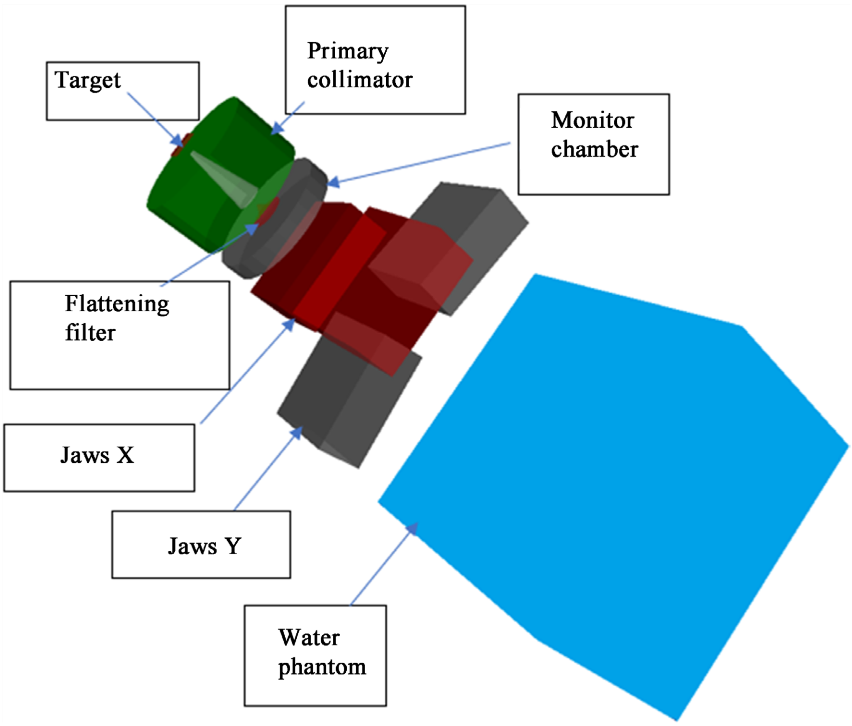

Figure 1. Modeling of the LINAC head with the water phantom positioned at 100 cm, visualized using VRML2FILE function of GAMOS code with view3dscene.

Physical characteristics of each particle passing through the recording plane were recorded in the phase space file, including information on particle types, energy, position, direction, and statistical weight. This phase space, positioned after the jaws, was used as a virtual source to calculate the dose distribution in the phantom for each of the three electromagnetic physics models and the three multiple scattering models. To enhance simulation efficiency, phase space particles were recycled 50 times for both electromagnetic physics and multiple scattering models, utilizing a XY mirror to reflect the reused particles.

2.3. Modeled Water Phantom

In radiotherapy, dose distributions in a water phantom play a crucial role in characterizing the incident beam. The curve showing the variation of absorbed dose in water along the beam axis is referred to as the depth-dose curve. Meanwhile, the variation of absorbed dose in a plane perpendicular to the beam axis is designated as the dose profile. For our simulations, a water phantom with dimensions of 60 × 60 × 41 cm^3 was utilized. We started with the initial voxel size of 120 × 120 × 41 along the x, y, z axes which was further divided into smaller voxels with dimensions of 5 × 5 × 10 mm^3 and a density of 1 $g.cm^3$.

This water phantom was placed at a source-surface distance (SSD) of 90 cm from the target, with field sizes of 5 × 5 cm^2 and 10 × 10 cm^2 at depths of 10 cm and 20 cm. These configurations were employed for the three electromagnetic physics models (Standard, Penelope, and Low-Energy) and the three multiple scattering models (Goudsmit-Saunderson, Urban, and Wentzel-VI) when modeling dose profiles. For depth-dose curves, the water phantom was positioned at 100 cm from the target. In experimental setups, measurements were conducted using a water phantom available at the International Cancer Center of Dakar in Senegal. Two detectors were utilized: a PTW-Freiburg microDiamond model (made in Germany) for dose profile data and a PTW-Freiburg Semiflex ionization chamber with a volume of 0.3 cm^3 (made in Germany) for depth-dose measurements.

2.4. Comparison with Gamma Index

The Gamma Index (GI) used in our study is a mathematical tool employed for the quantitative comparison of two dose distributions in radiotherapy. The gamma index values represent the agreement between the measured and simulated dose profiles. Its purpose is to quantify the accuracy of the delivered dose during treatment by comparing a reference dose distribution (D_r) with an evaluated dose distribution (D_c). This method, introduced by [27], and later by [28], takes into account two parameters: the dose difference criterion (ΔD in %) and the distance difference criterion (Δd or DTA—Distance To Agreement in mm) between two points. The formula for the gamma index is defined as follows:

$$\gamma = \sqrt{\frac{\left(D_r - D_c\right)^2}{\Delta D^2} + \frac{\left(d_r - d_c\right)^2}{\Delta d^2}}$$

where D_r is reference dose distribution at distance d_r; D_c is the dose distribution to be evaluated at distance d_c; ΔD is the criterion for dose difference (in English, dose deviation DD); and Δd is the criterion for distance difference (in English, distance to agreement DTA). If the gamma index is less than 1, it means that the comparison between the measured and calculated points is acceptable according to the set tolerance criteria. However, if the gamma index is greater than 1, the test is not satisfied as it falls outside the acceptability ellipse. The acceptance criteria for the gamma index (GI) test used in our research are a dose deviation of 3% and a distance difference of 3 mm.

