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Research Article

Evaluation of Bremsstrahlung Angular Distribution Models in the Monte Carlo Simulation of a 6 MV *Photon* Beam from an Elekta Synergy Agility Linear Accelerator Using the GAMOS Code

Nogaye Ndiaye[1, 2, *], Djicknack Dione[1, 2], Oumar Ndiaye[1, 2], Jean Paul Latyr Faye[1, 2], Alassane Traore[1, 2], Ababacar Sadikhe Ndao [2]

[1]Institute of Applied Nuclear Technology, University Cheikh Anta Diop, Dakar-Fann, Senegal
[2]Department of Physics, Faculty of Sciences and Technology, University Cheikh Anta Diop, Dakar-Fann, Senegal

Abstract

This study aims to validate the simulation model of the GAMOS/ GEANT4 code for a 6 MV photon beam produced by the Elekta Synergy Agility linear accelerator installed at the International Cancer Center of Dakar (CICD), Senegal. The simulation encompasses all major components of the accelerator head: the target, primary collimator, flattening filter, ionization chamber, and X and Y jaws, using a homogeneous water phantom. The phase space was placed after the jaws, and for each angular distribution model studied: Tsai, Koch–Motz 2BS, and Koch–Motz 2BN, the dose distribution was evaluated. This includes depth dose curves for field sizes of 5×5 cm ^{2}and 10×10 cm ^{2}at a source-to-axis distance (SAD) of 100 cm, as well as dose profiles at depths of 5, 10, 15, and 20 cm in the phantom, with a source-to-surface distance (SSD) of 90 cm from the target. The three bremsstrahlung angular distribution models implemented in GAMOS were then compared with experimental measurements. Validation was performed using the gamma index, with an acceptance criterion of 3% for dose difference (DD) and 3 mm for distance to agreement (DTA). For the depth dose curves, a 94% agreement was observed between simulated and experimental data for the 5×5 cm ^{2}field, and 96% for the 10×10 cm ^{2}field, regardless of the model. Regarding the dose profiles, the three models: Koch–Motz 2BN, Koch–Motz 2BS, and Tsai, exhibit perfect agreement (100%) with measurements for the 5×5 cm ^{2}field size at all depths. For the 10×10 cm ^{2}field, the Koch–Motz 2BN model shows excellent agreement of 100% at 5 cm and 20 cm depths, followed by the Tsai model with 99% at 20 cm. At 10 cm depth, agreement reached 99% for Koch–Motz 2BN and 97% for Tsai. At 15 cm, Koch–Motz 2BN and Tsai achieved 98%, followed by Koch–Motz 2BS with 92%. At 20 cm, Koch–Motz 2BN maintained 100% agreement, followed by Tsai (99%) and Koch–Motz 2BS (94%). This study compares three bremsstrahlung angular distribution models in GAMOS with experimental values, assessing their respective performances in photon beam simulation. These results may guide radiotherapy practitioners in selecting the most appropriate model. In summary, this work contributes to the validation and enhancement of simulation techniques in radiotherapy, thereby improving treatment optimization and patient safety in cancer care.

Keywords

Elekta Synergy, GAMOS, Tsai, Koch–Motz 2BS, Koch–Motz 2BN, Dose Distribution, Gamma Index

[*]Corresponding author: nogaye11.ndiaye@ucad.edu.sn (Nogaye Ndiaye)

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1. Introduction

Cancer remains one of the leading causes of mortality worldwide and represents a major public health challenge. In Senegal, it particularly affects the female population [1]. To address this issue, the authorities have established several specialized centers, including the *Centre International de Cancérologie de Dakar* (CICD), where we conducted the experimental measurements required to validate the simulation results obtained using the GAMOS code.

Cancer treatment is complex and involves various modalities such as chemotherapy, surgery, and radiotherapy. Radiotherapy, in particular, has benefited from significant advances in both particle accelerator technologies and computer systems. Linear accelerators (Linacs) are widely used in radiotherapy to produce photon or electron beams with energies above one mega-electron volt (MeV).

