Enhancing Dosimetric Precision in the Treatment of Cancerous Tumors: Gamma Index Validation and Monte Carlo Simulations of 6 and 12 megavoltage Photon Beams from Varian Medical Linear Accelerators

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Abstract

The accuracy of dose delivery in radiotherapy is paramount to maximize tumor control while minimizing damage to surrounding healthy tissues. This study presents a comprehensive analysis of gamma index validation in the treatment of cancerous tumors using Monte Carlo simulations with GAMOS and GATE codes on a Varian medical linear accelerator. By leveraging the Monte Carlo method' s robust statistical capabilities, the precision of dose distributions in external radiotherapy is aimed to be enhanced. The study specifically evaluates the effects of different field sizes and percentage depth dose (PDD) to provide a thorough validation framework. The GAMOS and GATE codes were implemented to simulate dose distributions within various phantom models, including water and anthropomorphic phantoms. These simulations were conducted using a Varian linear accelerator with a 6 and 12 megavoltage photon beams. The dose distributions obtained from the simulations were then compared against those calculated by the treatment planning system (TPS) using the gamma index method with 3%/3mm criteria. Our results demonstrated a high degree of accuracy in the simulated dose distributions, with gamma index pass rates exceeding 94% for most configurations. The comparative analysis between GAMOS and GATE showed consistent performance, with minor deviations attributable to differences in the underlying simulation algorithms. Furthermore, the study revealed significant insights into the impact of varying field sizes on dose distribution accuracy. The PDD analysis indicated that both GAMOS and GATE could reliably reproduce the TPS-calculated dose profiles, with deviations within clinically acceptable limits. These findings underscore the potential of Monte Carlo simulations to improve the accuracy and reliability of radiotherapy treatment plans. By validating the gamma index for different field sizes and PDD, this

study provides a robust framework for enhancing treatment efficacy and patient safety in clinical practice. The integration of GAMOS and GATE in routine clinical workflows could lead to more precise and individualized radiotherapy treatments, ultimately improving patient outcomes.

Full Text

Preamble

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Abstract

The accuracy of dose delivery in radiotherapy is paramount for maximizing tumor control while minimizing damage to surrounding healthy tissues. This study presents a comprehensive analysis of gamma index validation for cancerous tumor treatment using Monte Carlo simulations with GAMOS and GATE codes on a Varian medical linear accelerator. By leveraging the robust statistical capabilities of the Monte Carlo method, we aimed to enhance the precision of dose distributions in external beam radiotherapy. The study specifically evaluated the effects of different field sizes and percentage depth dose (PDD) to provide a thorough validation framework. We implemented GAMOS and GATE codes to simulate dose distributions within water and anthropomorphic phantom models using a Varian linear accelerator equipped with 6 and 12 megavoltage photon beams. The simulated dose distributions were then compared against treatment planning system (TPS) calculations using the gamma index method with 3%/3mm criteria.

Our results demonstrated high accuracy in the simulated dose distributions, with gamma index pass rates exceeding 94% for most configurations. Comparative analysis between GAMOS and GATE showed consistent performance, with minor deviations attributable to differences in underlying simulation algorithms. Furthermore, the study revealed significant insights into how varying field sizes impact dose distribution accuracy. PDD analysis indicated that both GAMOS and GATE reliably reproduced TPS-calculated dose profiles within clinically

acceptable limits. These findings underscore the potential of Monte Carlo simulations to improve the accuracy and reliability of radiotherapy treatment plans.

By validating the gamma index across different field sizes and PDD values, this study provides a robust framework for enhancing treatment efficacy and patient safety in clinical practice. Integrating GAMOS and GATE into routine clinical workflows could enable more precise and individualized radiotherapy treatments, ultimately improving patient outcomes.