3. Results and Discussions

3.1. Comparison of Measurement and Simulation for Depth-Dose, Field Size 5 × 5 cm^2 and 10 × 10 cm^2

In this study, we characterized the incident beam in radiotherapy using dose distributions in a water phantom. Depth-dose curves were calculated along the central axis of the irradiation beam, and dose profiles were calculated at a depth perpendicular to the central axis, for field sizes of 5 × 5 cm^2 and 10 × 10 cm^2. We employed the three electromagnetic physics models: Standard, Penelope, and Low-Energy, as well as the three multiple scattering models: Goudsmit-Saunderson, Urban, and Wentzel-VI. All these curves were compared to the experimentally measured data. The adjustment of simulated values to experimental data was performed using maximum normalization, where the dose per voxel was divided by the maximum dose. Subsequently, we used the gamma index with an acceptable criterion of 3% for dose difference and 3 mm for distance-to-agreement, following the study by [27]. These criteria allowed us to assess the consistency between experimental and simulated values. The results demonstrate satisfactory agreement between experimental and simulated values **Table 1** and **Table 2** for the three electromagnetic physics models and the three multiple scattering models. The gamma index is 94% for depth-dose curves for a field size of 5 × 5 cm^2 **Figure 2** and **Figure 3** and 96% for a field size of 10 × 10 cm^2 **Figure 4** and **Figure 5**.

Table 1. Results of the gamma index for depth dose curves between measurement and Low-Energy, Standard, and Penelope models.

Model/Field sizes	5 × 5 cm^2	10 × 10 cm^2
Low-Energy	94%	96%
Standard	94%	96%
Penelope	94%	96%
…		

Table 2. Results of the Gamma index for depth-dose curves between measurement and Goudsmit-Saunderson, Urban, and Wentzel-VI models.

Model/Field sizes	5 × 5 cm^2	10 × 10 cm^2
Goudsmit-Saunderson	94%	96%
Urban	94%	96%
Wentzel-VI	94%	96%
…		

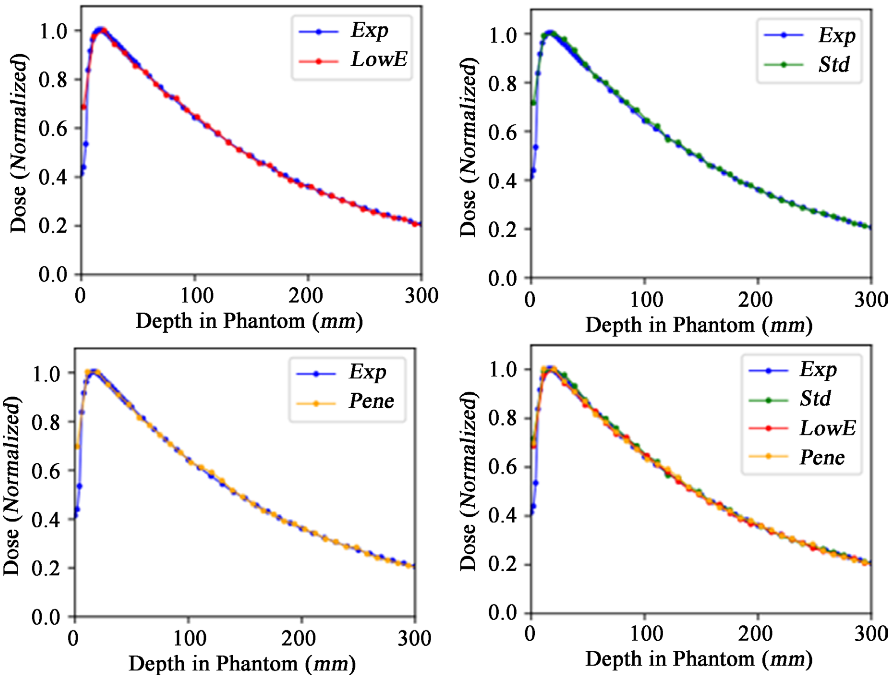

Figure 2. Comparison between measurement and simulation of depth-dose for 5 × 5 cm^2, using Low-Energy (LowE), Standard (Std), and Penelope (Pene) electromagnetic physics models.