The modeling of particle transport from accelerators is often performed using the Monte Carlo method, which is recognized as the gold standard for dose calculation in medical physics and is increasingly adopted.

Among the early Monte Carlo-based models for Linac head geometry [2-5], several simulation codes have been developed, including EGS [6-8], MCNP [9], PENELOPE [10] and GEANT. Within the GEANT4 framework, we find toolkits such as GATE [11], TOPAS [12], and the GAMOS platform [13, 14].

The most recent version, GEANT4, was the first in the field to use C++ programming and object-oriented methodologies. However, GEANT4 requires significant memory resources. Among the various available frameworks, we selected GAMOS [14] due to its flexibility in modifying GEANT4 physics parameters and its set of utilities for radiotherapy simulation, all while being user-friendly [15].

Previous studies have shown that Monte Carlo-based codes are the most accurate for dose calculations in radiotherapy [16-19]. Several works have already employed GEANT4 [20, 21] to simulate linear accelerators in radiotherapy [22, 23]. However, most of these studies have not explored bremsstrahlung angular distribution models, with the exception of [15], which focused on CPU time optimization and precise adjustment of GEANT4 physics parameters for simulating a VARIAN 2100 C/D gamma radiotherapy linear accelerator using GAMOS.

The main objective of our study, conducted using the GAMOS simulation platform, is to perform Monte Carlo simulations of a 6 MV photon beam produced by the Elekta Synergy Agility linear accelerator at the *Centre International de Cancérologie de Dakar* (CICD) in Senegal. We also compared the dose distributions obtained with each of the three bremsstrahlung angular distribution models with experimental data for field sizes of 5 × 5 cm^2 and 10 × 10 cm^2, in order to validate our simulation approach.

2. Materials and Methods

The head of the Elekta Synergy Agility linear accelerator was modeled using the GAMOS code to simulate a 6 MV photon beam for field sizes of 5 × 5 cm^2 and 10 × 10 cm^2. This modeling incorporated the three angular distribution models of Bremsstrahlung available in GAMOS. The simulated linac head components included the target, primary collimator, flattening filter, ionization chamber, and the X and Y jaws. After modeling these components, a phase-space file in IAEA [24] format was generated, containing 3 10^8 events, using one of the three angular distribution models: Tsai, Koch–Motz 2BS, or Koch–Motz 2BN, for each simulation. These phase-space files, positioned between the X and Y jaws and a homogeneous water phantom, were subsequently used as sources to calculate the dose distribution in the phantom corresponding to each model.

To enhance simulation efficiency, each phase-space file was recycled five times, and the particles within the phase space were reused 50 times for all three models. An XY mirror was applied to reflect the reused particles.

In radiotherapy, dose distributions (percent depth dose and dose profiles) in a water phantom play a crucial role in characterizing the incident beam. For this study, the same water phantom, with dimensions of 60 × 60 × 41 cm^3, was simulated [25]. The number of voxels along the x, y, and z axes was 120 × 120 × 41, subdivided into voxels measuring 5 × 5 × 10 mm^3, with a density of 1 g/cm^3 [25]. The water phantom was placed at a source-to-axis distance (SAD) of 100 cm for the measurement of depth dose, and at a source-to-surface distance (SSD) of 90 cm for the evaluation of dose profiles at depths of 5 cm, 10 cm, 15 cm, and 20 cm.

All technical data necessary for modeling were provided by the manufacturer. However, adjustments were made to certain parameters such as beam energy and the flattening filter.

For the experimental measurements, data were collected using a water phantom available at the International Cancer Center of Dakar (CICD), Senegal. Two detectors were used: for dose profile data, a PTW-Freiburg microDiamond detector (Germany); and for depth dose measurements, a PTW-Freiburg Semiflex ionization chamber with a volume of 0.3 cm^3 (Germany). The visual representation of the linac irradiation head and water phantom (see Figure 1), as well as the analysis of the generated data, were carried out using the Python programming language and the Visual Studio Code (VSC) development environment. All results were compared to the experimental data from the CICD.

