ORIGINAL ARTICLE

EGSnrc/BEAMnrc-Based Monte Carlo Simulation of the Gamma Knife 4C versus MCNP Code in Homogeneous Media

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Abstract

Purpose: Gamma Knife is applied as a superseded tool for inaccessible lesions surgery delivering a single high dose to a well-defined target through 201 small beams. Monte Carlo simulations can be an appropriate supplementary tool to determine dosimetric parameters in small fields due to the related dosimetry hardships.

Materials and Methods: EGSnrc/BEAMnrc Monte Carlo code was implemented to model Gamma Knife 4C. Single channel geometry comprising stationary and helmet collimators was simulated. A point source was considered as a cylindrical Cobalt source based on the simplified source channel mode. All of the 201 source channels were arranged in spherical coordinate by EGSnrc/DOSXYZnrc code to calculate dose profiles. The simulated profiles at the isocentre point in a spherical head phantom 160 mm in diameter along three axes for 4, 8, 14, and 18 mm field sizes were compared to those obtained by another work using MCNP code.

Results: Based on the results, the BEAMnrc and MCNP dose profiles matched well apart from the 18 mm profiles along X and Y directions with the average gamma index of 1.36 and 1.18, respectively. BEAMnrc profiles for 14 and 18 mm field sizes along X and Y axes were entirely flat in plateau region, whereas MCNP profiles represented variations as well as round shape. Besides, considering the identical results, radioactive source can be modeled by a point source instead of cylindrical one.

Conclusion: Thus, the EGSnrc/BEAMnrc code is recommended to simulate Gamma Knife machine as it is regarded as the most accurate computer program to simulate photon and electron interactions.

Keywords: Gamma Knife; Electron Gamma Shower National Research Council /BEAM National Research Council; Monte Carlo N-Particle; Point Source.

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1. Introduction

Stereotactic Radiosurgery (SRS) as an advanced technique in conformal radiotherapy is mainly applied to the intracranial tumors, arteriovenous malformations and brain dysfunctions. A single high-dose of x-ray or gamma non-coplanar beams is directed towards a well-defined small volume less than 4 cm in diameter. Radiosurgery is performed using Linac-based radiosurgery and Gamma Knife machine [1-7].

Gamma Knife, invented and developed by Lars Leksell, is widely used as a superseded procedure for deep-seated and inaccessible lesions surgery. Gamma Knife delivers a single high dose to a targeted lesion in one session by 201 gamma converged beams which allows steep dose gradient as well as minimum imparted radiation to nearby critical tissues [8].

Radiation fields are formed by small beam diameters of 4, 8, 14, and 18 mm at the isocentre machine. There are several challenges in such small fields, including the steep gradient at the beam edge, lack of charged particle equilibrium, partial occlusion of radiation source, volume averaging effect, and beam alignment. Moreover, the penumbra region defined as the distance between the 80%-20% or the 90%-50% isodose lines at a defined depth is an important portion of the field. Therefore due to the obstacles of physical dose measurement, Monte Carlo simulations can be a suitable and powerful complementary tool to accurate prediction of dosimetric parameters in small fields [4, 5].

There is a significant amount of work relating to Monte Carlo simulation of Gamma Knife machine by different Monte Carlo codes of EGS4, EGSnrc, PENELOPE, Monte Carlo N-Particle (MCNP), and FLUKA and source modeling [1, 3, 4-6, 9-14]. This study has been targeted on simulation of Gamma Knife 4C using ma Knife; Electron Gamma Shower National Research Council /BEAM National Research Council (EGSnrc/BEAMnrc) code. The simplified model of source channel [4] and point source were considered. The results were compared with the Trnka *et al.*'s work [11] performed using MCNP code.

2. Materials and Methods

2.1. Source Modeling

The Gamma Knife head geometry was simulated using EGSnrc/BEAMnrc Monte Carlo code developed for modeling radiotherapy sources [14]. The total dose delivered to the target is the sum of dose contribution from 201 Cobalt-60 sources with the average energy of 1.25 MeV. Each radioactive source is made of 20 Cobalt-60 pellets 1 mm in diameter and length, inside a stainless steel capsule, which is inside an aluminum bushing [1, 11]. To model the Cobalt source, a point source based on the Al-Dweri *et al.*'s study [4] was considered at a 401 mm distance from the isocentre (center of the Plexiglas phantom) with an average energy of 1.25 MeV, while in other studies, Cobalt-60 source has been modeled as a cylinder of 1 mm diameter [3, 5, 11] (Figure 1).