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1. Introduction

Radiotherapy is a pivotal modality in cancer treatment, with the primary goal of delivering precise radiation doses to malignant tissues while minimizing exposure to surrounding healthy structures [Paelinck et al., 2005]. Treatment efficacy hinges on accurate delivery of the planned dose to the target volume; any deviation can adversely impact outcomes, leading to suboptimal tumor control or unnecessary side effects. This challenge is addressed through various quality assurance (QA) methodologies [Morias et al., 2018], among which the gamma index is particularly effective for evaluating agreement between planned and delivered dose distributions [Majeed and Gupta, 2020]. This metric combines dose difference and distance-to-agreement criteria, providing a comprehensive assessment of dosimetric accuracy [Rocha et al., 2022] and simultaneously accounting for both spatial and dosimetric discrepancies [Bidmead et al., 1995].

Monte Carlo simulations have gained prominence in radiotherapy QA due to their superior accuracy in modeling complex radiation-matter interactions [Bidmead et al., 1995]. Unlike conventional dose calculation algorithms, Monte Carlo methods simulate the stochastic processes involved in radiation transport, yielding more detailed and precise dose distributions [Anjomani et al., 2011]. This approach is particularly beneficial in complex scenarios involving heterogeneous media and irregular geometries where traditional algorithms may fall short. This study leverages two advanced Monte Carlo tools—GAMOS (Geant4-based Architecture for Medicine-Oriented Simulations) and GATE (Geant4 Application for Tomographic Emission)—to validate the gamma index in external beam radiotherapy [Agostinelli et al., 2003]. Both platforms are built on the Geant4 toolkit, renowned for its robustness and flexibility in simulating particle interactions. GAMOS is tailored for medical physics applications [Al-Zain et al., 2019], offering extensive features for dose calculation and phantom modeling, while GATE provides high accuracy for imaging and radiotherapy simulations, making it valuable for dose verification [Arce et al., 2014].

The Varian linear accelerator [Zhang et al., 2009], a widely used clinical machine, serves as the radiation source in this study. Equipped with 6 and 12 megavoltage photon beams, it represents common clinical equipment, ensuring our findings are applicable to real-world practice [Kim and Lee, 2007]. By modeling this system, we evaluated dose delivery accuracy across different field sizes

and depth dose distributions [Jin et al., 2016]. Field size variations and percentage depth dose (PDD) are critical factors influencing dose distribution; field size affects the dose profile, while PDD curves describe dose delivery at varying depths within a phantom, evaluating beam penetration and distribution. Accurate PDD modeling ensures appropriate dose distribution throughout the target volume and surrounding tissues [Mesbahi and Zergoug, 2015].

In this study, we simulated dose distributions using GAMOS and GATE for various field sizes and depths in water and anthropomorphic phantoms [Gonias et al., 2016], comparing them with TPS calculations using the gamma index method [Teixeira et al., 2019]. Comparisons employed standard 3% dose difference and 3 mm distance-to-agreement criteria used in clinical QA [Harkness et al., 2012].

Our primary objectives were to validate the gamma index for different field sizes and PDD values using Monte Carlo simulations and to assess the consistency and reliability of GAMOS and GATE in reproducing TPS-calculated dose distributions [Al-Zain et al., 2019]. By providing a thorough comparison of simulated and planned doses, this study aims to enhance radiotherapy accuracy and contribute to improved patient outcomes [Mesbahi and Zergoug, 2015]. Overall, this research underscores the importance of precise dose verification and highlights the role of advanced Monte Carlo simulations in achieving high-quality treatment delivery.

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2. Percentage Depth Dose (PDD) in Radiation Therapy

Percentage Depth Dose (PDD) is a critical parameter in radiation therapy dosimetry that describes the relative dose delivered at different depths in a medium—typically a water phantom [Xhafa et al., 2014]—along the central axis of the radiation beam [Fiak et al., 2021]. It is defined as the ratio of the dose at a specific depth to the dose at a reference depth (usually the maximum dose depth), expressed as a percentage [Adom et al., 2023]. PDD is crucial for understanding how radiation dose attenuates with depth, which directly influences treatment planning and delivery [Mia et al., 2019].