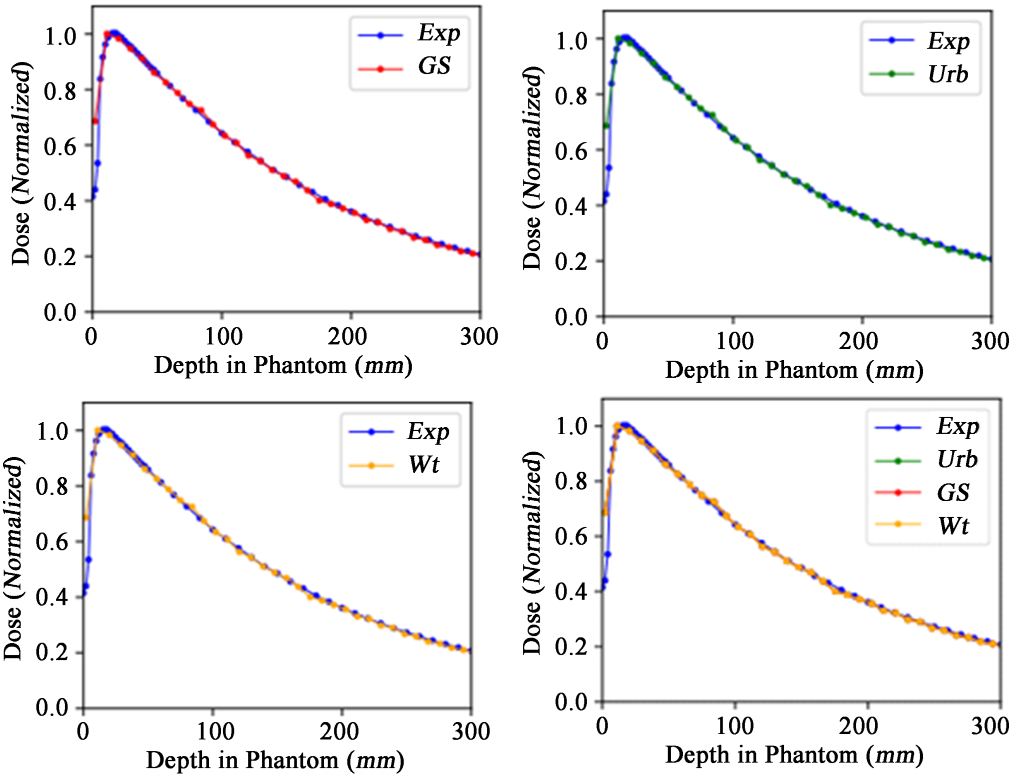

Figure 3. Comparison between measurement and simulation of depth dose curves for 5 × 5 cm^2 field size, using three multiple scattering models: Goudsmit-Saunderson (GS), Urban (Urb), and Wentzel-VI (Wt).

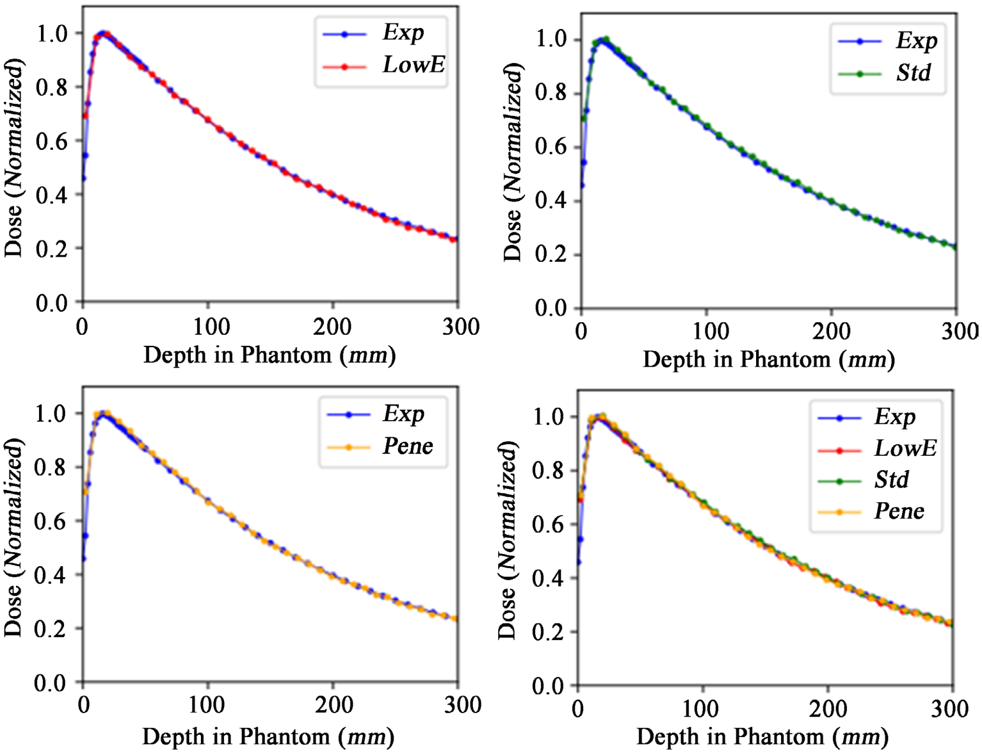

Figure 4. Comparison between measurement and simulation of depth-dose for 10 × 10 cm^2, using Low-Energy (LowE), Standard (Std), and Penelope (Pene) electromagnetic physics models.

