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Original Article

Monte Carlo Evaluation of Gamma Knife Dose Profile in Real Brain Phantom

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Abstract

Introduction
The Gamma Knife system is designed solely for non-invasive treatment of brain disorders, and it benefits from stereotactic surgical techniques. Dose calculations required in the system are performed by GammaPlan code; in this code, brain tissue is considered uniform. In the present study, we evaluated the effect of Gamma Knife system on the obtained dose through simulating a real human brain phantom.

Materials and Methods
In this study, a Monte Carlo simulation code (MCNPX2.7) was employed to simulate Gamma Knife system. Brain tissue equivalent Snyder phantom and combinations were considered according to International Commission on Radiological Units (ICRU)-44 report.

Results
To ensure accuracy of the simulations, patient's head was modeled by a spherical water phantom. At this point, the dosimetry parameters were compared with those obtained by the Monte Carlo code EGS4 and good consistency was observed (less than 7% difference). At the next stage, the above dosimetry parameters were compared with those obtained experimentally by polystyrene phantom and EDR2 dosimetry film and improved consistency was detected (less than 0.5% difference). Finally, the Snyder phantom, as the human brain, was simulated. The Full Width at Half Maximum (FWHM) and penumbra decreased by 4.7% and 18%, respectively. Moreover, an isocenter dose reduction of 30-40%, compared to the water phantom, was noted.

Conclusion
The calculation of the real phantom showed that water and polystyrene could function similarly, while evaluating dosimetry parameters in the Gamma Knife system; thus, water and polystyrene are not appropriate phantom matters for this purpose.

Keywords: Film Dosimetry, Gamma Knife radiosurgery, Monte Carlo method, Snyder Phantom

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1. Introduction

The Leksell Gamma Knife is designed solely for the treatment of brain disorders with a non-invasive technique that uses radiation stereotactic surgery [1]. This system is based on the principle of center of the arc, so when the lesion is located at the center of a 180-degree arc, it can be accessible from any direction [2]. This system concentrates several gamma radiation beams to treat tumors that are not accessible within the skull [3]. Individual beams are too weak to pose sufficient damage to cancerous cells, but when multiple radiations are focused at one point, the total dose of radiation is received by the target while minimizing the dose to the surrounding tissue.

In this study, to evaluate the dose profile of the Gamma Knife system, only model C of this system was considered. This model includes 201 sources of cobalt-60, which are distributed symmetrically on a hemispherical surface, and the sources are approximately 400 mm apart from the collision point of the beams [4].

In Perfexion model of this system, the number of sources are diminished to 192. In this system, the photons are collimated by a tungsten collimator. The collimator contains apertures with 4, 8, and 16 mm dimensions [5]. Currently, Gamma Knife is accompanied with a treatment planning system, GammaPlan, which is a standard computer-based treatment planning system for radiosurgery using Gamma Knife.

In GammaPlan, patient geometry is created as a 3-dimensional simulation of the skull inside a stereotactic frame based on the measurements of 24 pre-selected points on the surface of the patient skull. The dose calculation is based on a single beam calculation and the contributions from all the 201 cobalt sources are summed up for each point of interest. For a single beam, the dose on the beam axis can be calculated using the inverse-square law and linear attenuation exponential formula. The GammaPlan dose calculation algorithm ignores the scatter photon contribution and assumes patient geometry as homogeneous. Although brain tissues are relatively homogeneous, beams that pass through low-density air cavities or high-density skull bones are expected to be perturbed. Variations in attenuation of air-tissue inhomogeneity could cause errors in dose calculation [6].

In this study, we applied Monte Carlo technique to Gamma Knife system model C; also, we simulated three different brain phantoms to evaluate the effect of Gamma Knife dose profile on real brain tissue.

Using EGS4 code, Cheung et al. calculated the dose profile of the Gamma Knife system for the model C of different collimators. Their dosimetric parameter results were used to validate the present work.

2. Materials and Methods

For Gamma Knife model C, there are 201 cobalt-60 sources arranged on a hemispherical surface with a radius of about 400 mm. These are distributed along five radii, separated by an angle of 7.5 degrees. Each source is composed of 20 cobalt-60 pellets that are 1 mm in diameter and 1 mm in length. The final size of a single cobalt-60 source is 1 mm in diameter and 20 mm in length.