The PDD is calculated using the following formula:

$$\text{PDD} = \frac{D_Q}{D_P} \times 100 = \frac{\dot{D}_Q}{\dot{D}_P} \times 100$$

where D_Q and $\dot{D}_Q$ represent the dose and dose rate at point Q at depth z on the central axis of the phantom, and D_P and $\dot{D}_P$ represent the dose and dose rate at point P at $z_{\max}$ on the central axis of the phantom.

PDD curves are essential for treatment planning as they provide information on dose distribution within the patient' s body [Li et al., 2022], helping de-

termine appropriate beam energy and field size to ensure the tumor receives the prescribed dose while minimizing exposure to healthy tissues [Bilalodin and Abdullatif, 2022]. PDD curves also characterize radiation beam quality; higher energy beams exhibit deeper penetration, which is vital for selecting appropriate beam energies for different treatment sites [Kastrati et al., 2021]. Furthermore, PDD values are used in dose calculation algorithms to estimate dose distribution, making accurate calculations crucial for effective treatment [Niemela et al., 2017].

The deposition of dose from a megavoltage photon beam involves several key measurements: D_s is the surface dose at beam entry, while D_{ex} is the surface dose at exit. The maximum dose, $D_{\max}$, is often normalized to 100, creating a percentage depth dose distribution. The region between $z = 0$ and $z = z_{\max}$ is referred to as the dose build-up region.

[Figure 1: see original paper]

The PDD distribution can be divided into several key regions:

Build-up Region: This region extends from the surface to the depth of maximum dose ($z_{\max}$) [Jin et al., 2016]. Here, dose increases with depth due to secondary electron interactions, an effect crucial for skin sparing when treating superficial tumors without causing excessive skin damage [Mott and West, 2021].

Maximum Dose Depth ($z_{\max}$): This is the depth at which maximum dose is deposited [Xhafa et al., 2014], representing the peak dose delivered by the beam and serving as the reference for PDD calculations. The location of $z_{\max}$ helps align the beam to ensure deep-seated tumors receive maximum possible dose [Kim et al., 1991].

Beyond $z_{\max}$: Beyond the maximum dose depth, dose decreases with increasing depth due to beam attenuation and scattering. The slope of the PDD curve in this region indicates beam penetration capability and dose fall-off rate. A steeper fall-off is desirable to minimize dose to deeper healthy tissues [Mott and West, 2021].

Tail Region: This region at greater depths shows continued dose fall-off, eventually approaching zero. It indicates beam penetration extent and residual dose in deep tissues, helping assess dose delivery to distant tissues and ensure it remains within safe limits [Mesbahi and Zergoug, 2015].

Overall, PDD is fundamental to radiotherapy dosimetry, providing essential insights into dose distribution and guiding optimization of treatment plans for effective and safe cancer treatment.

3. Dose Profile in Radiation Therapy

The dose profile is a fundamental tool that depicts radiation dose distribution across a plane perpendicular to the central axis of the treatment beam [Xhafa et al., 2014]. This profile provides critical insights into field uniformity, symmetry, and sharpness—crucial for ensuring effective treatment while minimizing damage to healthy tissues [Adom et al., 2023].

The dose profile $D(x)$ is defined as a function of lateral position x, where $D(x)$ represents dose at a specific point and $f(x)$ describes dose distribution across beam width. Understanding this distribution helps radiation oncologists and physicists optimize treatment plans to deliver consistent tumor doses while sparing adjacent healthy tissues [Bilalodin and Abdullatif, 2022].

Key Parameters:

Symmetry: Symmetry ensures even radiation distribution on both sides of the central axis, preventing unintended under-dosing of tumor regions or overdosing of healthy tissues. Mathematically, symmetry is evaluated by comparing dose values at points equidistant from the central axis:

$$\text{Symmetry } (\%) = \frac{D(x, y)}{D(-x, -y)} \times 100\%$$

Maintaining symmetry ensures uniform treatment delivery and enhances precision.

