ORIGINAL ARTICLE

Gamma Knife Icon™ Single Sector Characterization Based on Monte Carlo Simulation

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Abstract

Purpose: Gamma Knife Radiosurgery refers to surgery using radiation to destroy intracranial tissues or lesions elusive or unsuitable for open surgery. This study aimed to simulate the Gamma Knife Icon™ (GKI™) single sector to assess various attributes of the output beam and evaluate the EGSnrc C++ Monte Carlo code capabilities to perform a complete simulation of GKI™ for more investigations.

Materials and Methods: The single source is simulated, and the geometries of the 4 and 16 mm collimators are defined based on the manufacturer data. The phase space files (PSFs) are recorded at the end of each collimator, and dose distributions are saved for the final analysis process in the last step.

Results: The beam spectrum has two energy peaks γ_1 =1.17 MeV and γ_2 = 1.33 MeV, and low energy photons from scattering are also evident. The Gamma Index (GI) values are less than 1 in comparing the dose profiles generated in simulation with reference data. The Full Width at Half Maximum (FWHM) is 4.55, 10.9, 5.13 (mm) and 16.7, 35.1, 17.65 (mm) for 4mm and 16 mm collimators along x, y, and z axes, respectively. The penumbra width (80%-20%) is also 1.48, 5.5, 1.54 (mm) and 3.76, 10.1, 2.78 (mm) for 4mm and 16 mm collimators along x, y, and z axes, respectively.

Conclusion: Results are in good agreement with what is expected, and it is possible to perform a complete simulation of the GKI™ system using egs++ for more investigations in phantoms and patients.

Keywords: Gamma Knife Icon™; Radiosurgery; Monte Carlo Simulation; Electron Gamma Shower National Research Council.

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1. Introduction

One of the most creative radiotherapy methods progressed over decades is Stereotactic Radiosurgery (SRS). Neurosurgeon Lars Leksell invented the SRS term to refer to surgery using radiation rather than the more typical and aggressive surgical instruments [1, 2] to destroy intracranial tissues or lesions elusive or unsuitable for open surgery [3].

The Gamma Knife Icon™ (GKI™, Elekta AB, Stockholm, Sweden) is the latest model of GK machine, which has 192 Co-60 gamma-ray beams, distributed in 8 separated moving sectors (24 sources per sector) converging at the Unit Center Point (UCP) in three nominal 4, 8, and 16mm diameters. The GKI™ can precisely irradiate single or multiple targets [1-3]. This treatment device has the advantages of radiation protection, positioning, and dosimetric accuracy. The GKI™ dosimetric accuracy is about 98% more promising than its ancestors (GK 4C > 95%). The GKI™ positioning accuracy is also less than 0.20 mm (GK 4C < 0.30 mm) [4, 5]. The GKI™ uses a 120-mm thick tungsten shield to provide good radiation protection. This configuration results in a remarkably lower extracranial dose of GKI™ vs. the prior versions [6, 7].

These unique capabilities made GKI™ the gold standard device to treat head and neck cancers worldwide and consequently demands a vast range of investigation and research. The limitations of practical studies, such as high-cost measurements, make Monte Carlo simulation an excellent alternative solution [8, 9].

The Electron Gamma Shower National Research Council (EGSnrc) C++ Monte Carlo (MC) code, in short egs++, is a versatile and general-purpose package for the MC simulation of the radiotherapy units. It can simulate the coupled transport of electrons and photons in an arbitrary geometry for particles with energies from a few keV up to several hundreds of GeV [10]. This simulation is performed to extract the characteristics of a single sector beam, including energy spectrum, electron contamination of the beam, Full Width at Half Maximum (FWHM) of profiles, and penumbra width (80%-20%) at isocenter, using the egs++ powerful toolkit and the confidential manufacturer data.

