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Author for correspondence:
Ghazale Geraily, Department of Medical Physics and Biomedical Engineering, Faculty of Medicine, Tehran University of Medical Sciences, Iran.
Email: gh-geraily@sina.tums.ac.ir

Penumbra width determination of single beam and 201 beams of Gamma Knife machine model 4C using Monte Carlo simulation

Atefeh Mahmoudi[1], Alireza Shirazi[1], Ghazale Geraily[1], Tahereh Hadisi nia[1], Masoume Bakhshi[1] and Maryam Maleki[2]

[1]Department of Medical Physics and Biomedical Engineering, Faculty of Medicine, Tehran University of Medical Sciences, Islamic Republic of Iran and [2]Department of Medical Physics and Biomedical Engineering, Faculty of Medicine, Isfahan University of Medical Sciences, Islamic Republic of Iran

Abstract

Background: One of the stereotactic radiosurgery techniques is Gamma Knife radiosurgery, in which intracranial lesions that are inaccessible or inappropriate for surgery are treated using 201 cobalt-60 sources in one treatment session. In this conformal technique, the penumbra width, which results in out-of-field dose in tumour-adjacent normal tissues should be determined accurately. The aim of this study is to calculate the penumbra widths of single and 201 beams for different collimator sizes of Gamma Knife machine model 4C using EGSnrc/BEAMnrc Monte Carlo simulation code and comparison the results with EBT3 film dosimetry data. *Methods and materials:* In this study, simulation of Gamma Knife machine model 4C was performed based on the Monte Carlo codes of EGSnrc/BEAMnrc. To investigate the physical penumbra width (80 − 20%), the single beam and 201 beams profiles were obtained using EGSnrc/DOSXYZnrc code and EBT3 films located at isocentre point in a spherical Plexiglas head phantom. *Results:* Based on the results, the single beam penumbra widths obtained from simulation data for 4, 8, 14 and 18 mm collimator sizes along *X* axis were 0·75, 0·77, 0·90 and 0·92 mm, respectively. The data for 201 beams obtained from simulation were 2·61, 4·80, 7·92 and 9·81 mm along *X* axis and 1·31, 1·60, 1·91 and 2·14 mm along *Z* axis and from film dosimetry were 3·21, 4·90, 8·00 and 10·61 mm along *X* axis and 1·22, 1·69, 2·01 and 2·25 mm along *Z* axis, respectively. *Conclusion:* The differences between measured and simulated penumbra widths are in an acceptable range. However, for more precise measurement in the penumbra region in which dose gradient is high, Monte Carlo simulation is recommended.

Introduction

The treatment techniques for radiation delivery have been changed substantially in recent decades to allow for more precise dose delivery. One of the high precision radiation treatment methods is stereotactic radiosurgery (SRS) that uses small, highly collimated photon beams to irradiate cranial tumours and functional abnormalities with high geometric precision while sparing normal tissue.[1,2]

Stereotactic radiosurgery can be performed in several modalities, such as Gamma Knife, CyberKnife and various linac-based machines. The Gamma Knife (Elekta Company, Stockholm, Sweden) is one of the radiosurgery machines used to treat brain lesions without surgery and haemorrhage. The high dose from 201 ^{60}Co radioactive sources is delivered to the target with accuracy better than 0·3 mm during one therapy session.[3–5] In the Gamma Knife machine model 4C, collimators with different sizes of 4, 8, 14 and 18 mm are available to shape the beam. In such small fields, due to the very small dimensions of the treatment fields, penumbra width (the distance between 20–80% isodose lines) is a highly important issue. This is caused by the fact that imparting a high dose in the SRS method leads to a high dose penumbra region.[6,7] This penumbra results in considerable out-of-field dose in tumour-adjacent normal tissues especially in critical structures and also reduces the dose homogeneity in the radiation filed.[8] Therefore, due to these challenges, penumbra width measurement and considering it, is very important to estimate the dose and possible radiation damage to the organs at risk, which are located in the penumbra region and then achieve the appropriate treatment plan.