Flatness: Dose flatness refers to uniformity across the central region of the beam, typically within the central 80% of field width. It is calculated as:

$$\text{Flatness } (\%) = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \times 100\%$$

where $D_{\max}$ and $D_{\min}$ are the maximum and minimum doses in this region. Flatness ensures the entire tumor volume receives a consistent dose [Mia et al., 2019], minimizing hot spots (excessively high dose areas) or cold spots (insufficient dose areas) and thereby enhancing treatment efficacy [Bilalodin and Abdullatif, 2022].

Penumbra: The penumbra is the transition region between high-dose and low-dose areas, characterizing how sharply dose falls off from the treatment field to surrounding tissues [Stanton and Stinson, 1996]. A narrow penumbra indicates a sharp dose gradient, limiting radiation exposure to adjacent healthy tissues, while a broad penumbra results in gradual dose fall-off, potentially increasing risk to healthy tissues. Precise penumbra measurement ensures the radiation field conforms closely to tumor shape. The geometric penumbra is given by:

$$\text{Geometric Penumbra (PG)} = s \times \frac{\text{SSD} + d - \text{SDD}}{\text{SDD}}$$

where s is the source size, SSD is source-to-surface distance, SDD is source-to-diaphragm distance, and d is depth of dose.

[Figure 2: see original paper]

Dose profile analysis focusing on symmetry, flatness, and penumbra is essential for optimizing radiation therapy. It enables clinicians to tailor treatment plans for precise and effective dose delivery, ensuring maximum tumor control while minimizing side effects to surrounding healthy tissues.

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4. GATE Code

GATE (Geant4 Application for Tomographic Emission) is a versatile Monte Carlo simulation toolkit tailored for the medical physics community [Agostinelli et al., 2003]. Built on robust GEANT4 libraries, GATE provides an adaptable, user-friendly platform for simulating various medical imaging and therapy systems, including linear accelerators (Linacs) [Teixeira et al., 2019]. The primary objective of using GATE for Linac simulation is to accurately model physical processes in radiation therapy [Gonias et al., 2016], including detailed beam generation, transport, and tissue interactions, thereby optimizing treatment plans and enhancing therapeutic efficacy while minimizing adverse effects [Harkness et al., 2012].

GATE' s modular framework encapsulates GEANT4 libraries, making it highly adaptable for nuclear medicine applications. It includes several hundred C++ classes organized into core and application layers, facilitating complex simulations without extensive C++ programming knowledge [Sahmaran and Yilmaz Koca, 2023]. A dedicated macro language extends GEANT4' s native command interpreter, enabling script-based simulation control [Chen et al., 2005] for automated and reproducible research and clinical workflows [Hrbacek et al., 2011].

GATE' s innovative approach to modeling time-dependent phenomena is crucial for Linac simulations, where synchronization of moving parts and temporal aspects of radiation delivery are vital [Abou-Shady et al., 2017]. The simulation divides processes into time-steps to accurately model decay kinetics and geometric movements, ensuring realistic dynamic process simulation. The application layer supports user-defined geometrical volumes and operations essential for modeling complex Linac components and patient anatomies [Gasteuil et al., 2019]. GATE can simulate detailed detector responses, including electronic effects such as cross-talk, energy resolution, and trigger efficiency, providing realistic output data [Sadoughi et al., 2014]. GATE includes well-validated physics models inherited from GEANT4, ensuring high accuracy in particle interaction and energy deposition simulation, with continuous testing and validation against commercial imaging systems and experimental data maintaining reliability.

4.1. Application to Linac Linear Accelerator

GATE simulates photon and electron beam generation and transport within the Linac [Zhang et al., 2009], considering complex geometries of beam-shaping devices such as collimators and multileaf collimators (MLCs). The simulation includes modeling primary and secondary particle interactions within the accelerator head and along the beam path [Kim and Lee, 2007]. Using CT-based patient models, GATE calculates 3D dose distributions for precise dosimetry tailored to individual treatment plans, supporting various tissue compositions and densities for accurate heterogeneous tissue dose calculations [Wilson et al., 2021]. Applications include photon beam simulations in patient CT images to generate 3D dose distribution maps, IMRT simulations with varying MLC positions to optimize beam delivery [Anjomani et al., 2011], and comparisons with experimental measurements and other simulation tools to ensure accuracy [Sjostrom et al., 2009]. GATE aids in treatment plan optimization by simulating different irradiation scenarios and their effects on tumors and healthy tissues, allowing refinement of treatment parameters to enhance outcomes while minimizing side effects.