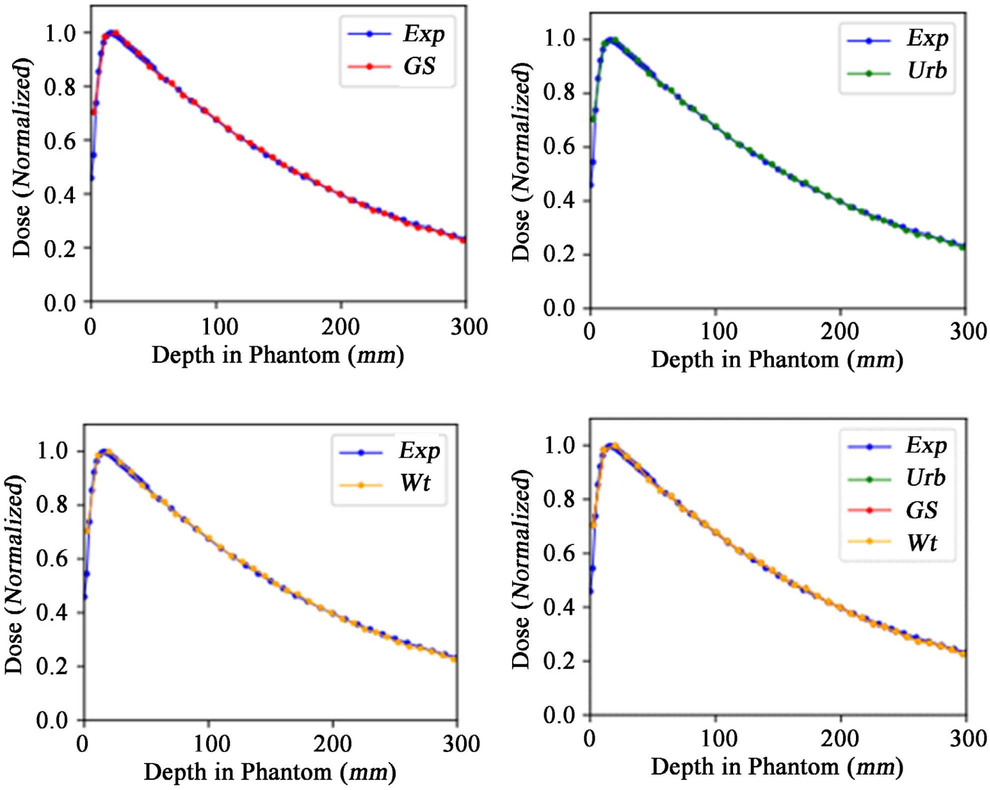

Figure 5. Comparison between measurement and simulation of depth dose curves for 10 × 10 cm^2 field size, using three multiple scattering models: Goudsmit-Saunderson (GS), Urban (Urb), and Wentzel-VI (Wt).

These findings reinforce the validity of our modeling approach, highlighting the capability of GAMOS code models to faithfully reproduce the dosimetry characteristics of the irradiation beam.

3.2. Comparison between Measurement and Simulation for Dose Profile, Field Size 5 × 5 cm², and 10 × 10 cm², Depths 10 cm and 20 cm

Concerning dose profiles at depths of 10 cm and 20 cm, the Penelope, Standard, and Low-Energy electromagnetic physics models show 100% agreement Table 3 for a field size of 5 × 5 cm^2 Figure 6 and Figure 7. Similarly, at a depth of 10 cm and 20 cm with a field size of 5 × 5 cm^2 Figure 8 and Figure 9, the multiple scattering models: Goudsmit-Saunderson, Urban, and Wentzel-VI show 100% agreement Table 4. For a field size of 10 × 10 cm^2 at a depth of 10 cm, the Penelope model shows 98% agreement, followed by the Standard model at 96%, while the Low-Energy model exhibits a slightly lower agreement of 92% Figure 10 and Table 3.

At 20 cm depth, the Penelope and Standard models show 100% agreement, followed by the Low-Energy model at 99% Figure 11 and Table 3. For the same field size of 10 × 10 cm^2 at 10 cm depth, the multiple scattering models: Goudsmit-Saunderson, Urban, and Wentzel-VI exhibit 98% agreement each Figure 12 and **Table 4**, while at 20 cm depth, these models show 100% agreement each **Figure 13** and **Table 4**.

It is important to note that [15] also used the Standard, Livermore, and Penelope electromagnetic physics models and strongly recommended the use of the Standard model.

Table 3. Results of the gamma index for the dose profile between measurement (Exp) and the Low-Energy, Standard, and Penelope models.

Model/Field sizes	5 × 5 cm²	10 × 10 cm²
Low-Energy		
10 cm	100%	92%
20 cm	100%	99%
Standard		
10 cm	100%	96%
20 cm	100%	100%
Penelope		
10 cm	100%	98
20 cm	100%	100%
…		

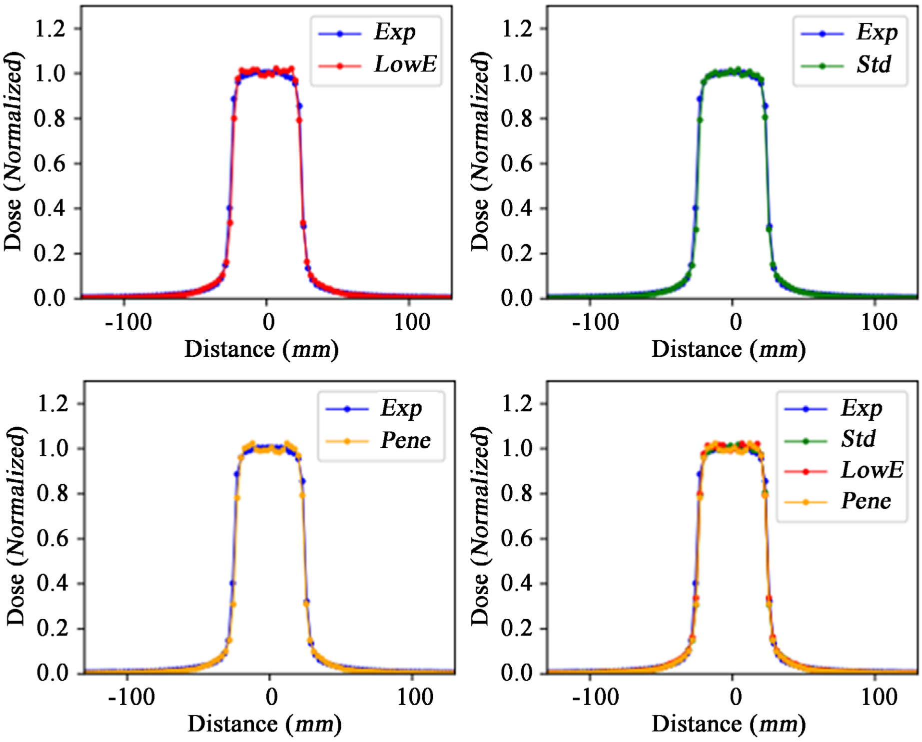

Figure 6. Comparison between measurements and simulations for Dose Profile, Field Size 5 × 5 cm², Depth 10 cm using Low-Energy (LowE), Standard (Std), and Penelope (Pene) electromagnetic physics models.