Various researches have been performed on photon beam penumbra, its effects on treatment output and factors affecting it using beam profile measurements. Laghlin et al.[9] in 1986 showed that using higher photon beam energies results in a wider penumbra due to the

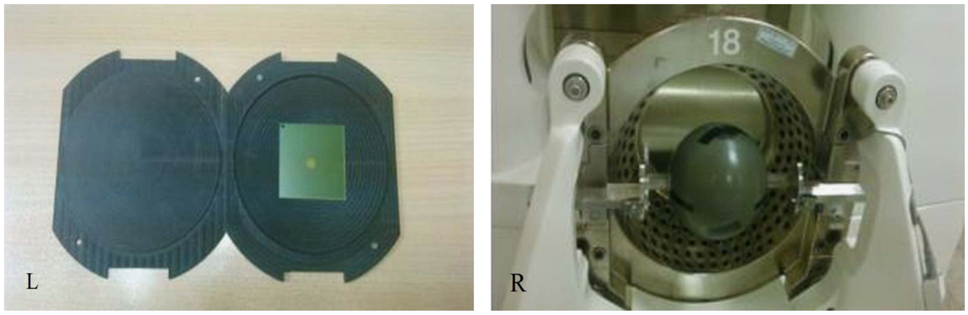

Figure 1. The piece of EBT3 film at the centre of the special cassette (left panel). The spherical head phantom with the cassette inside located in the 18 mm helmet (right panel).

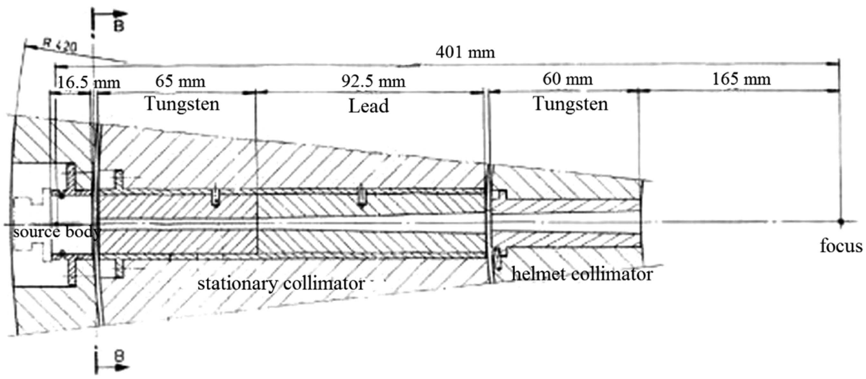

Figure 2. The view of the fixed and moving (helmet) collimators for 18mm collimator size.[3]

increased secondary electrons range. In another study, Oh et al.[10] reported that increasing beam energy, field size and depth lead to increased penumbra width. The aim of this study is to quantify and determine penumbra widths of the single beam and 201 beams penumbra widths for different collimator sizes of Gamma Knife machine model 4C. Accurate beam profile measurements of very small fields up to 4 mm are limited because they are difficult to measure due to the lack of electron equilibrium. Furthermore, because of the physical arrangement and simultaneous irradiation from the 201 ^{60}Co sources, the single beam dosimetry of the Gamma Knife machine is impossible. So, a method other than experimental measurement is required. Monte Carlo (MC) simulation is one of the most accurate dose calculation methods in radiotherapy. Therefore, the MC simulation was used in this study to determine the beam profiles and penumbra widths of the Gamma Knife machine. For MC validation, film dosimetry using EBT3 film (Ashland Inc., Covington, KY, USA) was undertaken and these results were compared with the MC simulation results for the largest field—18 mm.[3,11,12]

Methods and Materials

The experimental section of this work was carried out in Kamrani Gamma Knife center, Tehran, Iran.

Gafchromic EBT3 film measurement

To undertake the dose measurements, EBT3 films were selected due to the high spatial resolution, energy independency and water equivalent material which are well suited to determine the dose distribution. In order to measure each of the beam profiles, one piece of 5×5 cm^2 EBT3 film was placed between two hemispheres of a homogeneous Plexiglas head phantom (Elekta company, Stockholm, Sweden).[13,14] The spherical phantom was fixed into the hemispherical helmet of the treatment machine (Figure 1).