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5. GAMOS Code

GAMOS (Geant4-based Architecture for Medicine-Oriented Simulations) is a Monte Carlo framework built on the Geant4 toolkit [Agostinelli et al., 2003], designed to facilitate complex medical simulations with minimal coding effort [Harkness et al., 2012]. GAMOS provides a flexible, user-friendly environment enabling detailed simulations without requiring extensive C++ or Geant4 knowledge, making it accessible to users with limited programming expertise [Gonias et al., 2016].

A defining feature of GAMOS is its plug-in architecture, which enhances flexibility and ease of use [Bacala, 2020]. This architecture allows dynamic loading and combination of different simulation components (geometry, physics, user actions, histograms, etc.) without recompiling code [Arce et al., 2014]. Users specify components in a text input file, enabling seamless integration and customization. The plug-in system uses the CERN ROOT package to manage dynamic component loading [Arce et al., 2020], analogous to web browser plug-ins that extend functionality without modifying the browser itself. GAMOS includes several tools to help users understand and optimize simulations: verbosity control, histogram creation, and scoring mechanisms [Harkness et al., 2012].

5.1. Application in Medical Simulations

GAMOS is particularly well-suited for simulating medical applications [Zhang et al., 2009], such as linear accelerators (Linacs) in radiation therapy [Al-Zain

et al., 2019]. It can simulate the entire treatment process from beam generation and modulation to tissue interactions and dose distribution calculations, making it invaluable for optimizing treatment parameters, improving therapeutic outcomes, and minimizing side effects [Arce et al., 2020].

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6. Varian Medical Linear Accelerator (Linac)

A Varian Medical linear accelerator (linac) is sophisticated equipment essential for radiation therapy in cancer treatment [Adom et al., 2023]. It generates high-energy x-rays or electrons that can be precisely directed at tumors, minimizing damage to surrounding healthy tissues. The system comprises several key components working in concert:

The electron gun emits a stream of electrons from a heated cathode [Kim et al., 1991], which are accelerated through a potential difference toward the accelerating waveguide [Rezzoug et al., 2023]. This vacuum tube uses microwaves generated by a magnetron or klystron to create an electromagnetic field that accelerates electrons to near-light speed [Paelinck et al., 2005]. In some linacs, a bending magnet redirects electrons to align with the treatment beam axis. High-energy electrons strike the target, producing x-rays via bremsstrahlung—crucial for generating therapeutic radiation [Bidmead et al., 1995]. The primary collimator, located immediately after the target, shapes the initial x-ray beam, while the flattening filter ensures consistent dose distribution across the treatment field by flattening the x-ray beam intensity profile [Kim and Lee, 2007]. The ionization chamber measures delivered radiation dose and provides feedback to control systems, ensuring patients receive the prescribed dose. Movable jaws further shape the x-ray beam, adjusting to conform to the treatment area and improving therapy precision [Paelinck et al., 2005]. The output window is the final aperture through which the shaped and filtered x-ray beam exits the linac, ensuring accurate beam direction [Kim et al., 1991].

Additional components include the reticle, which aids in beam alignment; a mirror that reflects light for visual beam alignment, projecting a light field that mimics the x-ray field to aid patient positioning [Chen et al., 2005]; and the phase space plane—a conceptual plane used in simulations to assess dose distribution critical for planning effective radiation therapy [Zhang et al., 2009]. The gantry rotates around the patient [Adom et al., 2023], allowing beam delivery from different angles to enhance dose distribution and spare healthy tissues. Imaging systems like cone-beam CT verify patient positioning before and during treatment [Gonias et al., 2016], while the patient positioning system ensures accurate alignment via a treatment couch that moves in multiple directions. Phantoms simulate human tissue for testing and calibration, used in quality assurance and treatment planning to ensure accurate dose delivery.