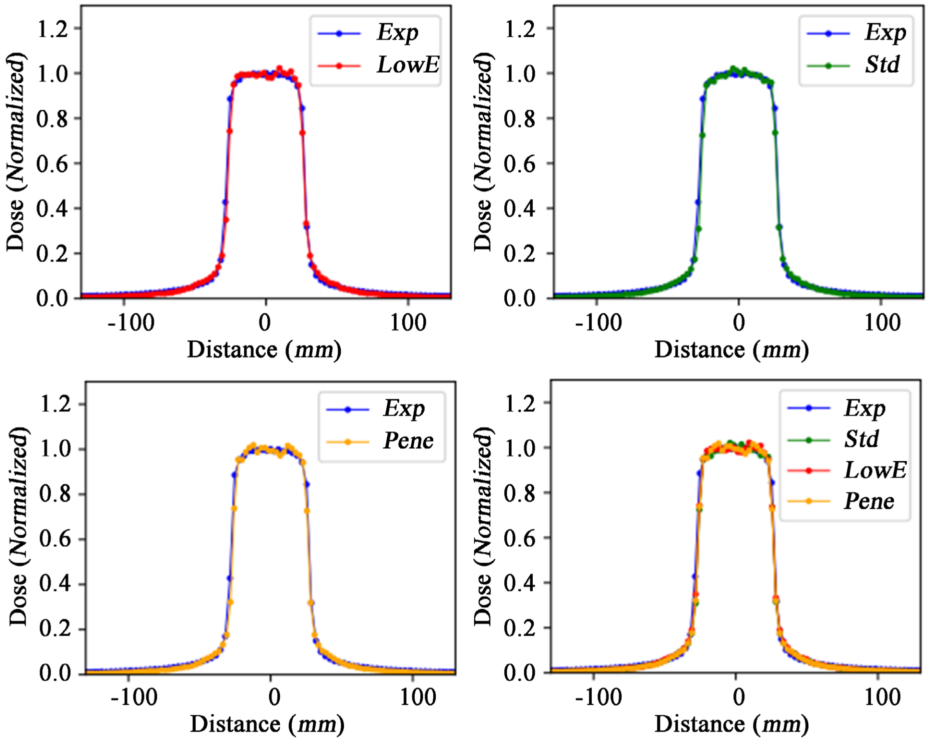

Figure 7. Comparison between measurements and simulations for Dose Profile, Field Size 5 × 5 cm², Depth 20 cm using Low-Energy (LowE), Standard (Std), and Penelope (Pene) electromagnetic physics models.

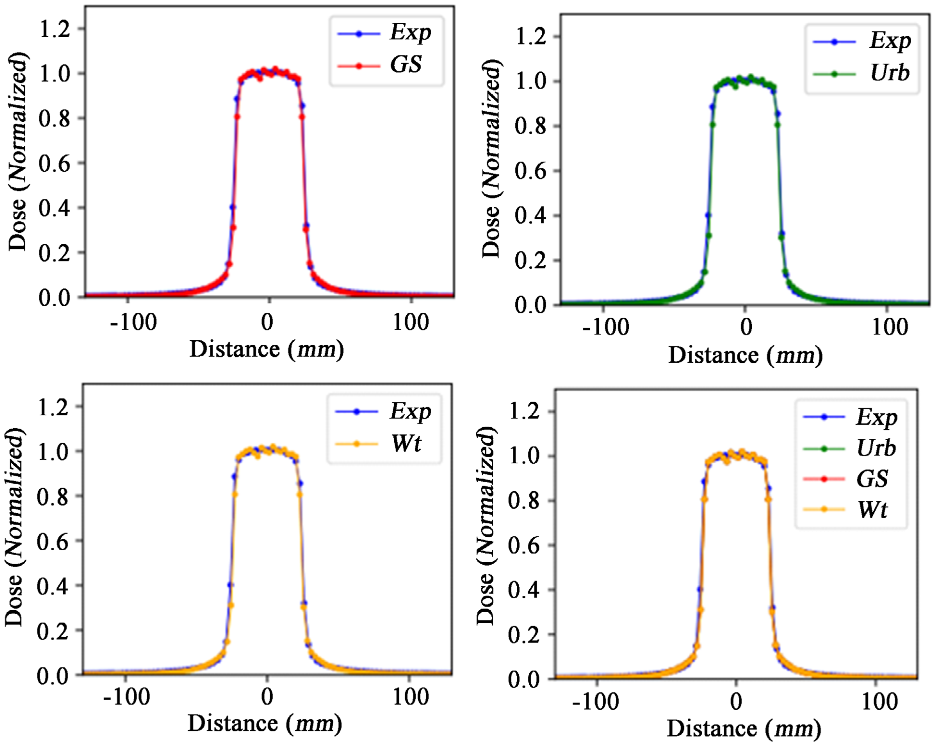

Figure 8. Comparison between measurements and simulations for Dose Profile, Field Size 5 × 5 cm², Depth 10 cm using three multiple scattering models: Goudsmit-Saunderson (GS), Urban (Urb), and Wentzel-VI (Wt).