The EBT3 films were irradiated in phantom for different circular fields at source to surface distance of 32·1 cm and scanned using Microtek 9800X scanner (Microtek Company, Hsinchu, Taiwan) 48 hours after irradiation. MATLAB software (MATLAB R2013a) was used to plot profiles along *X* and *Z* axes. Due to the similarity of profiles along both *X* and *Y* axes, only *X*-profiles were considered.[7] The irradiations were performed three times for each collimator size to calculate the measurement uncertainty.

Monte Carlo simulation

In this work, EGSnrc/BEAMnrc Monte Carlo code (D.W.O. Rogers et al, National Research Council of Canada) was used for simulation of radiation transport through Gamma Knife machine model 4C with 201 cobalt-60 sources and average energy of 1·25 MeV. Each cobalt source consists of 20 cobalt-60 pellets with diameter and length of 1 mm. Radiation beams are conducted by a fixed collimator in the machine body and several moving collimators. Fixed collimator consists of a tungsten cylinder with 65 mm length and a cone of 92·5 mm made of lead. The moving or secondary collimators that produce fields of 4, 8, 14 and 18 mm diameter at the treatment isocentre are made of tungsten with 60 mm length and are located in a hemisphere called the helmet.[4] The views of the fixed and moving collimators are shown in Figure 2.

In order to model a single channel including fixed and moving collimators, FLATFILT module was used (Figure 3). Component modules used in this study (FLATFILT and SLABS) are pre-made geometries provided by the BEAMnrc code to model the different

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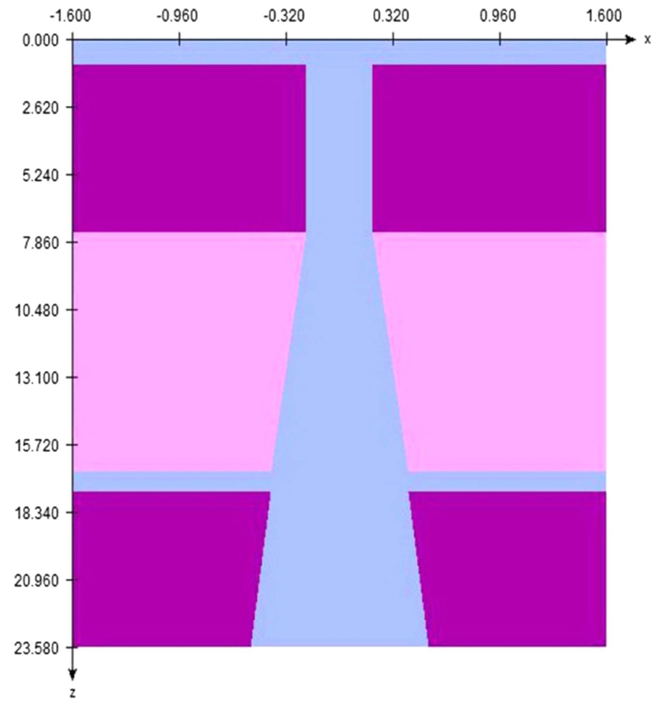

Figure 3. Simulation of single channel of Gamma Knife unit.

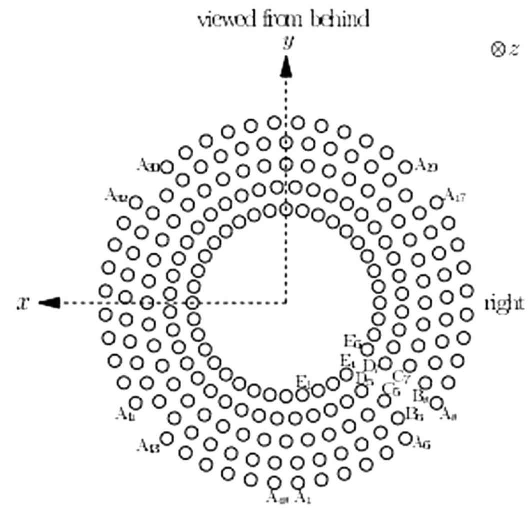

Figure 4. The view of the 201 sources arrangement of Gamma Knife unit.[4]