The comparison was performed using the gamma index, introduced by [26] and [27]. The acceptance criteria for the gamma index (GI) test in this study were a dose difference of 3% and a distance-to-agreement of 3 mm. The gamma index can be determined using the following equation:

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

In this expression, D_r refers to the reference dose measured at a distance d_r, while D_c represents the calculated dose at a distance d_c. The parameters ΔD and Δd correspond to the dose difference (DD) and distance-to-agreement (DTA) criteria, respectively.

A gamma index less than 1 indicates that the agreement between the measured and calculated values meets the established tolerance criteria. Conversely, a value greater than 1 means that the tested point falls outside the defined acceptance region, and the test is therefore considered to have failed.

This methodological approach and the use of GAMOS for modeling the linac head reflect our commitment to simulation accuracy, reinforced by systematic comparison with experimental data from the CICD.

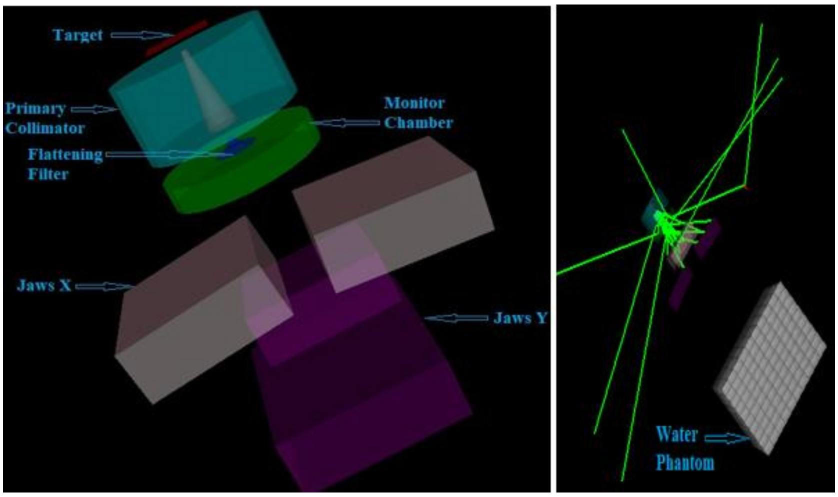

Figure 1. Modeling of the Elekta Synergy Agility linac head and the voxelized water phantom using the GAMOS code.

3. Results and Discussion

3.1. Depth Dose Curves for Field Sizes of 5 × 5 cm ^{2} and 10 × 10 cm ^{2}

Depth dose curves were calculated along the central axis of the beam for two field sizes (5 × 5 cm ^{2} and 10 × 10 cm ^{2}), using the three Bremsstrahlung angular distribution models available in GAMOS: Tsai, Koch–Motz 2BS, and Koch–Motz 2BN. All simulated curves were compared with experimental data. Each distribution (whether depth dose or dose profile) was normalized to its maximum value.

The gamma index was used for validation, with acceptance criteria of 3% dose difference (DD) and 3 mm distance-to-agreement (DTA). The results show satisfactory agreement between simulations and experimental measurements, with a gamma passing rate of 94% for the 5 × 5 cm ^{2} field and 96% for the 10 × 10 cm ^{2} field, regardless of the model used (see Table 1 and Figure 2).

These accuracy levels are comparable to those reported in study [25], which also achieved good agreement by combining different electromagnetic physics models (Penelope, Low-Energy, Standard) and multiple scattering models (Goudsmit–Saunderson, Urban, Wentzel-VI).