Previous investigators used the MC techniques to investigate the Cobalt-60 source properties in different devices. Best *et al.* [11] used Penelope, a set of Monte Carlo dosimetry codes, to create a radiological model of a sector of sources in the Perfexion and verified the model both by comparison to other models and to radiochromic film measurements. Rogers *et al.* [5] simulated a Cobalt-60 radiotherapy unit radiation beam using the EGS/BEAMnrc code. Various parameters have been assessed, and all agreed with the measurements at 2-3%. Mahmoudi *et al.* [12] used EGS/BEAMnrc code to evaluate the effect of different parameters on beam penumbra reduction of GK machine model 4C. There is no egs++ based model of GKI™ yet.

The fundamental parameters investigated in this study are energy spectrum, FWHM, and penumbra width at the isocenter and the dose profile curves similarity between simulation and Leksell Gamma Plan (LGP) treatment planning system. The outcomes of this investigation are necessary for further research on the characteristics of GKI™. The output of this project will be used for a more comprehensive simulation of GKI™ to evaluate dose distributions in phantoms and patients based on the Computed Tomography (CT) models.

2. Materials and Methods

The GK machine was simulated using egs++ Mc code developed to model radiotherapy units [10]. The MC simulation of GK has been done in three significant steps. The first step is the single source simulation, including the definition of source capsule and cobalt source in it (Figure 1A). The collimator geometries are simulated in the next step based on the manufacturer's confidential data of the internal channels' structure (Figure 1B). The materials used in the collimator layers and source capsule have a specific composition, and a PEGS4 library is created using egs_gui based on the actual compositions. The Phase Space Files (PSF) and dose distributions are recorded for the final analysis process in the last step.

Figure 1A represents the GK source internal structure configuration and is visualized using egs_view. As shown, the blue cylinder is the cobalt-60 source line, encapsulated in a stainless steel capsule. Seventeen point sources are defined in the current model, with a 1 mm distance along the 17 mm length of the cobalt source [11]. In an isotropic photon source, more than half of the initially emitted photons have no interaction with the collimator because the upper hemisphere emits photons in the opposite direction. The other photons will be absorbed in the collimator's primary thick and dense layer. Only a tiny

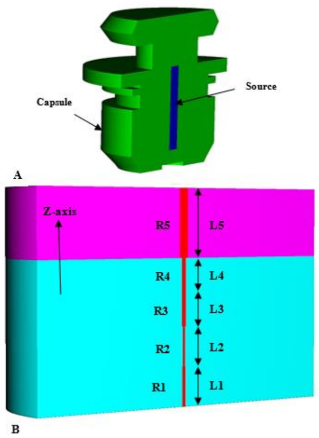

Figure 1. A: The schematic 3D view of the GKI™ source and capsule geometry, and B: A cutaway from collimator internal structure. Multi-radius red cylinder is the collimator's channel, R is the radius and L is the length of each layer (figures are generated by author utilizing egs_view)

portion of the initial photons pass through the collimator channel without interaction. So, it doesn't make sense to devote the computer's power and time to transport those photons which have no part in the final results of the simulation. Isotropic sources are more realistic, but they need about 26 times more histories than a collimated photon emission into a 45° cone. The closest source to focus distance in GKI™ is approximately 38.5 cm; therefore, an uncollimated 45-degree cone would be about 29 cm across the isocenter (Figure 2). The additional width supplies scattering effects within the collimator and bushing. These scatterings are the source of low-energy photons inside the output spectra reaching the target [11].

The collimator geometry model in the egs++ code is built utilizing technical data provided by the manufacturer. The simplified figure provided by the author (Figure 1B) describes concentric cylinders with various diameters forming a collimator straight through a tungsten slab.

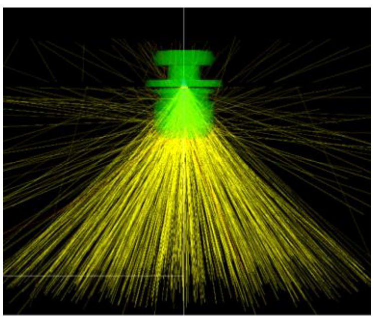

Figure 2. The Source model of GKI emitting photons in a 45° cone toward the isocenter simulated in egs++ code by author

The collimator and source materials were defined as a new PEGS4 library in code for a more realistic simulation using the egs_gui [13].