Table 1. Inner and outer aperture size of moving collimators

Inner aperture (mm)	2	3·8	6·3	8·3
Outer aperture (mm)	2·5	5·0	8·5	10·6

components of radiotherapy machines.[15] Before channel geometry simulation, the reference plane ($Z=0$) was selected at the source location. So that the distance from the front of the first module, FLATFILT, to source ($Z=0$) was 10 mm. The inner and outer aperture size of the helmet collimators can be seen in Table 1.[5]

For phase space file generating, SLABS module made of air with thickness of 8·5 cm was inserted under the FLATFILT module. To simulate cobalt-60 source, the point source with an average energy of 1·25 MeV was considered at the centre of the cobalt-60 cylindrical source to simulate cobalt-60 source.[4] Electron cut-off (ECUT) and photon cut-off (PCUT) energy values were set to 0·7 and 0·01 MeV, respectively; 5×10^8 histories were selected to achieve uncertainties below 1%. One scoring plane which is used to score all the particles information such as position, charge, direction, etc., for producing phase space files[15] was selected at the bottom of the SLABS module for scoring particles. This simulation process was repeated for all collimator sizes. After machine geometry simulation, obtained phase space files were used as a phase space source to dose calculations in DOSXYZnrc code.

The next step, EGSnrc/DOSXYZnrc MC code was used to calculate the dose in the head phantom. First, Gamma Knife Plexiglas head phantom with a diameter of 16 cm was simulated with voxel sizes of 1 mm. Using simulation of one source channel and specifying the positions of the 201 sources in helmet, the 201 channels were simulated. To arrange 201 Cobalt-60 sources, polar angle θ (theta) and azimuthal angle ϕ (phi) of all sources in spherical coordinates were determined, as it is shown in Figure 4.[4]

In the sources arrangement, the origin coordinates located at the machine isocentre and Z axis are along the patient body. All 201 sources are distributed in five rings in five polar angles of 96·0, 103·5, 111·0, 118·5 and 126·0 degree on the helmet surface. The azimuthal angle of each sources was also obtained by this $\varnothing_i^{\alpha} = \varnothing_1^{\alpha} - (i-1)\,\Delta\varnothing^{\alpha}$ formula.[4]

Then, 5×10^9 histories were considered to achieve a statistical uncertainty <1%. All dose profiles were obtained using Statdose program by reading the output. 3ddose file generated from DOSXYZnrc runs at the isocentre depth, in the head phantom centre with a distance of 401 mm from the source. In order to validate the simulation process, obtained profiles from simulation along X axis were compared with those obtained from measurements.

Penumbra determination

To determine 201 beams physical penumbra width (80–20% isodose lines) from simulation, dose profiles were calculated in the head phantom at the isocentre depth for four collimator sizes of 4, 8, 14 and 18 mm using MATLAB software. Because of the similarity of X-profiles and Y-profiles, just X-profiles were assessed. Experimental penumbra widths were calculated from measurement data. Finally, SPSS software version 2016 was used to compare the results.

Single beam penumbra width measurement of Gamma Knife is possible just with MC simulation, using DOSXYZnrc in a Plexiglas Cubic phantom. Voxel sizes along X direction for 18 and 14 mm collimator sizes were 0·5 mm, and for 8 and 4 mm sizes were 0·25 mm.[16] 6×10^9 and 8×10^9 incident particles were used for voxel sizes of 0·5 and 0·25 mm, respectively, to achieve the statistical errors <1%. Profiles along X axis were plotted in MATLAB to determine the physical penumbra widths (80–20%).