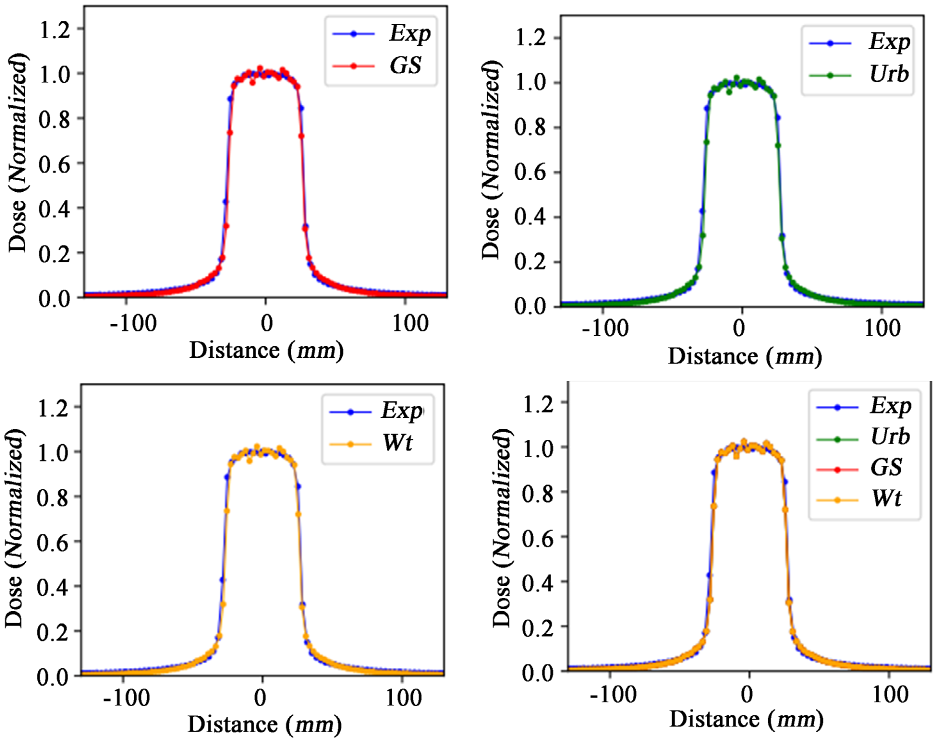

Figure 9. Comparison between measurements and simulations for the dose profile, field size 5 × 5 cm², depth 20 cm using the three multiple scattering models Goudsmit-Saunderson (GS), Urban (Urb), and Wentzel-VI (Wt).

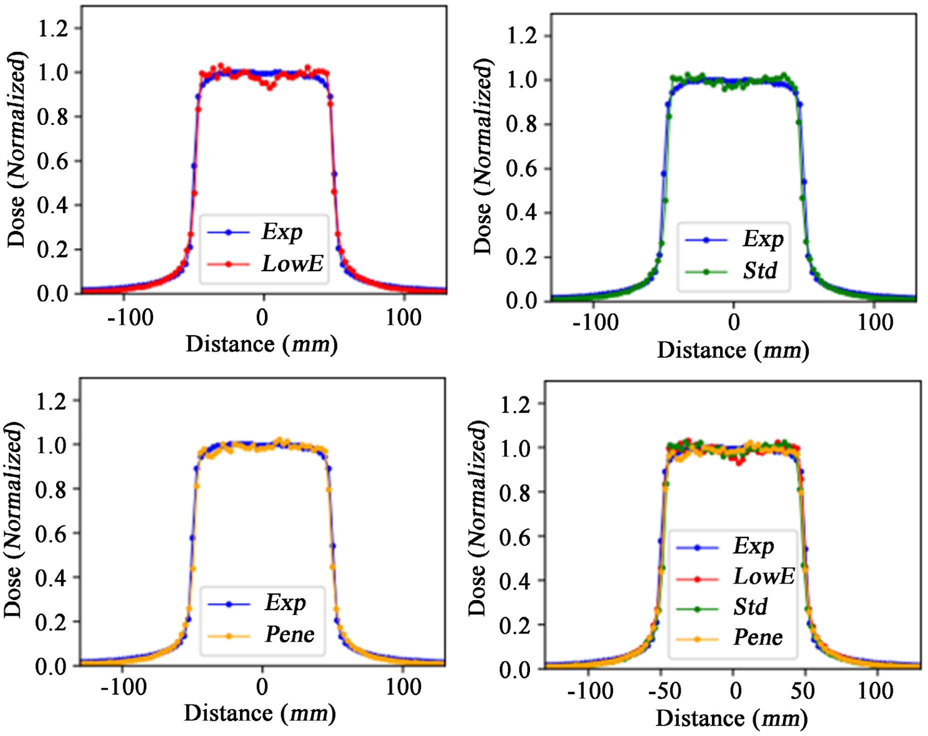

Figure 10. Comparison between measurements and simulations for the dose profile, field size 10 × 10 cm², depth 10 cm using the electromagnetic physics models Low-Energy (LowE), Standard (Std), and Penelope (Pene).