A complete source and collimator collection (Figure 3-A) is defined for 4 and 16 mm collimators. There are five rings in each sector (Figure 3B) with different collimator details (thickness of layers and radius of the internal channel) and source to focus distances. Also, in the 16 mm collimator, the source and collimator axis are not aligned entirely and must be considered in the simulation. In Figure 3B, the emitted photons' tracks of one sector, including 24 sources, are shown from the y-axis view. The green sphere is the focus volume. To increase the efficiency of the simulation and apply variance reduction techniques, typically, MC simulations of radiotherapy devices are divided into multiple steps [14]. In this study, the same method is used. At first, particles were generated from radioactive cobalt-60 point sources (γ_1 = 1.17 MeV, γ_2 = 1.33 MeV) and shot toward the isocenter inside the initial cone, defining the starting directions. After interaction of photons with source capsule, air, collimator pre-bushing, and bushing layers, just at the end of the collimator channel, the particles hit a phase space surface, a thick air plan 0.1 mm in thickness and 10 cm in radius, which records

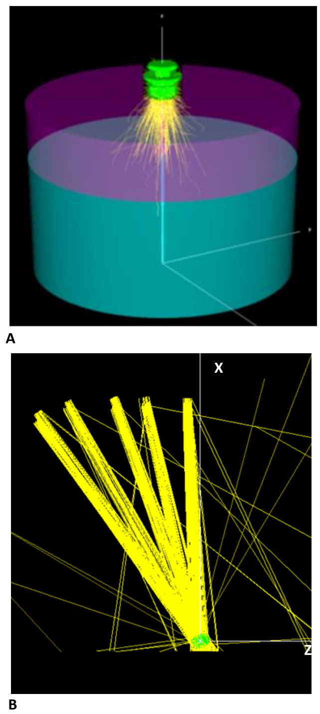

Figure 3. A: The GKI™ source and collimator and the track of emitted photons shown in transparent 3D view, and B: The first sector's photon tracks starting from the collimator end converging at the isocenter. (Both images are created by the author)

particles' final state (particle's type, energy, direction, and position) into a PSF. After recording the PSF, the second simulation step is to playback the PSF particles in their spatial position and orientation based on the first sector data. It is possible to playback the PSF many times to increase the number of histories and consequently increase the statistical accuracy. Each of the seventeen points emitting photons along the linear source produced about 108 initial photons, for a total 1.7×10^9 initial photons per GK source to produce PSF. Moreover, EGS_RadiativeSplitting Class Reference is used to increase the efficiency of radiative events in the dosimetry process.

About one million events were scored into each of the PSFs, and the total number of 1010 histories for all 24 sources is set to produce the dose distributions for each size of the collimator. Also, the Electron Cutoff energy (ECUT) is 521 KeV, and Photon Cutoff energy (PCUT) is 10 KeV. Three-dimensional voxelized geometry is defined as a dosimetry grid. The dosimetry grid and water equivalent spherical phantom (8cm in radius) are concentric. The grid is 160 × 160 × 160, producing a high-resolution bin size of 0.25 mm cubes generating a large cube of side 4 cm centered at the isocenter.

The software records the deposited doses into a .3ddose file, and the analysis process of this file is done using STATDOSE software. Profile curves, FWHM, and penumbra are extracted from this data along all coordinate system axes. Also, the PSF file is used to acquire the energy spectrum and electron contamination using BEAMDP.

3. Results

The beam spectrum for photons and electrons is derived using BEAMDP and is shown in Figure 4. The PSF analysis demonstrated that the beam spectrum has two energy peaks γ_1 =1.17 MeV and γ_2 = 1.33 MeV, and low-energy photons from scattering inside the collimator channel are also evident. In Figure 4-B, the secondary electrons' spectrum is shown as well. The 2D distribution of photons and electrons of the 4 mm collimator is shown in Figure 5 as X-Y scatter plots. Each recorded particle is visualized with an empty black circle. The solid black area centered at (0,0) is made of superposition of these open circles in the collimator aperture area.