Results

MC validation

To validate the MC simulation process, all measured and MC calculated profiles for 4, 8, 14 and 18 mm collimator sizes were compared. Validation was performed using GNUPLOT software (GNUPLOT version 4.4). Measurement and simulation profiles

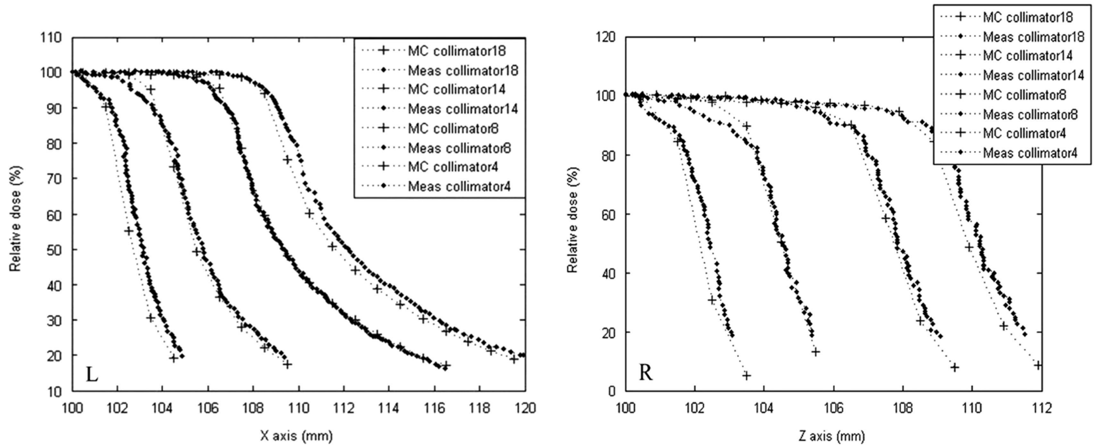

Figure 5. Comparison of measured and simulated profiles for four field sizes along *X* axis (left panel) and *Z* axis (right panel).

Table 2. Measured and Monte Carlo (MC) calculated physical penumbra widths (80–20%) of 201 beams along *X* axis

Collimator size (mm)	MC simulation (mm)	Film measurement (mm)	Percentage difference (%)
4	2·61	3·21 ± 0·02	22·99
8	4·80	4·90 ± 0·05	2·10
14	7·92	8·00 ± 0·00	1·01
18	9·81	10·61 ± 0·25	8·15

Table 3. Measured and Monte Carlo (MC) calculated physical penumbra widths (80–20%) of 201 beams along *Z*-axis

Collimator size (mm)	MC simulation (mm)	Film measurement (mm)	Percentage difference (%)
4	1·31	1·22 ± 0·05	6·87
8	1·60	1·69 ± 0·10	5·63
14	1·91	2·01 ± 0·11	5·24
18	2·14	2·25 ± 0·07	5·14

along *X*-axis and *Z*-axis in Figure 5 showed a good agreement (2% and 2 mm).

Beam Penumbra width determination

In Figure 5, simulated and measured physical penumbra widths (80–20%) for 201 beams were extracted for collimator sizes of 4, 8, 14 and 18 mm which are presented in Tables 2 and 3.

Single beam profiles of all given field sizes along *X* direction at isocentre depth were also obtained from simulations that are shown in Figure 6.

Table 4 shows penumbra width values for single and 201 beams along *X* axis.

Discussion

In Figure 5, all simulated and measured profiles for collimator sizes of 4, 8, 14 and 18 mm were compared to ensure the accuracy of MC simulation. There was a good agreement between the simulated and measured results (difference dose (DD) = 2% and distance to agreement (DTA) = 2 mm) and gamma index value that is a combination of DD and DTA was <1 for all field sizes. Therefore, these results show that our MC simulation process of the Gamma Knife machine is valid and can be used for other research too.

Tables 2 and 3 show the differences between MC calculation and film dosimetry measurement of 201 beams physical penumbra width (80–20%) along *X* and *Z* axes, respectively. It can be found that by increasing the field sizes, the penumbra width increases which is in agreement with other researches.[8,10,17,18] Furthermore, the maximum difference between the