[Figure 3: see original paper]

Varian Medical linear accelerators represent the forefront of modern radiation oncology, combining advanced engineering and state-of-the-art technology to provide effective and precise cancer treatments [Chen et al., 2005]. Their capabilities to deliver various forms of radiotherapy, coupled with sophisticated imaging and patient positioning systems, make them indispensable tools in cancer treatment [Paelinck et al., 2005].

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7. Gamma Index Analysis

Gamma Index Analysis was conducted to evaluate agreement between calculated and measured dose distributions [Bacala, 2020], utilizing criteria of 3% dose difference (DD) and 3 mm distance-to-agreement (DTA) [Reynaert et al., 2007]. The Gamma Index γ at each point in the dose distribution is calculated using:

$$\gamma = \sqrt{\left(\frac{\Delta r}{r_m}\right)^2 + \left(\frac{\Delta D}{D_m}\right)^2}$$

where Δr is the spatial distance between reference and evaluated dose points, r_m is the user-defined DTA criterion (3 mm), ΔD is the dose difference between reference and evaluated points, and D_m is the user-defined DD criterion (3%).

Results indicated a gamma passing rate ($\gamma < 1.0$) of 97.5%, with 85% of points showing excellent agreement ($\gamma \leq 0.5$), 12.5% showing good agreement ($0.5 < \gamma < 1.0$), and 2.5% showing poor agreement ($\gamma \geq 1.0$) [Bacala, 2020]. Excellent agreement predominantly occurred in regions with uniform dose distribution, good agreement near high-dose gradient boundaries, and poor agreement in high-dose gradient regions or areas with heterogeneous tissue compositions.

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8. Phase-Space Data at 90 cm from Water Phantom

Phase-space data refers to comprehensive information about particle distribution (photons or electrons) in the radiation field [Al-Zain et al., 2019]. In this study, data were collected at 90 cm from a homogeneous water phantom surface —a common reference material in radiotherapy simulations. This distance was chosen to replicate clinical conditions and ensure accurate radiation dose and distribution measurements [Arce et al., 2020]. The homogeneous water phantom provides a consistent medium for assessing beam characteristics, and the 90 cm distance enables analysis of beam behavior and distribution over clinically relevant distances [Arce et al., 2014].

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9. Phantom Output Factor (S_{cp})

The Phantom Output Factor (S_{cp}) is a key dosimetric parameter in radiotherapy with Varian Linear Accelerators, representing the ratio of dose output for a given field size in a phantom to that of a reference field size (typically 10 cm $\times$ 10 cm). This factor accounts for changes in scatter conditions and output variations with field size. Accurate measurement and calculation of S_{cp} are essential for precise dose delivery in treatment planning, particularly for 6 and 12 megavoltage photon beams. Monte Carlo simulations using GAMOS and GATE codes are often employed to calculate S_{cp} values, which are then compared with experimental data to validate accuracy and ensure optimal patient treatment.

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10. Head Scatter Factor (S_c)

The Head Scatter Factor (S_c) measures additional dose contributed by scatter radiation from the treatment head of a Varian Linear Accelerator. It is defined as the ratio of dose rate measured with the radiation head in place to that measured with the head removed or in a reference setup. S_c accounts for scatter produced by machine components and is crucial for accurate dose calculations and treatment planning, particularly for small or irregular fields. Accurate measurement and Monte Carlo simulation of S_c ensure precise dose delivery and effective patient treatment in radiotherapy.

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11. Results and Discussion

Photon beam parameters for 6 and 12 megavoltage beams at 100 cm SSD were evaluated using GAMOS and GATE Monte Carlo simulations and compared with experimental data from a Varian medical linear accelerator. Key observations include:

The depth of maximum dose ($d_{\max}$) was consistently 1.4 cm for 6 megavoltage beams and 2.5 cm for 12 megavoltage beams across all field sizes, indicating uniform penetration depth in clinical settings. PDD values at 5 cm, 10 cm, and 20 cm depths, along with D_{20}/D_5 ratios, showed high consistency between GAMOS, GATE, and experimental data, underscoring the reliability of these Monte Carlo codes for accurate dosimetric calculations .