Each gamma beam from the source is collimated by a stationary collimator and a final helmet collimator. The stationary collimator is assembled with the Gamma Knife unit, while the helmet collimator has various sizes, which are selected according to the treatment requirements. Each beam channel in the stationary collimator consists of a 65 mm long cylinder with a radius of 2 mm in a pre-collimator followed by a 92.5 mm cone in a tube-collimator.

In the helmet, each beam channel ends in a 60 mm final collimator. When the helmet moves to a treatment position, the entire collimator system forms a cone shaped passage from the cobalt source to the isocenter. Four different final collimator helmets produce 4, 8, 14, and 18 mm nominal beam diameters at the isocenter [6].

As mentioned above, the apertures are cone-shaped and the inner and outer final helmet collimator diameters depend on the dimensions of collimator helmet. To simulate the brain tissue, three different phantoms were employed. Dosimetric parameters that were evaluated in this study include width at 50% isodose level (FWHM) and the penumbra of the dose profile. Penumbra is defined as the distance between the 20% and 80% isodose levels [10].

The Monte Carlo code implemented for this study was MCNPX2.7, and to evaluate the simulated geometry, WRQ Reflection X 2003 was used. As mentioned earlier, when the system is in the treatment position, all the openings from the sources to focus point form a cone-shaped aperture; therefore, each of these openings in geometry can be simulated by a truncated cone. Accordingly, depending on the type of helmet used, diameters of the inner and outer apertures will be in accordance with Table 1

In this code, the ability to simulate complex geometry (macro body) is included, so that a complex area such as a truncated cone can be simulated with a simple command. To simulate the above geometry the focus point of the beams (isocenter) is assumed to be in the origin, and the collimator helmet (the radiation unit of the Gamma Knife system) is located along the z axis. In this case, according to coordinates of each of the sources, all collimator apertures can be simulated [4].

It is worth noting that this system has a scaled aluminum frame. Before treatment, patient's head is attached to the frame by four screws; thereafter, magnetic resonance imaging from patient's head is performed to estimate the coordinates of the lesion relative to the frame. This frame can be set up so that the patient’s head tumor is laid in the helmet isocenter point [7]. In this study, the lesion is assumed to be located exactly in the center of the patient’s head.

2.1 Water phantom

At first, to evaluate the dose profile, patient’s head was modeled by a spherical water phantom with a diameter of 160 mm at coordinates of x=0, y=0, z=0. In this phantom, the brain tissue was modeled by water with density of 0.998 $\frac{g}{cm^3}$. To calculate the dose profile, scoring bins with dimensions of 0.5×0.25×0.25 mm were defined along the stereotactic x, y, z axes.

In addition, to reduce error due to scattering, cut-off energies were defined for photons and electrons; if energies of the particles reach these values, they will not follow the code and will not play a role in the calculation.

The cut-off energies for photons and electrons were set to be 0.01 MeV and 0.521 MeV, respectively [8]. High cut-off energies shortened the simulation time at the expense of reliable results. In our study, further lowering of these cut-off energies caused no observable differences to the output results. The F6 tally (energy deposition averaged over the cell) and photon library (PLIB=04P) were applied. Histories of 1.5×10^7 photons were followed, for which the standard error was less than 6% and the variance was not more than 0.47%.

In order to express the relative output of the code the following formula was used. In this formula, normal dose values are calculated by dividing the dose of each scoring bin by the maximum dose.

$$D_{norm}(x,y,z)=\frac{D(x,y,z)}{[D(x,y,z)]max}\times 100 \qquad (1)$$

Table 1. Inner and outer diameters of the collimator apertures [6].

Collimator size(mm)	Inner diameter(mm)	Outer diameter(mm)
4	2.0	2.5
8	3.8	5.0
14	6.3	8.5
18	8.3	10.6

2.2 Snyder phantom

According to the geometric features that are defined in the code, different phantoms were used to simulate the human head. To establish an accurate and safe method for the treatment of brain disorders, attempts are made to choose geometry and tissue of the brain as close to reality as possible, in which case Snyder phantom can be beneficial. In this phantom, patient’s head was simulated by three elliptical layers as follows.

