Optimizing dosimetric accuracy for cancer treatment with flattened and flattening filter-free photon 6 megavoltage beams: Using GAMOS and GATE Monte Carlo codes

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Abstract

This research investigates the optimization of cancer treatment by analyzing the dosimetric characteristics of 6 megavoltage flattened and flattening filter-free photon beams through detailed Monte Carlo simulations utilizing the GAMOS and GATE codes. Photon beams generated by a Varian medical linear accelerator were assessed based on critical factors such as dose rate, percentage depth doses(PDDs), out-of-field doses(OFDs), beam profiles scatter factor, energy spectrum, surface dose, and head and total scatter correction factor. The results demonstrate that FFF beams, as modeled with GAMOS and GATE, provide a notably higher dose rate-approximately 2.3 times greater than that of FF beams-potentially leading to reduced treatment durations. Specifically, the dose rate for FFF beams was 3.8 Gy/min compared to 1.6 Gy/min for FF beams. Additionally, the FFF beams produced a 25.0% decrease in out-of-field dose(OFD) 3.5 cm away from the field edge, attributed to reduced head scatter. However, simulations also indicated increased surface and buildup doses for FFF beams, with surface doses being around 15% higher than FF beams. By substituting the air below the secondary collimator jaws of the linear accelerator with helium(He), the ratio of surface dose was reduced from 1.24 to 1.14, while the buildup dose and dmax values were brought back in line with those of FF beams. This in-depth Monte Carlo analysis underscores the potential benefits of FFF beams in delivering more efficient radiation doses and lowering out-of-field exposure. Nonetheless, managing surface and build-up doses remains essential. With appropriate modifications, FFF technology could significantly enhance cancer treatment outcomes while reducing radiation exposure to surrounding healthy tissue, making it a promising tool for clinical use.

Full Text

Preamble

Optimizing Dosimetric Accuracy for Cancer Treatment with Flattened and Flattening Filter-Free Photon 6 Megavoltage Beams: Using GAMOS and GATE Monte Carlo Codes

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Abstract

This research investigates the optimization of cancer treatment by analyzing the dosimetric characteristics of 6 megavoltage flattened and flattening filter-free photon beams through detailed Monte Carlo simulations utilizing the GAMOS and GATE codes. Photon beams generated by a Varian medical linear accelerator were assessed based on critical factors including dose rate, percentage depth doses (PDDs), out-of-field doses (OFDs), beam profiles, scatter factor, energy spectrum, surface dose, and head and total scatter correction factors.

The results demonstrate that FFF beams, as modeled with GAMOS and GATE, provide a notably higher dose rate—approximately 2.3 times greater than that of FF beams—potentially reducing treatment durations. Specifically, the dose rate for FFF beams was 3.8 Gy/min compared to 1.6 Gy/min for FF beams. Additionally, FFF beams produced a 25.0% decrease in out-of-field dose at 3.5 cm from the field edge, attributed to reduced head scatter. However, simulations also indicated increased surface and buildup doses for FFF beams, with surface doses approximately 15% higher than FF beams. By substituting the air below the secondary collimator jaws of the linear accelerator with helium (He), the surface dose ratio was reduced from 1.24 to 1.14, while the buildup dose and dmax values were brought back in line with those of FF beams.

This in-depth Monte Carlo analysis underscores the potential benefits of FFF beams in delivering more efficient radiation doses and lowering out-of-field exposure. Nonetheless, managing surface and buildup doses remains essential. With appropriate modifications, FFF technology could significantly enhance cancer treatment outcomes while reducing radiation exposure to surrounding healthy tissue, making it a promising tool for clinical implementation.

Keywords: PDD, FF/FFF beams, GAMOS/GATE Codes, Varian, HSCF, TSCF

1. Introduction

Cancer remains one of the leading causes of death worldwide [?], necessitating continuous advancements in treatment modalities [?]. Radiotherapy, particularly external beam radiotherapy (EBRT) [?], plays a crucial role in managing various cancers, offering a non-invasive approach to tumor eradication [?]. Among different radiation therapy modalities [?], photon beam therapy using linear accelerators (linacs) has been a cornerstone due to its ability to deliver precise doses to target tissues while sparing surrounding healthy structures [?]. However, optimizing dose delivery remains an ongoing challenge, requiring careful balancing of treatment efficacy with minimization of adverse effects [?].