PDD values for 12 megavoltage beams were higher than for 6 megavoltage beams at all depths, reflecting greater penetration capability. For example, at 10 cm depth, PDD for 12 megavoltage beams was approximately 79.0-81.7% depending on field size, compared to 71.4-74.1% for 6 megavoltage beams. This indicates 12 megavoltage beams maintain higher doses at depth, beneficial for treating deep-seated tumors.

PDD values increased slightly with larger field sizes due to increased scatter contribution. For 6 megavoltage beams, PDD at 20 cm depth increased from 36.8% for 5 × 5 cm^2 fields to 39.2% for 40 × 40 cm^2 fields. Similarly, for 12 megavoltage beams, PDD at 20 cm increased from 46.5% to 49.0% as field size increased from 5 × 5 cm^2 to 40 × 40 cm^2. The D_{20}/D_5 ratio, indicating beam attenuation characteristics, was consistently higher for 12 megavoltage beams (ranging from 0.493 to 0.511) than for 6 megavoltage beams (ranging from 0.411 to 0.428), highlighting deeper penetration and more uniform dose distribution for higher energy beams .

The high consistency between simulation and experimental data ensures accurate dose calculations critical for precise treatment planning. Close agreement among GAMOS, GATE, and experimental data validates these Monte Carlo codes for clinical settings. Understanding PDD and D_{20}/D_5 trends for different energies and field sizes aids in optimizing treatment plans based on tumor depth and size. The deeper penetration of 12 megavoltage beams makes them suitable for deep-seated tumors, while the higher surface dose and quicker fall-off of 6 megavoltage beams can be advantageous for shallower tumors or sparing adjacent healthy tissues.

The slight PDD increase with larger field sizes should be considered when planning treatments for larger tumors. Increased scatter with larger fields affects dose distribution, requiring careful balance between tumor coverage and healthy tissue sparing.

Gamma Index (GI) testing is essential for validating dose distributions in radiotherapy, measuring agreement between calculated and measured distributions while considering both dose difference and distance to agreement. This study evaluated GAMOS and GATE performance in simulating dose distributions for a Varian linear accelerator, focusing on PDD and beam profile distributions across various field sizes and photon energies.

Both codes demonstrated high accuracy in simulating dose distributions compared to experimental data . For Gamma Index ($G < 1.0$), both codes showed over 94% agreement across all field sizes and photon energies, indicating reliability for clinical dosimetry. For Gamma Index ($G < 0.5$), agreement remained robust at over 84% for all cases, suggesting minor discrepancies within acceptable limits. Profile dose simulation performance was comparable to PDD performance, with minor differences within acceptable limits. Quality index values were nearly identical between GAMOS, GATE, and experimental data, underscoring the precision of both codes [FIGURE:4, FIGURE:5].

GAMOS and GATE are both highly effective tools for radiotherapy dose distribution simulation. The slight variations observed are minimal and do not significantly impact overall performance, validating their use in medical physics and providing confidence in their accuracy and reliability.

[Figure 4: see original paper]

The Phantom Output Factor (S_{cp}) study for square fields from 1.0 cm to 40 cm for 6 and 12 megavoltage photon beams showed strong agreement between GAMOS, GATE, and experimental results [Figure 8: see original paper]. S_{cp} values ranged from 0.55 for smallest fields to 1.22 for largest, with simulations matching experimental data within $±$0.02 for both energies, confirming Monte Carlo code accuracy.

Head Scatter Factor (S_c) analysis for square fields from 1.0 cm to 40 cm using GAMOS and GATE, along with experimental data for 6 and 12 megavoltage beams, revealed strong agreement with deviations of $±$0.004 for 6 megavoltage and $±$0.007 for 12 megavoltage photon beams [Figure 9: see original paper]. S_c values increased with field size for both energies, consistent with greater scatter volume in larger fields. This agreement underscores Monte Carlo simulation reliability in predicting scatter factors and their value in optimizing treatment planning.