Table 2. Composition of the materials assumed in the MC simulations performed in this work. The values correspond to the weight fraction of each element in the material. ICRU-44 report [9].

Brain	Weight fraction	Cranium	Weight fraction	Scalp	Weight fraction
H	0.107	H	0.05	H	0.1
C	0.145	C	0.212	C	0.204
N	0.022	N	0.04	N	0.042
O	0.712	O	0.435	O	0.645
Na	0.002	Na	0.001	Na	0.002
P	0.004	Mg	0.002	P	0.001
S	0.002	P	0.081	S	0.002
Cl	0.003	S	0.003	Cl	0.003
K	0.003	Ca	0.176	K	0.001

1) Brain: The phantom's innermost layer was filled with a material with a density of 1.04 $\frac{g}{cm^3}$
2) The skull: Another layer on top of the previous one, which was filled with a material with density of 1.61 $\frac{g}{cm^3}$ of bone tissue equivalent to the skull;
3) Scalp tissue: This layer simulates patient's head skin and hair, and it was filled with a material with density of 1.09 $\frac{g}{cm^3}$.
Substance and weight fraction of each layer material are provided in Table 2 [9]. Similar processes used for calculation of the dose profiles in a water phantom were repeated for this phantom.

3. Results

In this section, at first we compared results of the simulation with those obtained from computational code EGS4 to validate the simulation. In addition, we compared our simulation results with those of the experimental measurements made in the polystyrene phantom with EDR2 dosimetry film.
In Figure 1, dose profiles calculated with EGS4 code for the 4 mm collimator helmet along the x and y axes are demonstrated. In this figure, taken from reference [4], the dose profiles for the two models of this system are compared with each other. In Figures 2 and 3, dose profiles were calculated for the 4 mm and 18 mm collimator helmets along the x and y axes by the MCNPX computational code. It should be noted that in the calculations made by the EGS4 code, the isocenter was considered at coordinates of x=100, y=100, z=100. In addition, due to symmetry radiation, the dose profiles along the x and y axes will be the same. In Table 3, the calculated dosimetric parameters with EGS4 and MCNPX2.7 are exhibited.

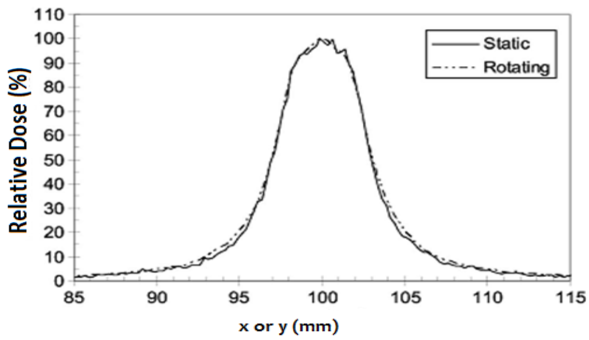

Fig 1. Comparison of dose profiles along the *x* or *y* axis of the 4 mm collimator helmet between the cases using 201 static sources and rotating sources calculated by EGS4 [4].

In order for closer simulation, an empirical study conducted by Novotny et al. was used. In that study, the human brain was simulated by a polystyrene phantom with diameter of 160 mm. This phantom was made of two hemispheres with the EDR2 dosimetry film in between to calculate the dosimetry parameters. The phantom was simply attached to the bed by Trunion (stereotactic frame holder), and then directed into the system [10].