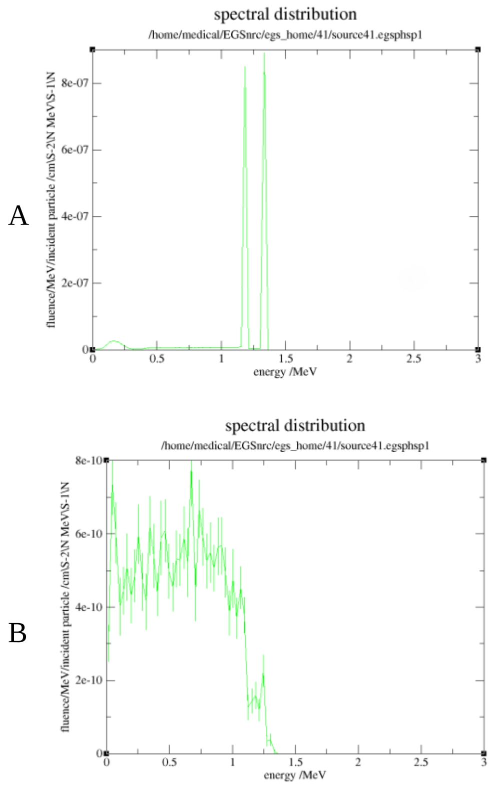

Figure 4. A: The radioactive Cobalt-60's photon spectral distribution recorded at the collimator's end including the scattered photons, B: The secondary electrons spectral distribution at the same position

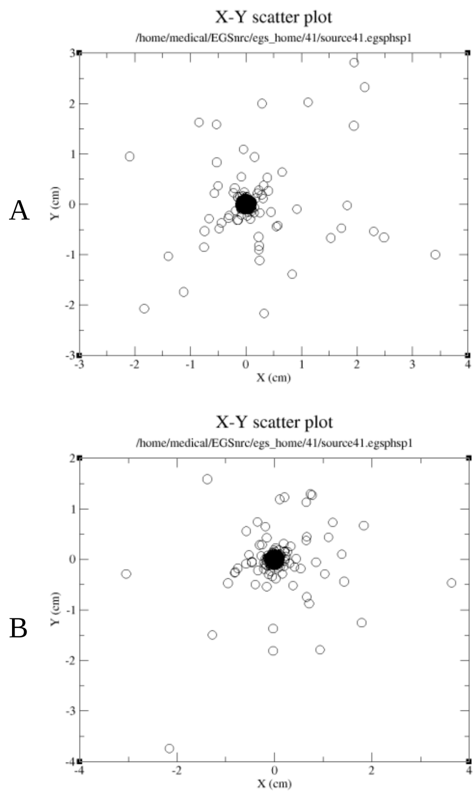

Figure 5. A: The photon's scatter plot recorded at the collimator's end, B: The secondary electrons' scatter plot recorded at the same position

The single sector dose distributions recorded in the .3ddose files are analyzed by STATDOSE to extract the profiles along the coordinate axes shown in Figure 6 and Figure 7. The profile curves are indicated at 0.25 mm resolution along all axes from irradiation with the first GKI™ 4- and 16-mm collimator size sectors. The GI values are less than 1 in comparing the dose profile curves generated in simulation with the LGP treatment planning system. This study used the 3% / 0.5 mm criterion for evaluating dose profiles. The FWHM and penumbra of these profiles are reported in Table 1 (4mm collimator) and Table 2 (16mm collimator) compared to the LGP penumbra and FWHM [11].

Full Width at Half Maximum (FWHM) calculated in simulation is 4.55, 10.9, 5.13 (mm) and 16.7, 35.1, 17.65 (mm) for 4 mm and 16 mm collimators along x,y, and z axes, respectively. The penumbra is also 1.48, 5.5, 1.54 (mm) and 3.76, 10.1, 2.78 (mm) for 4 mm and 16 mm collimators along x,y, and z axes, respectively.