A significant factor influencing dose distribution in photon beam therapy is the use of a flattening filter (FF) [?]. Traditionally, FFs have been incorporated into the linac beam path to produce uniform dose distribution across the treatment field [?], particularly at a reference depth of 10.0 cm. While FFs achieve the desired beam flatness [?], they introduce several drawbacks. The presence of an FF reduces the overall dose rate, increasing treatment times [?]. Furthermore, FFs contribute to scattered radiation, which can increase out-of-field doses and potentially impact healthy tissue adjacent to the treatment area [?]. These limitations have driven interest in unflattened (FFF) photon beams [?], which are increasingly explored for their potential to enhance treatment efficiency and safety [?].

The removal of the flattening filter from the linac beam path offers several potential advantages [?]. FFF beams are characterized by significantly higher dose rates [?], which can reduce treatment times and improve patient throughput [?]. Additionally, the absence of the filter results in reduced head scatter [?], which lowers out-of-field dose (OFD) and diminishes radiation exposure to healthy tissues surrounding the tumor [?]. However, FFF beams also present unique challenges, including increased surface and buildup doses [?], which must be carefully managed to avoid compromising the treatment' s therapeutic ratio [?].

Monte Carlo (MC) simulation using GAMOS and GATE codes has emerged as a powerful tool for detailed analysis of photon beam characteristics [?]. MC methods allow precise modeling of complex radiation interactions within the linac head and patient tissues, providing invaluable insights into the dosimetric properties of both FF and FFF beams. By leveraging MC simulations, researchers can explore the impact of various beam configurations on dose distribution [?], enabling optimization of treatment plans for maximum therapeutic benefit.

This study performed a comprehensive Monte Carlo analysis using GAMOS and GATE codes to compare the dosimetric characteristics of 6 megavoltage flattened (FF) and unflattened (FFF) photon beams [?] generated by a Varian linac [?]. Critical parameters including percentage depth doses (PDDs), dose rate, out-of-field doses (OFDs), beam profiles, energy spectrum, scatter factor, and surface dose were evaluated [?]. The aim was to determine the potential advantages of FFF beams in optimizing cancer treatment, particularly in improving dose delivery efficiency and minimizing exposure to surrounding healthy tissues [?]. These findings contribute to the ongoing refinement of radiotherapy techniques, with the ultimate goal of enhancing treatment outcomes for cancer patients.

This investigation provides a detailed comparison of FF and FFF beams and explores the practical implications of adopting FFF technology in clinical settings. By addressing both the benefits and challenges associated with FFF beams, this study offers a balanced perspective that can inform future developments in photon beam therapy, supporting the advancement of radiotherapy techniques that provide more precise, effective, and safer cancer treatments.

2. Materials and Methods

This study investigated the dosimetric properties of a 6 megavoltage photon beam generated by a Varian medical linear accelerator [?], utilizing the GAMOS and GATE Monte Carlo simulation codes [?]. The linac head geometry, including critical components such as the target, primary collimator [?], flattening filter, and jaws, was meticulously modeled following detailed specifications from Varian Medical Systems (Palo Alto, CA, USA). These elements are vital for shaping and delivering the photon beam, and their accurate configuration is crucial for precise simulations [?]. To ensure simulation accuracy, the Monte Carlo models were rigorously validated against experimental data obtained using a 40 × 40 × 40 cm^3 water phantom [?], a standard medium for replicating human tissue in radiotherapy dosimetry [?]. The phantom was positioned at a source-to-surface distance (SSD) of 100.0 cm, a typical clinical setup ensuring relevant and reproducible results [?]. Data obtained from the water phantom were compared with simulation results, providing a comprehensive assessment of the beam’ s dosimetric characteristics [?].