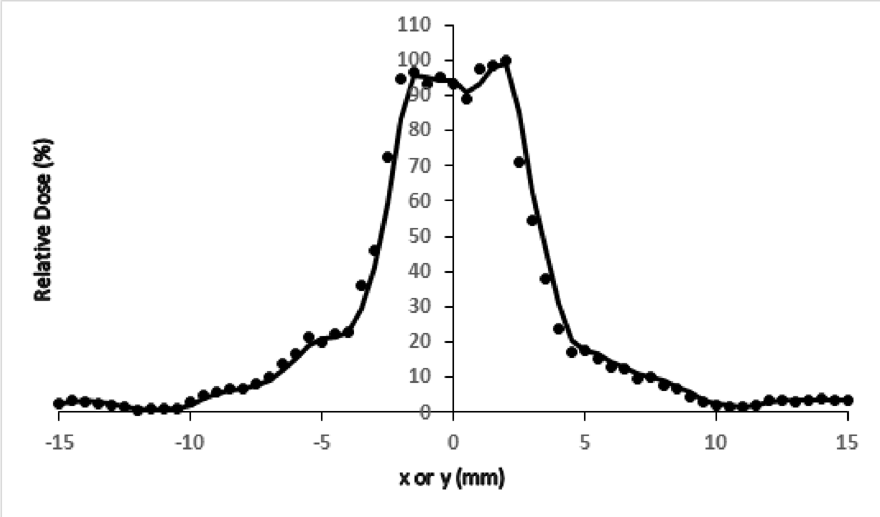

Fig 2. Gamma knife dose profile along the x or y axis of the 4 mm collimator helmet calculated by MCNPX2.7 .

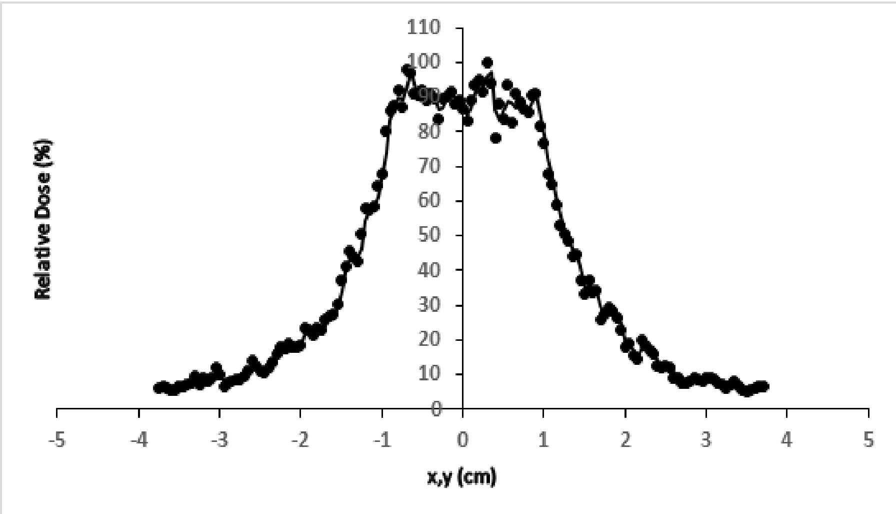

Fig 3. Gamma knife dose profile along the x or y axis of the 18 mm collimator helmet calculated by MCNPX2.7

Table 3. Comparison of the calculated dosimetric parameters with EGS4 and MCNPX2.7

Collimator-Direction	Width at 50% level(mm) (FWHM)		Width at 20% level(mm)	
	MCNPX	EGS4	MCNPX	EGS4
4mm-x,y	6.0	6.0	9.8	9.5
4mm-z	4.8	4.8	5.6	5.9
8mm-x,y	12.0	11.1	18	17.9
8mm-z	9.6	9.1	11.1	10.6
14mm-x,y	19.9	18.8	30.1	30.3
14mm-z	16.6	15.6	18.2	17.6
18mm-x,y	24.5	24.0	40.0	39.2
18mm-z	20.2	19.7	23.6	22.2

*The precision of the numbers are 0.1mm.

Table 4. Measured width in 50% level with EDR2 dosimetry film [10]

Collimator \ Direction	FWHM(mm) x	y	z
4mm	6.1	6.1	4.6
8mm	11.0	11.2	8.9
14mm	19.2	19.4	15.5
18mm	24.7	24.9	19.9

*The precision of the numbers are 0.1mm.