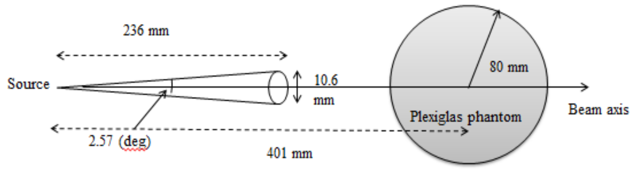

Figure 1. The simplified model of the GK source channel [4]

2.2. The Single Channel Simulation

Gamma beams are shaped by fixed or stationary collimators inserted in the machine body made of a tungsten cylinder 65 mm in length and a 92.5 mm lead cone. The secondary or helmet collimators, defining beam diameters of 4, 8, 14, and 18 mm are made of tungsten cone 60 mm in length. The 201 cone-shaped passages of radiation beam from the point source to the isocentre are formed when the helmet is placed in a treatment position, beneath the fixed collimators [4, 5].

Source channel consisting of fixed and helmet collimator was simulated using FLATFILT module (Figure 2). Component modules are pre-made geometries presented by BEAMnrc code for fully and accurate modeling of the radiotherapy machines geometry. To score the phase space file at the source to phantom surface distance, one SLABS module made of air was simulated under the FLATFILT module. The number of 5 × 108 histories was selected for each phase space file pertaining to each of the 4 collimator sizes. Photon and electron cut off energy values, PCUT and ECUT, were set to 0.01 and 0.70 MeV, respectively. To obtain phase space file recording all particles, one scoring plane was placed under the SLABS module. The whole process was performed to model 4 collimator sizes [13].

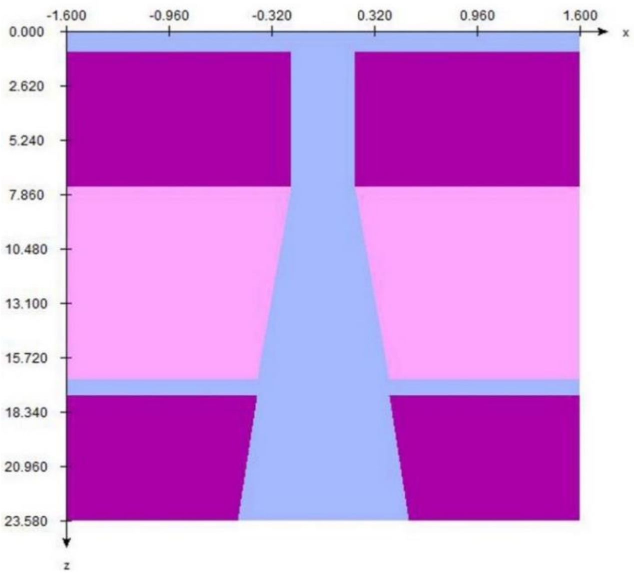

Figure 2. The geometry of the single channel of Gamma Knife for 18 mm collimator [13]

2.3. Dose Calculation

Three-dimensional dose calculation was performed using EGSnrc/DOSXYZnrc [15] in a spherical QA phantom made of Plexiglas with 1 mm voxel size. Phase space file generated by BEAMnrc code [16] was applied as a source in DOSXYZnrc. The arrangement of 201 Cobalt-60 sources disposing in five rings with polar angles (θ) of 96.0, 103.5, 118.5, and 126.0 degree and azimuthal angles (ϕ) was carried out by this $\phi i\alpha = \phi 1\alpha - (i-1)\ \Delta\phi\ \alpha$ formula [4].