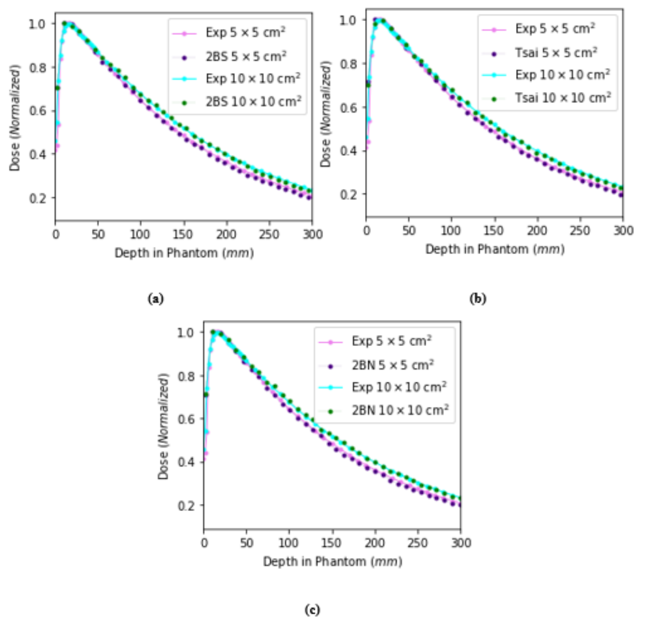

Figure 2. Comparison of percent depth dose curves for field sizes of 5 × 5 cm ^{2} and 10 × 10 cm ^{2} between the three Bremsstrahlung angular distribution models (Koch–Motz 2BS (a), Tsai (b), and Koch–Motz 2BN (c)) and experimental data.

__Table 1.__ Gamma index values for the three Bremsstrahlung angular distribution models: Tsai, Koch–Motz 2BS, and Koch–Motz 2BN.

Model / Field sizes	**5 x 5 cm ^{2}**	**10 x 10 cm ^{2}**
Koch-Motz 2BS	94%	96%
Koch-Motz 2BN	94%	96%
Tsai	94%	96%

The strong agreement between the simulated and experimental depth dose curves for both field sizes confirms the validity of our modeling approach. These results highlight the ability of the models implemented in GAMOS to reliably reproduce the dosimetric characteristics of the irradiation beam.

3.2. Dose Profile Curves for a 5 × 5 cm ^{2} Field Size at Depths of 5 cm, 10 cm, 15 cm, and 20 cm

For the dose profile curves, all three Bremsstrahlung angular distribution models: Koch–Motz 2BN, Koch–Motz 2BS and Tsai, show excellent agreement, with a 100% gamma passing rate (see Table 2), when compared to experimental data for a 5 × 5 cm ^{2} field size at all investigated depths (5 cm, 10 cm, 15 cm, and 20 cm) (see Figure 3).

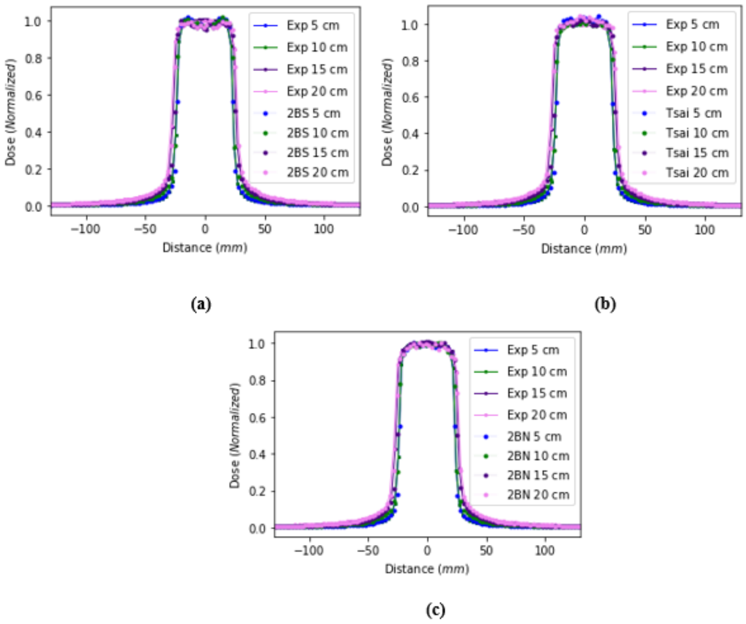

__Figure 3.__ Comparison of dose profiles for a field size of 5 × 5 cm ^{2} at depths of 5 cm, 10 cm, 15 cm, and 20 cm between the Bremsstrahlung angular distribution models (Koch–Motz 2BS (a), Tsai (b) and Koch–Motz 2BN (c)) and the experimental data.

There is a strong agreement between the simulated dose profiles for the three angular distribution models and the experimental data across all depths for the 5 × 5 cm ^{2} field size, confirming the reliability of the models in reproducing lateral dose distributions.