2.1 Monte Carlo Simulations

The GAMOS and GATE codes were employed to simulate photon interactions within the linac head and water phantom [?]. These Monte Carlo codes are well-established in radiotherapy for modeling complex radiation transport processes with high accuracy [?]. By simulating the beam’ s passage through linac components and subsequent interactions within the water phantom, the study aimed to replicate actual dose distributions observed in clinical settings [?].

2.2 Monte Carlo Validation

The Monte Carlo simulations were validated by comparing them with experimental measurements [?]. These measurements were obtained using a 40 × 40 × 40 cm^3 water phantom positioned at a source-to-surface distance (SSD) of 100.0 cm. Experimental data, including dose distributions and beam profiles, were thoroughly compared with simulated results to verify model accuracy. Any observed discrepancies were carefully evaluated and corrected to improve simulation precision [?].

2.3 Dosimetric Properties Calculations

This study performed comprehensive calculations of essential dosimetric parameters for both flattened (FF) and unflattened (FFF) photon beams [?]. Key metrics including percentage depth dose (PDD) [?], dose rate, scatter factor, and energy spectra were analyzed to evaluate the beams' ability to deliver precise and effective radiation doses to the target region while minimizing unnecessary exposure to adjacent healthy tissues. These calculations provide critical insights for optimizing beam performance and improving clinical outcomes [?].

2.4 PDDs, dmax, and Dose Rate

Percentage depth dose (PDD) curves were generated for various field sizes to assess dose variation with depth within tissue [?]. The maximum dose depth (dmax) and dose rate were calculated and compared between FF and FFF beams. These parameters are critical for understanding beam penetration and the ability to deliver prescribed doses at different tissue depths \cite{S¸ ahmaran and Yılmaz Koca (2023)}.

2.5 Beam Profiles and Out-of-Field Dose

Beam profiles were evaluated to assess dose distribution across the treatment field at varying depths [?]. Both dose delivery uniformity and penumbra characteristics were examined for flattened (FF) and unflattened (FFF) beams [?]. Additionally, out-of-field dose was quantified, with particular attention to reduced radiation delivered beyond the primary treatment field when using FFF beams, attributed to decreased head scatter. This analysis is critical for understanding the advantages of FFF beams in minimizing radiation exposure to healthy tissues surrounding the treatment area [?].

2.6 Surface Dose and Buildup

Surface dose and buildup regions were analyzed for both flattened and unflattened beams using different field sizes [?]. The study focused on comparing surface dose delivered to skin or superficial tissues and examining the buildup region where dose rapidly increases to a maximum (dmax). The effects of removing the flattening filter on these parameters were evaluated, with special consideration given to modifications such as replacing the air column under the secondary collimator jaws with helium (He).

2.7 Head and Total Scatter Correction Factor

The head scatter correction factor (HSCF) accounts for scatter from linac head components [?], while the total scatter correction factor (TSCF) includes both head scatter and medium scatter. Using GAMOS and GATE Monte Carlo simulations, these factors were calculated for 6 megavoltage flattened (FF) and flattening filter-free (FFF) photon beams across different field sizes. This analysis helps evaluate the impact of the flattening filter on beam scatter, which is crucial for improving treatment accuracy [?].

3. Results

Table 1 provides the D20/D10 ratios for flattened and unflattened 6 megavoltage photon beams at field sizes ranging from 5×5 cm^2 to 20×20 cm^2, calculated using GAMOS and GATE codes for a Varian medical linear accelerator [?].

For the 5×5 cm^2 field size, D20/D10 ratios for FF beams were 0.55 with GAMOS and 0.56 with GATE, indicating moderate dose gradient and relatively gradual dose fall-off [?]. In contrast, FFF beams exhibited slightly lower ratios of 0.52 for GAMOS and 0.53 for GATE, reflecting a steeper dose gradient and more pronounced dose fall-off at the edges. This result is expected given that FFF beams, lacking a flattening filter, have a more pronounced central dose peak and more rapid dose decrease at the periphery.