A total of 5 × 109 histories were simulated for all collimators to achieve a statistical uncertainty below 1%. Dose profiles were calculated in X, Y, and Z directions at SAD = 401 mm at the phantom center from 3D dose file reading by statdose program [17]. The MC simulated profiles were normalized to the isocentre points of (x, 0, 0), (0, y, 0), (0, 0, z) for X, Y, and Z profiles, respectively. The validation of simulation process was performed by comparing simulated and measured dose profiles along three axes of coordinate for 4, 8, 14, and 18 mm helmet collimators. Threshold values for DD and DTA generated by gamma index method (GNUPLOT software) were set to 2% and 2 mm.

Dose measurements were undertaken by EBT3 films owing to the high spatial resolution, water equivalency, and energy independency. The film pieces inserted between QA head phantom were exposed three times on axial (x-y) and coronal (x-z) planes for each collimator. The scanned data were plotted in MATLAB software [13].

The results of this study were compared to those achieved by Trnka *et al.* [11] with MCNP code.

3. Results

3.1. Description of Study Population

To validate MC simulation of head machine, measured and simulated profiles were compared based on the gamma index method considering DD = 2% and DTA = 2 mm. The MC simulation agreed very well with measurements, the gamma index of all points of interest were < 1 and passed the test [13]. So, the gamma Knife simulation can be considered validated.

Simulated dose profiles of EGSnrc/BEAMnrc (this work) and MCNP code (Trnka *et al.*) along X, Y, and Z axes at isocentre point (0, 0, 0) for four field sizes are presented in Figures 3, 4, and 5, respectively. Simulated profiles from two codes adapted well (DD = 2% and DTA = 2 mm) except for 18 mm profiles along both X and Y directions in plateau region.

Table 1 demonstrates the calculated standard deviation (SD) by SPSS Statistics 26 for plateau of dose profiles of the 14 and 18 mm collimators along X and Y axes. As can be seen, the standard deviation for the profiles generated by MCNP code in the plateau region is greater than those for BEAMnrc code.

Tables 2 and 3 display physical penumbra width (80%-20%) for 201 beams of simulated profiles against film measured profiles for both BEAMnrc and MCNP codes along X and Z axes. Due to the correspondence of the X- and Y-profiles, only the penumbra of X-profiles were assessed.