3.3. Dose Profile Curves for a 10 × 10 cm ^{2} Field Size at Depths of 5 cm, 10 cm, 15 cm, and 20 cm

For the dose profile curves, the Koch–Motz 2BN model shows excellent agreement with the experimental data, with a 100% gamma passing rate (see Table 2) at depths of 5 cm and 20 cm for a 10 × 10 cm ^{2} field size (see Figure 4). At 10 cm and 15 cm depths, the agreement remains very good, with respective passing rates of 98% and 99%.

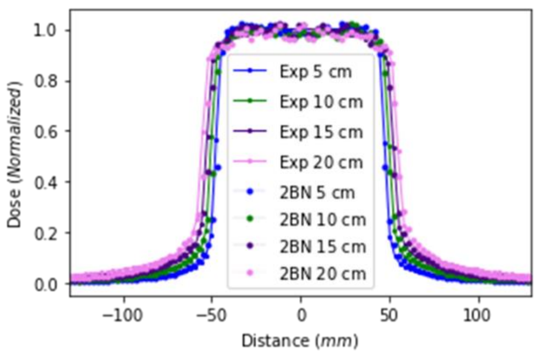

__Figure 4.__ Comparison of dose profiles for a field size of 10 × 10 cm ^{2} at depths of 5 cm, 10 cm, 15 cm, and 20 cm between the Koch–Motz 2BN Bremsstrahlung angular distribution model and the experimental data.

The Tsai model also demonstrates excellent agreement with a 99% passing rate at 20 cm depth (see Table 2 and Figure 5), and slightly lower values at other depths: 98% at 15 cm, 97% at 10 cm, and 95% at 5 cm.

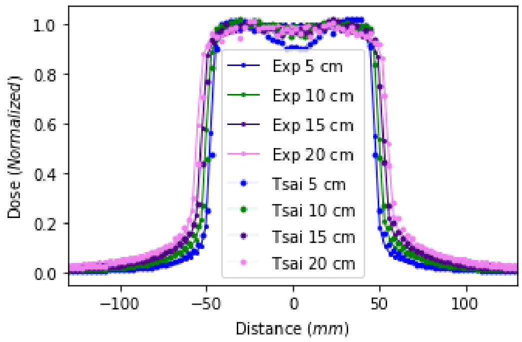

Figure 5. *Comparison of dose profiles for a field size of 10 × 10 cm ²at depths of 5 cm, 10 cm, 15 cm, and 20 cm between the Tsai Bremsstrahlung angular distribution model and the experimental data.*

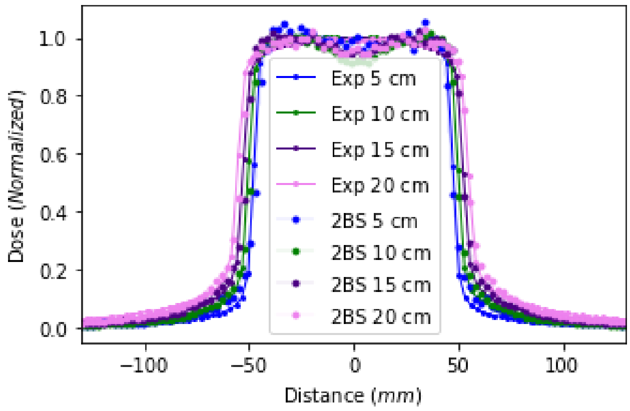

Figure 6. *Comparison of dose profiles for a field size of 10 × 10 cm ²at depths of 5 cm, 10 cm, 15 cm, and 20 cm between the Koch–Motz 2BS Bremsstrahlung angular distribution model and the experimental data.*

As for the Koch–Motz 2BS model, it shows good agreement at 5 cm and 20 cm depths, with 94% passing rates (see Table 2 and Figure 6). At 10 cm and 15 cm, the agreement decreases slightly, with passing rates of 90% and 92%, respectively.