At the 10×10 cm^2 field size, D20/D10 ratios for FF beams increased to 0.57 (GAMOS) and 0.58 (GATE), showing a slightly larger dose gradient compared to smaller field sizes. This suggests that while FF beams continue to offer reasonable dose uniformity in medium-sized fields, the dose fall-off becomes more noticeable. For FFF beams, the ratios were 0.54 (GAMOS) and 0.55 (GATE), indicating a more pronounced dose gradient and sharper dose fall-off compared to FF beams, consistent with effects observed in larger fields.

For the 20×20 cm^2 field size, D20/D10 ratios for FF beams further increased to 0.61 (GAMOS) and 0.62 (GATE), reflecting a broader dose fall-off region. This increase highlights the challenge of maintaining dose uniformity in larger fields with FF beams. In comparison, FFF beams exhibited ratios of 0.57 (GAMOS) and 0.58 (GATE), showing a significant dose gradient at the edges of the large field [?]. The absence of the FF in FFF beams results in a sharper dose fall-off that becomes more pronounced as field size increases [?].

These D20/D10 ratios indicate that FF beams generally provide more gradual dose fall-off, leading to better dose uniformity across various field sizes. In contrast, FFF beams, while advantageous for high-dose treatments in smaller fields, exhibit a steeper dose gradient and more pronounced dose fall-off in larger fields [?]. The choice between FF and FFF beams should be guided by clinical requirements, considering the trade-off between dose uniformity and dose delivery efficiency.

Table 1: Ratios of D20/D10 for different field sizes of 6 megavoltage flattened (FF) and unflattened (FFF) photon beams at a 10.0 cm depth, calculated using GAMOS and GATE Monte Carlo (MC) simulations for a Varian medical linear accelerator.

Field Size (cm^2)	Flattened (FF) GAMOS	Flattened (FF) GATE	Unflattened (FFF) GAMOS	Unflattened (FFF) GATE
5 × 5	0.55	0.56	0.52	0.53
10 × 10	0.57	0.58	0.54	0.55
20 × 20	0.61	0.62	0.57	0.58

Analysis of Dmax/Dmin ratios for 6 megavoltage photon beams using flattened and unflattened configurations reveals significant insights into dose distribution characteristics at field sizes of 5 × 5 cm^2, 10 × 10 cm^2, and 20 × 20 cm^2, calculated at a depth of 10.0 cm using GAMOS and GATE codes for a Varian medical linear accelerator.

For the 5 × 5 cm^2 field size, both flattened (FF) and unflattened (FFF) beams exhibited minimal dose variation within 80% of the field size, with Dmax/Dmin ratios of 1.01 for FF beams and slightly higher values for FFF beams (1.06 with GAMOS and 1.05 with GATE). This reflects that in small field sizes, FF beams maintain nearly uniform dose distribution, while FFF beams show modest increase in dose variation due to the absence of the flattening filter, resulting in a more concentrated central dose and more pronounced dose gradient at the periphery [**?**].

As field size increased to 10 × 10 cm^2, FF beams continued to show stable dose distribution with Dmax/Dmin ratios remaining at 1.01 for both GAMOS and GATE. In contrast, FFF beams exhibited increased dose variation, with ratios rising to 1.13 (GAMOS) and 1.12 (GATE). This increase indicates that larger field sizes exacerbate the dose gradient effects of FFF beams, leading to more noticeable dose variation compared to FF beams.

For the 20 × 20 cm^2 field size, FF beams maintained excellent dose uniformity with ratios of 1.01 for both GAMOS and GATE. However, FFF beams showed a significant increase in dose variation, with ratios reaching 1.32 (GAMOS) and 1.30 (GATE), as shown in Table 2 . This substantial rise highlights the impact of the absent flattening filter, which results in a pronounced central dose peak and steeper dose fall-off at field edges, leading to greater dose variability in larger fields [**?**].

Table 2: Ratios of the maximum dose (Dmax) to the minimum dose (Dmin) within 80% of the field size for flattened (FF) and unflattened (FFF) 6 megavoltage photon beams at a depth of 10 cm, using GAMOS and GATE codes for a Varian medical linear accelerator.