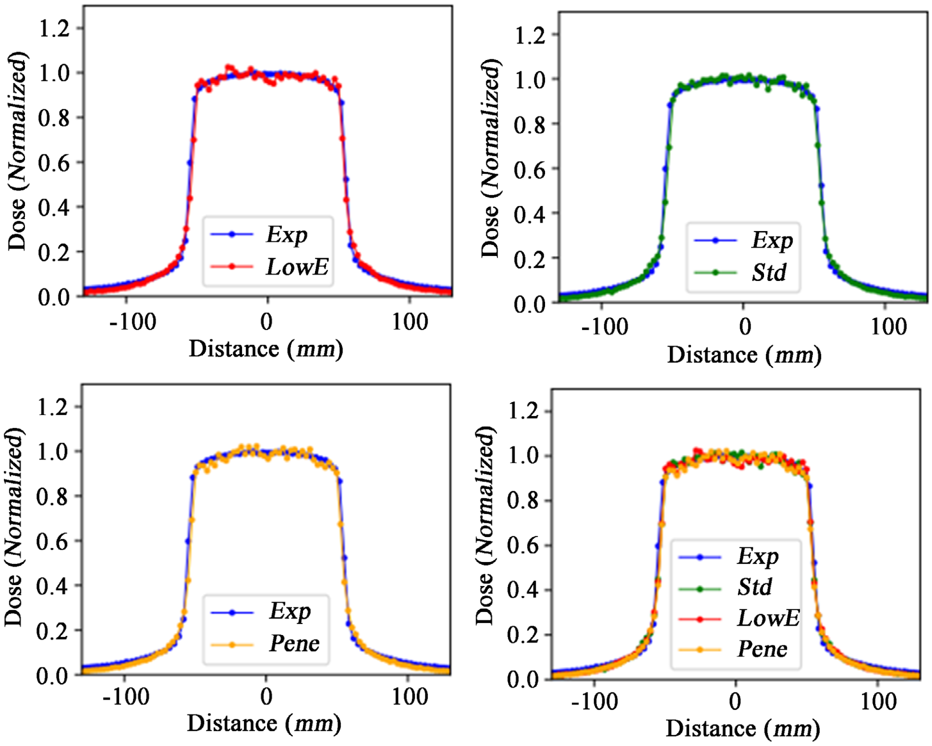

Figure 11. Comparison between measurements and simulations for the dose profile, field size 10 × 10 cm², depth 20 cm using the electromagnetic physics models Low-Energy (LowE), Standard (Std), and Penelope (Pene).

Table 4. Results of the gamma index for the dose profile between measurement (Exp) and the Goudsmit-Saunderson (GS), Urban (Urb), and Wentzel-VI models.

Model/Field sizes	5 × 5 cm²	10 × 10 cm²
Goudsmit-Saunderson		
10 cm	100%	98%
20 cm	100%	100%
Urban		
10 cm	100%	98%
20 cm	100%	100%
Wentzel-VI		
10 cm	100%	98%
20 cm	100%	100%
…		

We observe good agreement between experimental and simulated curves for the field size of 5 × 5 cm² at depths of 10 cm and 20 cm for all three electromagnetic physics models and the three multiple scattering models (100%).

However, for a field size of 10 × 10 cm², discrepancies in dose profile curves are noted for the three electromagnetic physics models. The difference between

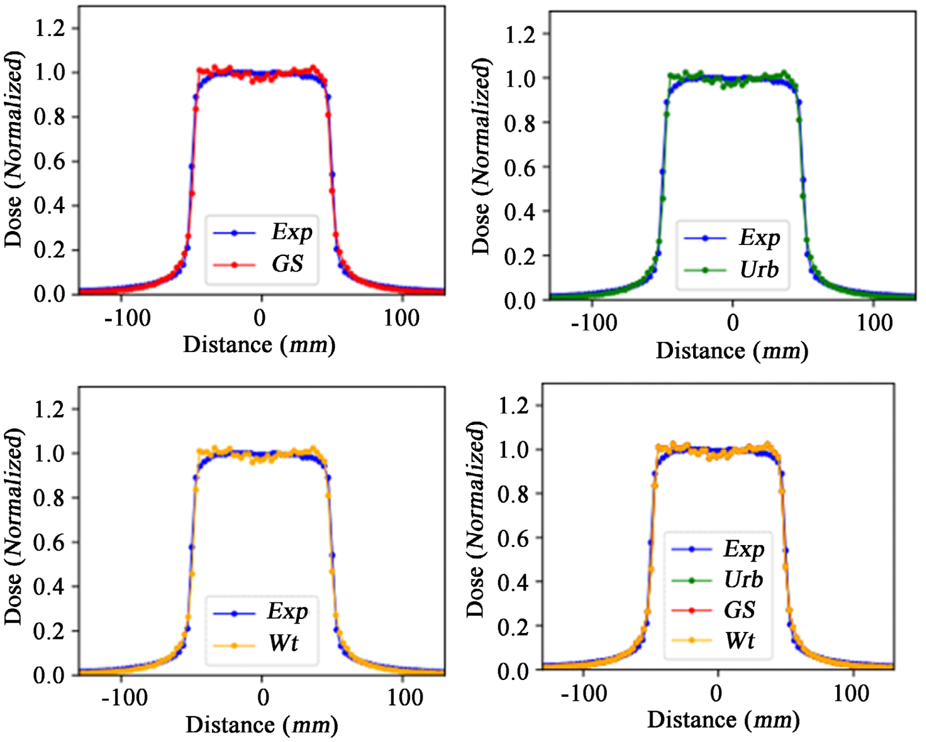

Figure 12. Comparison between measurements and simulations for Dose Profile, Field Size 10 × 10 cm^2, Depth 10 cm using three multiple scattering models: Goudsmit-Saunderson (GS), Urban (Urb), and Wentzel-VI (Wt).