Among the three Bremsstrahlung angular distribution models evaluated: Koch–Motz 2BN, Tsai, and Koch–Motz 2BS, the Koch–Motz 2BN model provides the best results across all depths for the 10 × 10 cm ² field size. However, slight differences are observed between the models at each depth. These discrepancies may stem from statistical fluctuations inherent to Monte Carlo simulations, as well as from potential mismatches between manufacturer-provided specifications and the actual linac configuration in clinical settings. This highlights the importance of accurate geometric modeling of the linear accelerator.

Table 2. *Gamma index values for the three Bremsstrahlung angular distribution models: Tsai, Koch–Motz 2BS, and Koch–Motz 2BN, compared with the measurements.*

Model / Field sizes	**5 x 5 cm ²**	**10 x 10 cm ²**
Koch-Motz 2BS		
5 cm	100%	94%
10 cm	100%	90%
15 cm	100%	92%
20 cm	100%	94%
Koch-Motz 2BN		
5 cm	100%	100%
10 cm	100%	99%
15 cm	100%	98%
20 cm	100%	100%
Tsai		
5 cm	100%	95%
10 cm	100%	97%
15 cm	100%	98%
20 cm	100%	99%

The strong agreement observed between simulated and experimental depth-dose and lateral dose profile curves obtained using the three angular distribution models confirms the reliability of the models implemented in GAMOS. This study provides valuable insight into selecting the most appropriate model for accurate simulation, ultimately contributing to improved radiotherapy practices and better treatment outcomes for cancer patients. The results support the validity and reliability of the tested simulation models and pave the way for continuous advancements in radiotherapy accuracy.

4. Conclusions

This study successfully validated the Monte Carlo GAMOS model for simulating the 6 MV photon beam of an Elekta Synergy Agility linear accelerator, for field sizes of 5 ×5 cm ² and 10 × 10 cm ². To our knowledge, few studies, apart from [15], have compared experimental and simulated results using all three Bremsstrahlung angular distribution models (Tsai, Koch–Motz 2BS, and Koch–Motz 2BN) in the context of radiotherapy.

The depth-dose curves showed good agreement with experimental data, with gamma passing rates of 94% and 96%

for the 5 × 5 cm ²and 10 × 10 cm ²fields, respectively. For the dose profiles, all three models (Koch–Motz 2BN, Koch–Motz 2BS, and Tsai) exhibited excellent agreement (up to 100%) for the 5 × 5 cm ²field size.

For the 10 × 10 cm ²field, the Koch–Motz 2BN model stood out, achieving 100% agreement at 5 cm and 20 cm depths, followed by the Tsai model with 99% at 20 cm. At 10 cm depth, the Koch–Motz 2BN model reached 99%, Tsai 97%, and Koch–Motz 2BS 90%. At 15 cm, both the Koch–Motz 2BN and Tsai models achieved 98%, while the Koch–Motz 2BS model reached 92%. No significant differences were observed between the three models, as all gamma indices were greater than or equal to 90% across all tested depths.

These findings confirm the relevance of the three Bremsstrahlung angular distribution models for simulating the 6 MV photon beam of the Elekta Synergy Agility linear accelerator in the studied context. This work represents a valuable contribution to the validation of Monte Carlo models, particularly GAMOS, for simulating therapeutic beams used in radiotherapy. Such validation is crucial to ensure the reliability of dosimetric results obtained through simulation.

The outcomes of this study may have practical clinical implications by providing healthcare professionals with reliable guidance for selecting simulation models. A promising future direction would be to conduct further comparative studies using different beam energies and clinical conditions, in order to refine recommendations on the most suitable angular distribution model depending on the specific clinical context.

Abbreviations

CICD	International Cancer Center of Dakar
SAD	Source-to-Axis Distance
SSD	Source-to-Surface Distance
DD	Dose Difference
DTA	Distance to Agreement
VSC	Visual Studio Code

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Author Contributions

Djicknack Dione: Writing – review & editing
Oumar Ndiaye: Writing – review & editing
Jean Paul Latyr Faye: Supervision, Writing – review & editing
Alassane Traoré: Supervision, Writing – review & editing
Ababacar Sadikhe Ndao: Supervision, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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