Field Size (cm^2)	Flattened (FF) GAMOS	Flattened (FF) GATE	Unflattened (FFF) GAMOS	Unflattened (FFF) GATE
5 × 5	1.01	1.01	1.06	1.05
10 × 10	1.01	1.01	1.13	1.12
20 × 20	1.01	1.01	1.32	1.30

In this study, percentage depth doses (PDDs) for unflattened (FFF) and flattened (FF) 6 megavoltage photon beams were compared using both measurements (for FF) and Monte Carlo simulations (GAMOS and GATE codes) in a water phantom for field sizes of 5 × 5 cm^2, 10 × 10 cm^2, and 20 × 20 cm^2. The results showed that FFF beams delivered higher surface and buildup doses compared to FF beams due to the absence of the flattening filter, which reduces scatter. For all field sizes, PDD curves of FFF beams exhibited steeper dose fall-off beyond the maximum depth (dmax), leading to reduced dose in deeper tissues. In contrast, FF beams showed more gradual dose decrease with depth, reflecting the impact of beam flattening.

Simulations using GAMOS and GATE codes closely matched measured PDDs for FF beams, confirming the accuracy of the Monte Carlo models [**?**]. For FFF beams, simulations consistently predicted higher dose rates at shallow depths, in agreement with experimental observations [**?**]. These findings highlight the dosimetric benefits of FFF beams, particularly in decreasing treatment time and sparing deeper healthy tissues [**?**], as shown in Figure 1.

Figure 1 [Figure 1: see original paper] compares beam profiles between flattened and unflattened 6 megavoltage photon beams for field sizes from 5 × 5 cm^2 to 20 × 20 cm^2 using GAMOS and GATE codes, demonstrating significant variations in dose distributions. For smaller field sizes (5 × 5 cm^2), the FFF beam shows a sharper dose peak at the central axis with faster dose fall-off toward the periphery, while the FF beam exhibits more uniform dose distribution. As field size increases (10 × 10 cm^2 and 20 × 20 cm^2), this trend persists, with the FFF beam consistently showing higher central axis dose and reduced penumbra compared to the FF beam [**?**].

GAMOS and GATE simulations closely align with measured data for FF beams, confirming Monte Carlo model accuracy. However, FFF beams result in lower out-of-field doses due to the absence of scattering from the flattening filter. Slight discrepancies between simulations and measurements in penumbra regions likely result from limitations in modeling secondary scatter [**?**]. Overall, these results suggest that FFF beams offer dosimetric advantages in high-precision radiotherapy, particularly for smaller fields.

Figure 1: Comparison of Percentage Depth Doses (PDDs) and photon beam spectra for flattened (FF) and unflattened (FFF) 6 megavoltage photon beams across 5 × 5 cm^2, 10 × 10 cm^2, and 20 × 20 cm^2 field sizes: experimental

measurements for FF beams and Monte Carlo simulations using GAMOS and GATE codes.

Photon energy spectra of flattened and unflattened 6 megavoltage photon beams were compared for field sizes from 5 × 5 cm^2 to 20 × 20 cm^2 using GAMOS and GATE Monte Carlo codes. The results revealed notable differences in energy spectra between flattened and unflattened beams across all field sizes. For FFF beams, the spectra were generally softer, with a higher proportion of lower-energy photons due to the absence of the flattening filter, which typically hardens the beam by attenuating lower-energy photons [?]. In contrast, FF beams displayed a more uniform and hardened spectrum, especially in larger field sizes. The softening of the FFF beam spectrum was more pronounced at smaller field sizes (5 × 5 cm^2), while the difference decreased with increasing field size (20 × 20 cm^2). Monte Carlo simulations using both GAMOS and GATE codes closely aligned with experimental data, accurately reflecting the impact of the flattening filter on energy spectra. These differences in photon spectra between FF and FFF beams contribute to variations in dose distribution and out-of-field dose [?], highlighting potential advantages of FFF beams in certain radiotherapy applications, as shown in Figure 2.

Figure 2: Comparative analysis of photon beam spectra for 6 megavoltage flattened (FF) and unflattened (FFF) photon beams across field sizes of 5 × 5 cm^2, 10 × 10 cm^2, and 20 × 20 cm^2, obtained using GAMOS and GATE Monte Carlo simulations.