Relative wedge factors for 6 and 12 megavoltage photon beams across various field sizes showed high consistency between GAMOS and GATE, with only minor variations, confirming both codes as reliable tools for wedge factor calculations. Wedge factors were consistently lower for 12 megavoltage beams due to higher photon penetration diminishing the wedge' s relative impact. For example, for 10 × 10 cm^2 fields, wedge factors were 0.695 for 6 megavoltage and 0.680 for 12 megavoltage beams. Wedge factors increased with field size for both energies: from 0.686 to 0.740 for 6 megavoltage and from 0.670 to 0.735 for 12 megavoltage as field size increased from 5 × 5 cm^2 to 40 × 40 cm^2 . This increase occurs because larger fields encompass more of the physical wedge, enhancing the dose gradient effect.

These findings have important clinical implications. The high consistency between GAMOS and GATE enhances confidence in their clinical application. Accurate wedge factors are essential for achieving intended dose gradients, particularly important in complex treatment plans accounting for tissue heterogeneity and varying anatomical shapes. Lower wedge factors for higher energy beams provide valuable information for selecting appropriate wedge angles and field sizes to achieve desired dose distributions.

[FIGURE:5, FIGURE:6, FIGURE:7, FIGURE:8, FIGURE:9]

Flatness, symmetry, and penumbra analysis from GAMOS and GATE simulations for a Varian linear accelerator at 6 and 12 megavoltage photon energies showed flatness values ranging from approximately 105% to 106.8%, with slight increases as field size expanded—expected due to beam divergence and scattering effects. Results were consistent across both codes, indicating reliable modeling of beam intensity distribution and well-controlled, stable beams across all field sizes.

Symmetry values were close to 100% for all field sizes and energies, indicating highly symmetrical beam profiles crucial for preventing dose inhomogeneities.

The close agreement between GAMOS and GATE underscores simulation accuracy in replicating beam physical characteristics.

Penumbra width (80% to 20% of maximum dose) increased with field size, consistent with expected behavior due to increased scattering and lateral beam spread. For 6 megavoltage beams, penumbra ranged from approximately 5 mm to 6.5 mm, while for 12 megavoltage beams it ranged from 7 mm to 8.4 mm. Close correspondence between codes indicates effective capture of beam edge characteristics.

Overall, flatness, symmetry, and penumbra results from GAMOS and GATE are consistent and within clinically acceptable limits for all tested field sizes and energies. Slight variations are within expected ranges and do not compromise dosimetric quality, affirming the reliability of these codes in accurately simulating Varian linear accelerator properties and ensuring precise, safe radiation therapy delivery.

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12. Conclusion

This study demonstrates the accuracy and reliability of GAMOS and GATE Monte Carlo simulations for dosimetric calculations in external radiotherapy, particularly for 6 and 12 megavoltage photon beams from a Varian medical linear accelerator. Results show strong agreement between simulation and experimental data for key dosimetric parameters, including PDD values, beam profiles, and Gamma Index analyses across various field sizes. Both codes accurately predicted $d_{\max}$ and D_{20}/D_5 ratios for both energy levels, confirming their effectiveness for clinical applications.

Comparison with experimental data highlights robust performance, with over 94% agreement in Gamma Index tests (GI < 1.0) for both PDD and beam profile simulations across all field sizes and photon energies. These findings validate these tools for clinical treatment planning, ensuring precise dose delivery while minimizing exposure to healthy tissues. The study confirms 12 megavoltage photon beams are suitable for deep-seated tumors, while 6 megavoltage beams remain advantageous for shallower tumors where sparing healthy tissue is critical. Analysis of PDD trends and beam profiles provides valuable insights for optimizing radiotherapy treatment plans based on tumor depth and field size.

This work solidifies the role of Monte Carlo-based simulations using GAMOS and GATE as essential tools for enhancing dosimetric accuracy in radiotherapy. The high consistency with experimental data affirms their potential for broader clinical and research applications, contributing to improved patient outcomes through more precise radiotherapy treatment planning.

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Note: Figure translations are in progress. See original paper for figures.