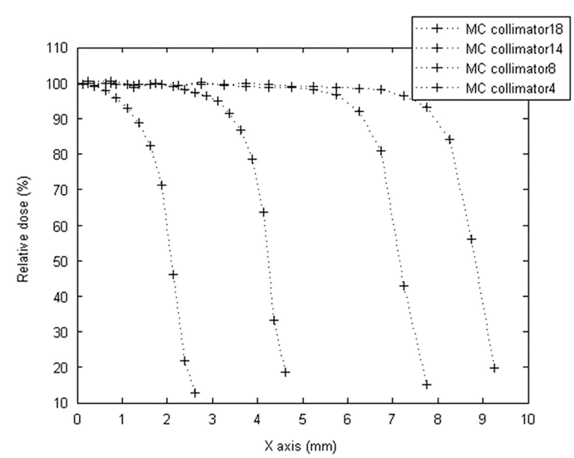

Figure 6. Simulated single beam profiles for 4, 8, 14 and 18-mm collimator sizes along *X* axis at isocentre depth.

measured and the MC calculated values is observed in the 4 mm collimator. This can be attributed to the problem of dosimetry in small fields. Furthermore, due to the source size limitation, lack of electronic equilibrium, detector size and experimental dosimetry of small fields is challenging. Although today studies on miniature pinpoint chamber and EBT3 films show acceptable results for Gamma Knife field sizes of 18, 14 and 8 mm, for smaller fields up to 4 mm and less, empirical results have an approximate error of 11% relative to the simulation.

So, it makes impossible to use empirical results for these small fields. Many studies have emphasised the precision of MC

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Table 4. Comparison of single and 201 beam physical penumbra widths (80–20%) using Monte Carlo simulation along *X* axis

Collimator size (mm)	Single beam (mm)	201 beams (mm)	Diff (mm)	Penumbra ratio to the field size	
				Single beam	201 beams
4	0·75	2·61	1·86	0·06	0·21
8	0·77	4·80	4·03	0·02	0·09
14	0·90	7·92	7·02	0·01	0·05
18	0·92	9·81	8·89	0·00	0·04

simulation in small filed dosimetry compared with other dosimetric methods. With respect to the acceptable range of experimental measurements in small fields, the experimental results of fields 8, 14 and 18 mm can be used to validate small fields MC simulations. But in most, literatures have been illustrated that use of the largest field size (18 mm) is the most accurate.[3,11,18–20]

From MC simulated single beam profiles of Gamma Knife in Figure 6, and physical penumbra values (80–20%) of beam profiles listed in Table 4, it can be seen that the physical penumbra widths of 201 beams are larger than those of single beam due to penumbra overlapping. This fact has been illustrated by Keller et al.[18] using 18-beam coplanar beam. In addition, data from Table 4, column 4 shows that the difference between these values is greater for the larger field size which illustrates the importance of the overlapping effect for larger field size. The data from Table 4, column 5 shows that the ratio of the penumbra width to the field size decreases with increasing field size, which emphasises the importance of penumbra in smaller field sizes. The reason for this phenomenon is occurred due to the fact that, in the range of small stereotactic fields, the scatter contribution that causes increased penumbra is not proportional to the increase in field size.

The limitations of this study were related to the EBT3 film for 2D dosimetry. Gel dosimetry as a 3D dosimeter is more effective in achieving dose distributions in all axial, sagittal and coronal sections. In addition, film readout is not an on-line process and exposed films must be scanned after 48 hours. This can cause some changes in scanning conditions and introduce possible errors.

Conclusion

Gamma Knife head was simulated using BEAMnrc code and its profiles were calculated using DOSXYZnrc code and EBT3 film dosimetry to determine the penumbra width. The EBT3 film because of having many special properties, such as good spatial resolution, water equivalent material, linear response, energy independency and dose-rate independency, is appropriate for different field size dosimetry including small fields especially for penumbra determination of Gamma Knife.

Penumbra width specification is required for a better understanding of radiation doses to critical organs and to improve the treatment plan. The investigation of physical penumbra sizes for a single beam and 201-beam profiles using MC simulation and EBT3 measurement showed that despite the differences between measured and simulated penumbra width, they are in an acceptable range. For more precision in the penumbra region with high dose gradient, the results suggest the use of MC simulation for radiosurgery field penumbra evaluation especially for 4-mm collimator size. In addition, based on the penumbra width specification and its significance especially for 4 mm collimator, a new study can be considered to beam penumbra reduction of this model of Gamma Knife machine.

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Conflicts of Interest. The authors declare that they have no conflicts of interest to declare.

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