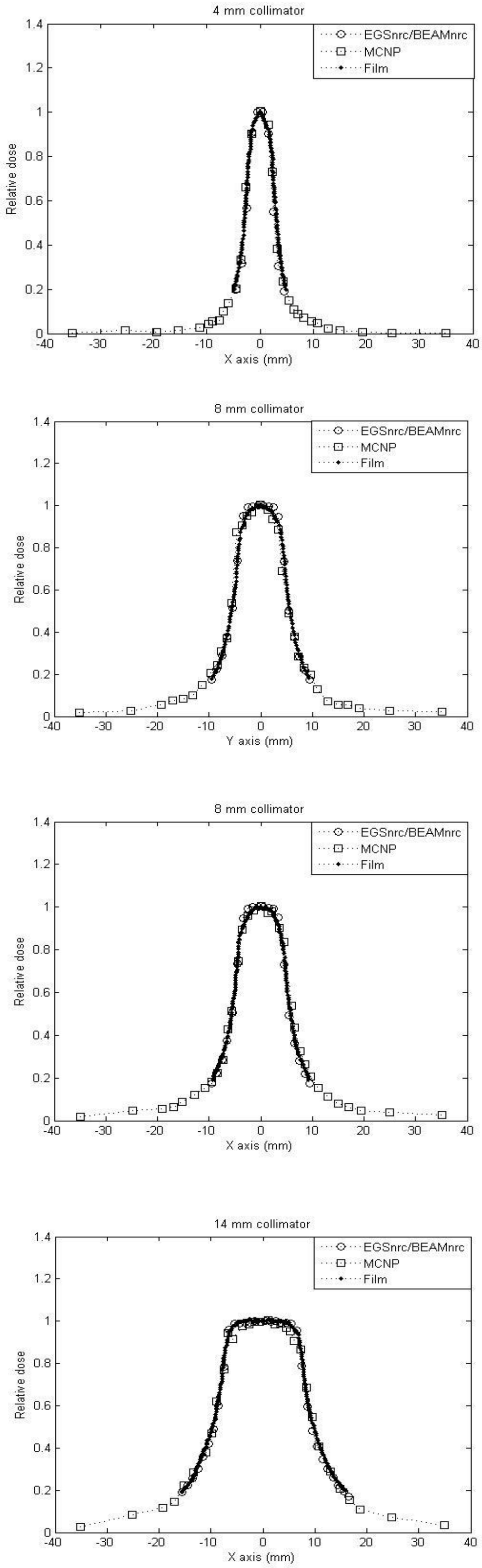

Figure 3. Simulated dose profiles of EGSnrc/BEAMnrc (this work, circle) and MCNP code (Trnka *et al*., square) along X axis at isocentre point (0, 0, 0) in QA head phantom

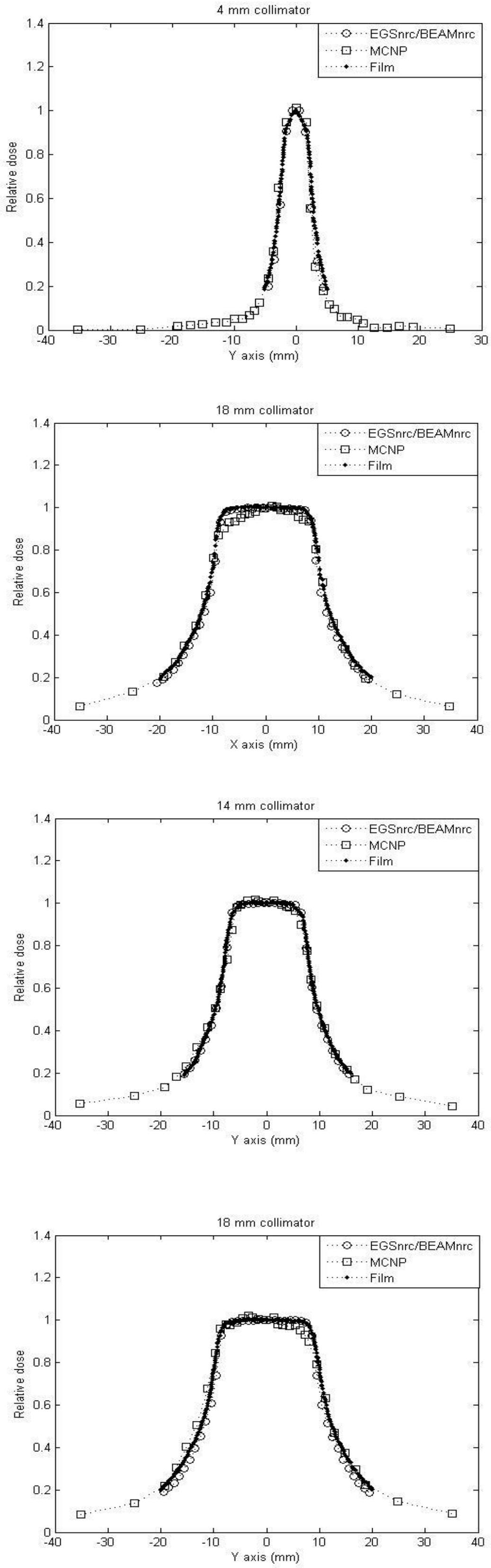

Figure 4. Simulated dose profiles of EGSnrc/BEAMnrc (this work, circle) and MCNP code (Trnka *et al*., square) along Y axis at isocentre point (0, 0, 0) in QA head phantom