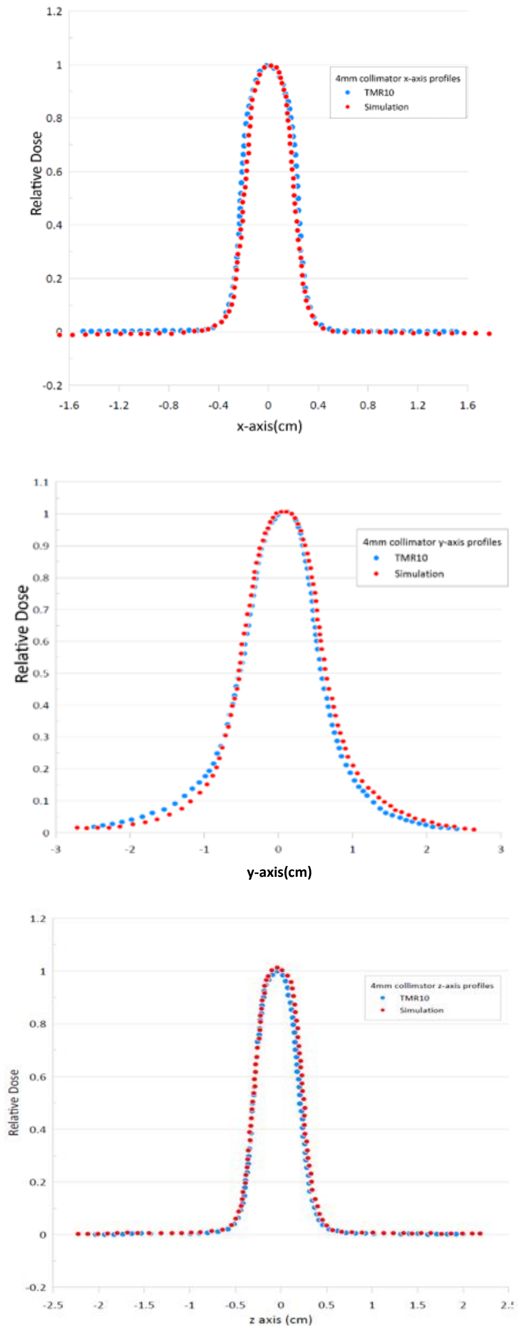

Figure 6. Single sector 4mm collimator dose profile curves generated by EGSnrc MC simulation in red compared to dose profile curves generated by LGP's TMR10 algorithm in blue

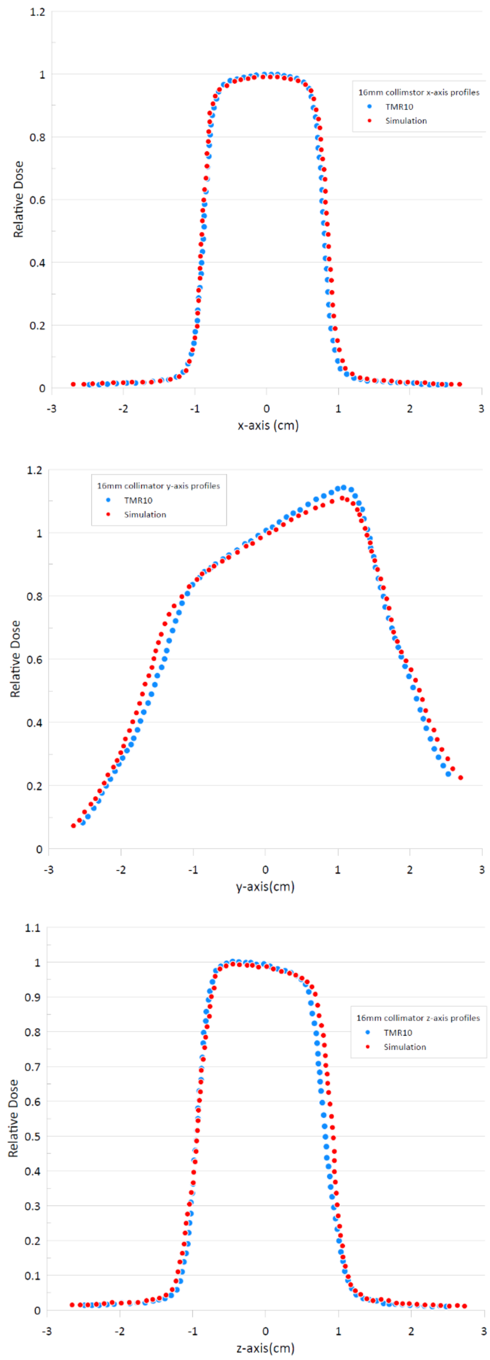

Figure 7. Single sector 16 mm collimator dose profile curves generated by EGSnrc MC simulation in red compared to dose profile curves generated by LGP's TMR10 algorithm in blue