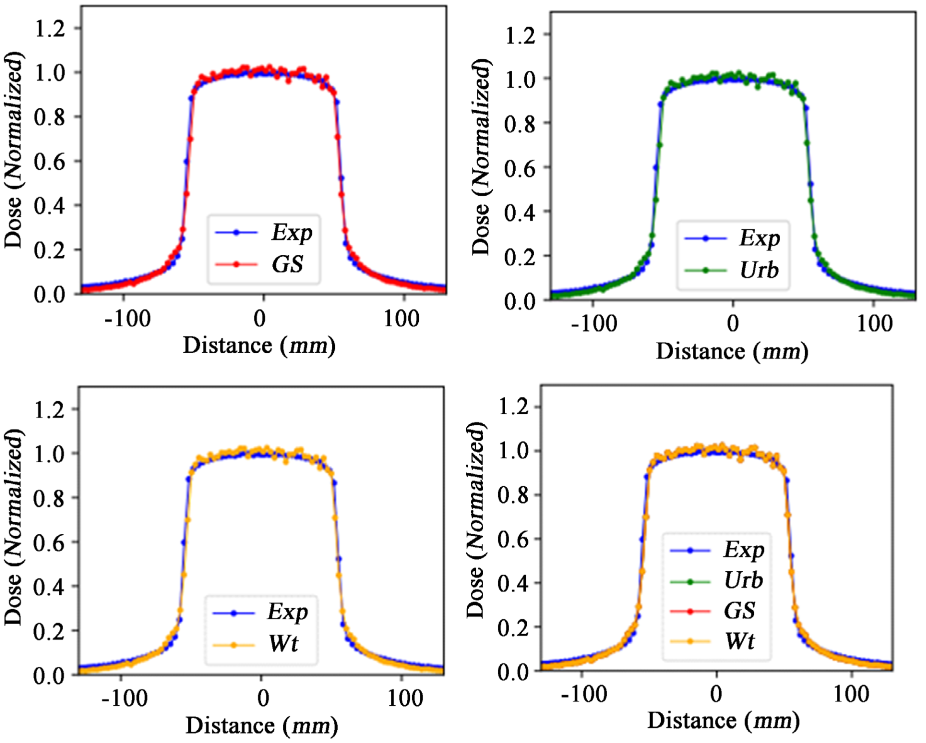

Figure 13. Comparison between measurements and simulations for the dose profile, field size 10 × 10 cm^2, depth 20 cm using the three multiple scattering models Goudsmit-Saunderson, Urban, and Wentzel-VI.

the found models is due to statistical fluctuations.

These differences could be attributed to potential variations between manufacturer-provided values and the actual characteristics of the LINAC installed at the hospital, emphasizing the importance of precision in accelerator geometry modeling.

The good agreement observed in the comparison of depth dose curves and simulated dose profiles, utilizing electromagnetic physics models and multiple scattering models, with experimental measurements, indicates that our study offers vital information for selecting models that guarantee the most reliable results. This paves the way for broader adoption in treatment planning. Additionally, this study highlights that the phase spaces generated in each of the electromagnetic physics and multiple scattering models can be utilized as templates for simulating a 6 MV photon beam from an Elekta Synergy linear accelerator, making them accessible to researchers interested in conducting further studies.

4. Conclusion

The Monte Carlo simulation of the treatment head of the Elekta Synergy Agility linear accelerator using the GAMOS code based on Geant4 has been successfully carried out. This study validated the GAMOS Monte Carlo model for simulating a 6 MV photon beam with field sizes of 5 × 5 cm^2 and 10 × 10 cm^2 at 10 and 20 cm depths. To our knowledge, this comparison between experimental and simulated values using the three electromagnetic physics models Standard, Penelope, and Low-Energy, as well as the three multiple scattering models Goudsmit-Saunderson, Urban, and Wentzel-VI of the GAMOS code for an Elekta Synergy Agility linear accelerator with flattening filter, has never been conducted in the field of radiotherapy, besides the work performed by Pedro Arce and Juan Ignacio Lagares 2018 which focused on CPU time optimization and precise adjustment of the Geant4 physics parameters for a VARIAN 2100 [15]. The comparison results show a good agreement for the depth-dose curves for field sizes of 5 × 5 cm^2 and 10 × 10 cm^2, with no significant difference between the three electromagnetic physics models and the three multiple scattering models. Regarding the dose profile curves, the Penelope, Low-Energy, and Standard models show an excellent agreement with experimental data for a field size of 5 × 5 cm^2 at 10 cm and 20 cm depths, just like the Goudsmit-Saunderson, Urban, and Wentzel-VI models (100%). For a field size of 10 × 10 cm^2 at 10 cm depth, the Penelope model gives the best results (98%), while at 20 cm depth, the Penelope and Standard models dominate (100%). No obvious difference is observed between the three multiple scattering models: Goudsmit-Saunderson, Urban, and Wentzel-VI for dose profile curves, with a field size of 10 × 10 cm^2 at 10 cm depth (98%) and at 20 cm depth (100%). This study demonstrates that the three electromagnetic physics models and the three multiple scattering models of the GAMOS code provide reasonably consistent results with experimental data. Although it is challenging to provide an in-depth assessment of the observed differences, some generic conclusions can be drawn, including that the Penelope and Standard models perform well in comparison with experimentation, as do the three multiple scattering models. There is no obvious difference between the three electromagnetic physics models and the three multiple scattering models. This suggests that these models are all suitable for simulating linac photon beams in the context of this study. In summary, this study validates the use of the GAMOS code based on Geant4 for simulating linac photon beams and confirms their suitability for this application. These results are promising for the continuous improvement of Monte Carlo simulation techniques in radiotherapy, which could contribute to better accuracy and treatment planning. The developed methodology can be applied to other linear accelerators to assess the generalizability of the results and identify any specificities. For clinical validation, aspects such as patient variability and specific treatment configurations should be integrated. Collaboration with clinical experts, medical physicists, and other healthcare professionals is essential to ensure that the simulations meet the practical requirements of radiotherapy. The results and insights from this study should be compiled into practical guidelines for the radiotherapy community to optimize the use of Monte Carlo simulations.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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