Table 5. Comparison of the means of penumbras measured by EDR2 dosimetry film according to [10] and calculated by MCNPX2.7

	Penumbra(mm)						
	EDR2			MCNPX			
Direction	x	y	z	x or y		z	
Collimator				Left penumbra	Right penumbra	Left penumbra	Right penumbra
4mm	3.2	3.3	1.3	3.0	2.3	0.9	1.0
8mm	4.9	5.0	1.8	4.9	4.6	1.1	1.5
14mm	8.0	8.2	2.1	7.7	7.0	1.7	1.4
18mm	10.6	10.7	2.3	10.1	10.0	2.6	2.6

*The precision of the numbers are 0.1mm.

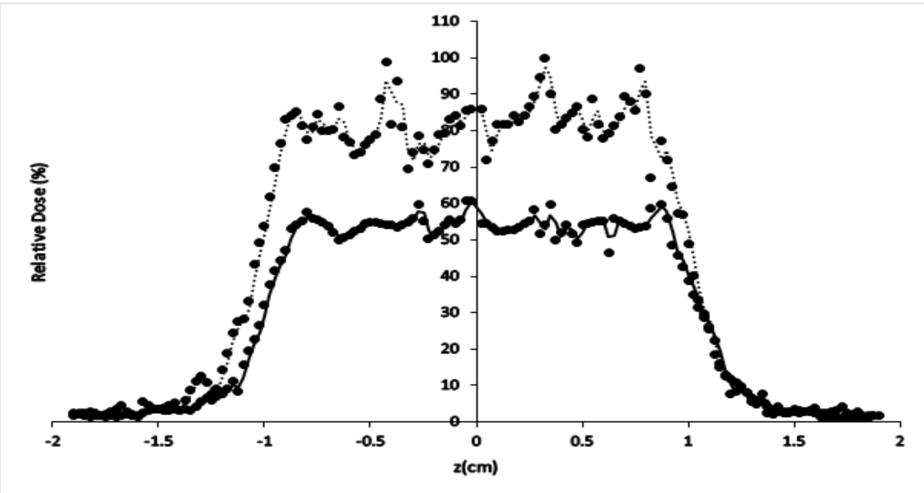

Fig 4. Comparison of the gamma knife dose profile of 18mm collimator for Snyder phantom (solid line) and water phantom (dotted line)

In Tables 4 and 5, the parameters measured by EDR2 dosimetry film are reported. It should be borne in mind that in Table 5 the average values of the right and left penumbras in different directions are shown and compared with values calculated by MCNPX code. Figure 4 compares the Gamma Knife system dose profile results in Snyder and water phantoms.

4. Discussion

In this study, the results of simulation of Gamma Knife system by MCNPX, in terms of shape and width of the dose profiles along all the axes were compared with a study conducted by Cheung et al. The comparison of the data calculated by the computational codes EGS4 and MCNPX (Table 3) shows a good consistency between width at 50% and 20% isodose levels, and they have at most 5.8% and 6.3% difference, respectively, from the amounts reported by the EGS4 code.

In addition, in order for more accurate assessment, the results of MCNPX simulation were compared with the work performed by Novotny using EDR2 dosimetry film [10]. Comparison of the data measured by EDR2 dosimetry film (Tables 4 and 5) with values obtained by MCNPX code showed a good consistency, so that at most 0.4% difference in 50% isodose levels and less than 1 mm difference in penumbra were observed.

Thus, MCNPX code calculations are close to the experimental results, and the outcomes indicate that the water and polystyrene phantoms have the same procedures in terms of the impact on dosimetry parameters and dose profiles, so they are not proper alternatives for simulation of the brain tissue. Finally, having considered a real brain phantom, the brain tissue was simulated and dose profiles were calculated. By comparing the Gamma Knife doses in water and real phantoms, it was observed that the dose profile in both phantoms were almost identical, except for the dose delivered to the tissue at isocenter in the Snyder phantom, which showed 30-40% reduction. In addition, 4.7% decrease in 50% isodose level revealed that the volume of the tissue covered by the beams significantly diminished. In addition, a reduction of 18% in penumbras was noted.

5. Conclusion

The key finding of this study was an excellent consistency between the dosimetric characteristics of Gamma Knife system in water and polystyrene phantoms. However, they are not suitable materials for accurate estimation of the Gamma Knife dosimetry parameters and employing a more realistic structure of the human brain such as Snyder is recommended to assess the appropriate dose for tumor treatment.

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