Table 1. The FWHM and penumbra of the simulated single sector profiles at isocenter compared with the FWHM and penumbra of 4mm collimator dose profile curves generated by LGP's TMR10 algorithm

Profile	FWHM (mm)			Penumbra (mm)		
	Single Sector MC	Single Sector TMR10	Difference	Single Sector MC	Single Sector TMR10	Difference
X	4.55	4.7	-0.15	1.48	1.43	+0.05
Y	10.9	10.8	+0.1	5.5	5.6	-0.1
Z	5.13	5.18	-0.05	1.54	1.57	-0.03

Table 2. The FWHM and penumbra of the simulated single sector profiles at isocenter compared with the FWHM and penumbra of 16 mm collimator dose profile curves generated by LGP's TMR10 algorithm [11]

Profile	FWHM (mm)			Penumbra (mm)		
	Single Sector MC	Single Sector TMR10	Difference	Single Sector MC	Single Sector TMR10	Difference
X	16.7	16.84	-0.14	3.76	3.87	-0.11
Y	35.1	36.09	-0.99	10.2	10.4	-0.2
Z	17.65	17.74	-0.09	2.78	2.7	+0.08

4. Discussion

An uncomplicated inspection of the simulation validity is cheque the photon energy spectrum recorded in the PSF at the collimator's end. The photon energy spectrum is shown in Figure 4-A fits the predicted results for the radioactive decay of Cobalt-60 with two-photon peaks in γ_1 = 1.17 MeV and γ_2 = 1.33 MeV energies. There is a nonzero level of scattered photons for energies lower than the maximum peak, which is considerable around 0.13 MeV. The scattered photons and the secondary electron contamination (Figure 4-B) demonstrate that the code considers fundamental photon interactions with matter. These results indicate that the photon production process and the following interactions are correctly modeled [4, 15].

Dose distributions for a single sector in different collimator sizes are created using the LGP's TMR10 algorithm in the previous studies. The LGP's results have been validated by film dosimetry [11]. The GKI™ is an upgraded version of GKP™, and the source and collimator geometries are unchanged. The new features that are available with GKI™ are Image-Guided Radiation Therapy (IGRT) with stereotactic Cone Beam CT (CBCT) and adaptive planning [16]. Therefore, it is possible to use those profile curves for simulation validation. The smallest and largest collimator sizes (4 mm and 16 mm) are chosen to be simulated as proof of the accuracy of MC code in different field sizes.

Profile curves along the x, y, and z axes created by MC simulation and TMR10 LGP algorithm are compared for 4- and 16-mm collimators (see Figure 6 and Figure 7). In a complete device, the arrangement of the sources has symmetry around the z-axis. Consequently, the profiles along the x and y-axis are almost the same [17]. A single sector does not have such symmetry, so the x and y axes profiles are different for all collimator sizes (Table 1 and Table 2). Numerical analysis shows the y-axis FWHM and penumbra are (2.4, 2.1) and (3.7, 2.7) times greater than the x-axis for 4- and 16-mm collimators, respectively.

There is a strong agreement between the MC and TMR10 dose distributions by high pass rate in GI analysis in many cases. Also, the penumbra and FWHM for both collimator sizes are close, as reported in Table 1 and Table 2.

5. Conclusion

This study performs an MC simulation to characterize the GKI™ single sector using the egs++ MC code based on confidential manufacturer data. Various parameters, including beam spectrum at the collimator aperture, electron contamination, beam profiles, FWHM, and penumbra, are investigated. Results are in good agreement with the treatment planning system and measurement. It demonstrates the code is capable of high accuracy small field dosimetry and paves the way for a complete simulation of this device. The next project will simulate the whole GKI™ system to evaluate dose distributions in phantoms and patients based on the CT models.

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