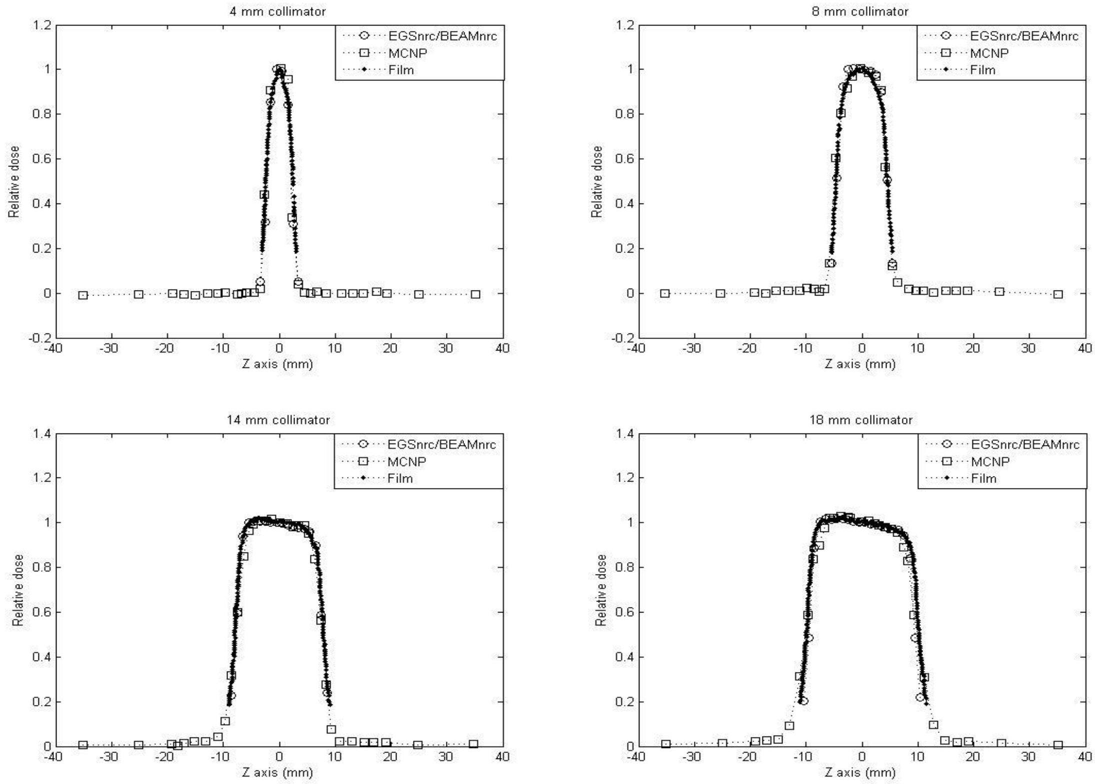

Figure 5. Simulated dose profiles of EGSnrc/BEAMnrc (this work, circle) and MCNP code (Trnka *et al.*, square) along Z axis at isocentre point (0, 0, 0) in QA head phantom

Table 1. Standard deviation for points in plateau region of profiles by EGSnrc/BEAMnrc and MCNP along X and Y directions

Collimator size (mm)	EGSnrc/BEAMnrc		MCNP	
	X (mm)	Y (mm)	X (mm)	Y (mm)
14	0.00	0.00	0.03	0.02
18	0.00	0.00	0.03	0.02

Table 2. Simulated and measured physical penumbra widths (80%-20%) of 201 beams along X axis for EGSnrc/BEAMnrc and MCNP code

Collimator size (mm)	EGSnrc/BEAMnrc code			MCNP code		
	Simulation	Film measurement	Difference (%)	Simulation	Film measurement	Difference (%)
4	2.61	3.21 ± 0.02	18.69	2.76	3.21 ± 0.02	13.96
8	4.80	4.90 ± 0.05	2.04	5.19	4.90 ± 0.05	5.92
14	7.92	8.00 ± 0.00	1.00	7.44	8.00 ± 0.00	7.03
18	9.81	10.61 ± 0.25	7.50	9.25	10.61 ± 0.25	12.82

Table 3. Simulated and measured physical penumbra widths (80%-20%) of 201 beams along Z axis for EGSnrc/BEAMnrc and MCNP code

Collimator size (mm)	EGSnrc/BEAMnrc code			MCNP code		
	Simulation	Film measurement	Difference (%)	Simulation	Film measurement	Difference (%)
4	1.31	1.22 ± 0.05	7.38	1.13	1.22 ± 0.05	7.05
8	1.60	1.69 ± 0.10	5.33	1.66	1.69 ± 0.10	1.78
14	1.91	2.01 ± 0.11	4.98	2.27	2.01 ± 0.11	12.79
18	2.14	2.25 ± 0.07	4.89	3.63	2.25 ± 0.07	61.11

4. Discussion

The Gamma Knife 4C was modeled by EGSnrc/BEAMnrc Monte Carlo code. To validate the simulation process gamma index method was applied. The differences between simulated and measured profiles at all points were successfully in an acceptable range (DD = 2% and DTA = 2 mm) [13]. Therefore, Gamma Knife unit is possible to be accurately simulated by EGSnrc/BEAMnrc code.