Monte Carlo simulations using GAMOS and GATE codes demonstrate differences in dosimetric characteristics between 6 megavoltage flattened (FF) and unflattened (FFF) photon beams [?]. The Total Scatter Correction Factor (TSCF) and Head Scatter Correction Factor (HSCF) show distinct patterns that highlight the advantages and limitations of both beam types. For all field sizes, TSCF was higher for FF beams compared to FFF beams. This is expected due to scattering introduced by the flattening filter, which interacts with the primary photon beam and contributes additional scatter within and beyond the treatment field. As field size increased, TSCF values also rose for both beam types, reflecting increased scatter contributions from the larger irradiated tissue volume [?]. However, FFF beams consistently showed lower TSCF values, indicating less scatter and more concentrated dose distribution, which is favorable for reducing unwanted radiation to healthy tissues.

HSCF followed a similar trend, with higher values observed for FF beams across all field sizes. The presence of the flattening filter significantly increases head scatter by interacting with primary photons and generating secondary scatter. This effect is especially pronounced in larger fields where photon scatter from linac head components is more substantial. Conversely, FFF beams, which eliminate the flattening filter, demonstrate considerable reduction in head scatter, as shown by lower HSCF values. This scatter reduction is particularly advantageous for modern radiotherapy techniques prioritizing dose precision [?], such as intensity-modulated radiotherapy (IMRT) [?] and stereotactic body radiotherapy (SBRT) [?], as shown in Figures 3 and 4.

Figure 3: Comparison of total scatter correction factor (TSCF) curves along the lateral sides of the irradiation field for flattened and unflattened 6 megavoltage photon beams across various square field sizes of 5×5 cm^2, 10×10 cm^2, and 20×20 cm^2, obtained using GAMOS and GATE Monte Carlo simulations.

Figure 4: Comparison of head scatter correction factor (HSCF) curves along the lateral sides of the irradiation field for flattened and unflattened 6 megavoltage photon beams across various square field sizes of 5×5 cm^2, 10×10 cm^2, and 20×20 cm^2, obtained using GAMOS and GATE Monte Carlo simulations.

A key finding is the potential clinical benefit of FFF beams. The increased dose rate associated with FFF beams can significantly shorten treatment times, improving patient comfort and reducing the likelihood of motion artifacts during treatment. Additionally, the reduced out-of-field dose (OFD) for FFF beams, resulting from lower head scatter, minimizes radiation exposure to surrounding healthy tissues, enhancing the safety profile of FFF-based treatments. However, the higher surface and buildup doses associated with FFF beams present a challenge. These effects, while manageable, require careful consideration in treatment planning, especially for patients with tumors located near sensitive structures. Notably, this study found that replacing the air column under the linac jaws with helium mitigated some of these effects, restoring dose characteristics closer to those of FF beams.

Overall, the results indicate that FFF beams provide distinct dosimetric advantages, including higher dose rates, reduced scatter, and lower out-of-field doses. These features make FFF beams a promising option for advanced radiotherapy techniques, though careful management of surface and buildup doses remains essential.

4. Conclusion

This study presents a comprehensive analysis of the dosimetric characteristics of 6 megavoltage flattened (FF) and unflattened (FFF) photon beams generated by a Varian medical linear accelerator, using GAMOS and GATE Monte Carlo simulations. The results demonstrate that FFF beams offer significant advantages, including increased dose rates and decreased out-of-field doses (OFDs), which can lead to shorter treatment times and reduced exposure to healthy tissue. While FFF beams exhibit higher surface and buildup doses, these can be mitigated by adjusting the treatment setup, such as introducing helium to reduce surface dose. The detailed comparison of photon energy spectra, beam profiles, and percentage depth doses (PDDs) confirms the clinical viability of FFF beams, particularly for modern radiotherapy techniques such as IMRT and SBRT. This study underscores the potential of FFF beams to enhance therapeutic outcomes while maintaining safety, making them a promising option for optimizing cancer treatment in clinical settings.

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