The results of this study were compared with those simulated by Trnka *et al.* [11] with MCNP code. The simulated dose profiles of 201 sources obtained by two different codes at isocentre depth along three axes for all available collimators were compared by considering DD = 2% and DTA = 2 mm. There was a good agreement between profiles. The gamma index of all points was below 1 for all collimators excluding the 18 mm collimator. The values of gamma index for points between -6.4 and -2.5 mm for X-profile and the points between 2.59 and 5.86 mm for Y-profile were greater than 1, on average 1.36 and 1.18, respectively. This discrepancy is due to the observed fluctuations in plateau of dose profiles obtained by MCNP code.

As it can be shown from Figures 3 and 4, the X and Y profiles of the 14 and 18 mm collimators obtained by MCNP code is not as flat as the ones produced by BEAMnrc code in plateau area. The BEAMnrc profiles are straight and match very well with the measured ones, while the MCNP profiles are round and have fluctuations in the plateau region. It can be attributed to the statistical errors due to low incident particles in each voxel. This observation has also been reported by Trnka *et al.* [11]. These differences were not seen for Z-profiles.

The calculated standard deviations listed in Table 1 for both 14 and 18 mm collimators in the plateau regions confirm the observed dose fluctuations for MCNP profiles. The standard deviations for 14 and 18 mm collimators in X-profiles and for 14 and 18 mm collimators in Y-profiles by MCNP code are 0.03 and 0.02, respectively, whereas all standard deviations for profiles along X and Y directions of 14 and 18 mm collimators calculated by BEAMnrc are 0.00.

Each of the 201 gamma sources comprising 20 Cobalt-60 pellets forming a cylinder 1 mm in diameter and length was modeled by a point source placed at the active point of the cylinder against the modeled source by cylindrical stainless steel capsule of Trnka *et al.*'s work [11]. Based on the comparison results, the simplified model leads to the similar results achieved by the full modeling of the source which is more time consuming and complicated. Accordingly, the cylindrical Cobalt source can be considered as a point source. This result is in accordance with those obtained by AL-Dweri *et al.*'s work [4].

Physical penumbra width (80%-20%) of dose profiles generated by BEAMnrc and MCNP were determined for four collimator sizes along X and Z directions. Although the difference between simulated and measured penumbra width along X direction for 4 mm collimator size with MCNP code (13.96%) is smaller than that produced by BEAMnrc code (18.69%), this difference for the other field sizes is less in BEAMnrc code. The obtained values along Z-axis for 4 and 8 mm collimators show lower differences of 7.05 and 1.78% by MCNP code against values of 7.38 and 5.33% produced by BEAMnrc code, while the observed differences of 4.98% and 4.89% for 14 and 18 mm collimators by BEAMnrc code are less than those obtained by MCNP where it is 12.79 and 61.11%, respectively. The high penumbra difference of 61% by MCNP for 18 mm collimator size along Z-axis cannot be negligible because the largest collimator size (18 mm) was recommended [13] for validation of simulation.

5. Conclusion

The EGSnrc/BEAMnrc code was employed to simulate the Gamma Knife head and was compared with the Trnka *et al.* work by MCNP code. The results of this study agreed with those obtained by Trnka *et al.* study. While BEAMnrc profiles for 14 and 18 mm collimators along both X and Y axes were totally flat in plateau area, MCNP profiles showed variations as well as being round. Likewise, based on the identical results, a point source can easily be used instead of the cylindrical one. Thus, the EGSnrc/BEAMnrc code is recommended to simulate Gamma Knife machine since it is regarded as the most accurate computer program to simulate photon and electron transfer.

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