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Exploration of Monte Carlo Simulation from a Case Study of Particle Transport in the Gamma Knife Perfexion™ Machine

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ABSTRACT

Introduction: Gamma Knife Perfexion™ delivers 192 Cobalt-60 sources to the focal point (isocenter), and the patient is fixed using a stereotactic frame. In conformal techniques, the width of the penumbra resulting in an out-of-field dose of normal tissue adjacent to the tumor must be accurately determined. The purpose of this study was to calculate the penumbra widths of a single beam and 192 beams for different collimator sizes of the Gamma Knife Perfexion™ using the BEAMNRC/DOSXYZNRC Monte Carlo simulation code and compare the results with EBT3 film dosimetry data.

Material and Methods: To investigate the physical penumbra width (80-20%), the single beam and 192 beam profiles were obtained using the DOSXYZNRC code and EBT3 films located at the isocenter point in a spherical solid water phantom with a diameter of 160 mm.

Results: The results showed that the Gamma Passing Rate (GPR) value for all collimator sizes has a value above 97%. The single-beam penumbra widths obtained from simulation data for 4, 8, and 16 mm collimator sizes along the X-axis were 0.75, 0.77, and 0.87 mm, respectively. The data for 192 beams obtained from the simulation were 2.60, 4.80, and 8.70 mm along the X-axis.

Conclusion: The differences between measured and simulated penumbra widths are in an acceptable range. However, for more precise measurement in the penumbra region with a high dose gradient, a Monte Carlo simulation is recommended.

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Introduction

The treatment techniques for radiation delivery have been changed substantially in recent decades to allow for more precise dose delivery [1]. One of the high-precision radiation treatment methods is stereotactic radiosurgery (SRS), which uses small, highly collimated photon beams to irradiate cranial tumors and functional abnormalities with high geometric precision while sparing normal tissue [2, 3].

192 Cobalt-60 radioactive sources provide a highly concentrated dose of ionizing radiation to the Gamma Knife Perfexion™ (Elekta Oncology Systems). SRS is the term for this method, which is commonly utilized to preserve normal tissue while irradiating cranial tumors and functional abnormalities with high geometric precision. The Gamma Knife is perfect for treating small targets near important structures since each source's collimated beam is focused on an isocenter with an accuracy of better than 0.2 mm [4]. Eight sectors of 24 beams are spherically grouped around the isocenter in a tungsten mechanical collimator device.

The collimator device facilitates the delivery of circular field sizes measuring 4, 8, or 16 mm in diameter. The resultant spherical dose distribution at the convergence of the radiation beams generates a zone with pronounced dose gradients, ensuring accurate coverage of the target volume while preserving adjacent tissue. Patients are arranged to ensure the target volume is at the isocenter utilizing a robotic couch, with positioning precision reported to exceed 0.1 mm [5, 6].

The use of Gamma Knife Perfexion™ technology has negative impacts if the dose increase is greater than 5%. A 5% excess dose to the tumor will result in an increased dose to healthy tissue, exceeding the tolerated dose. The American Association of Physicists in Medicine (AAPM) recommends that inaccuracies in patient doses be allowed within a tolerance of approximately ± 5% [7]. Providing the optimal dose for Gamma Knife Perfexion™ irradiation is essential for successful treatment, based on quality control and quality assurance [8]. Dosimetric studies and

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verifications are required for precise and accurate dose calculations [9].

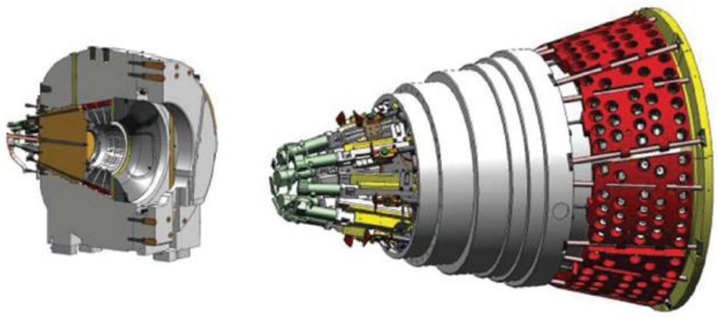
Using beam profile measurements, numerous studies have been conducted on photon beam penumbra, its implications on treatment output, and factors influencing it. Novotny et al. measured FWHM and penumbra using Kodak EDR2 films for both the Model 4C and Perfexion™ [10]. For all collimators and along the three stereotactic axes, the FWHM and penumbra (which is the distance between the 20% and 80% isodose lines) are comparable. There was a 0.2 mm FWHM discrepancy for the 4 mm collimator and a 0.6 mm difference for the 8 mm collimator. The Perfexion system displayed a penumbra that was 0.3 mm larger along the Z-axis for the 4 mm collimator and 0.5 mm larger for the 8 mm collimator. For all models, the X and Y stereotactic axes showed the same penumbra for the 4 mm collimator; however, the Gamma Knife Model 4C showed a 1.0 mm bigger penumbra for the 8 mm collimator along the X and Y axes. The geometric penumbra, which is a function of the distance between the collimator and the isocenter (the penumbra grows with distance), can be used to explain this. The distance between the collimator and the isocenter for all sources is constant for the Gamma Knife Model 4C, whereas it changes for the PerfexionTM [10]. According to Oh et al. (2012), penumbra width increases as beam intensity, field size, and depth increase [11]. Using the EGSNRC/BEAMNRC algorithms, Mahmoudi et al. (2019) determined the penumbra width of a single beam and all 201 beams for various collimator sizes of the Gamma Knife 4C [12]. According to research on the EBT Gafchromic film by Donmez Kesen et al., the energy is dependent on the dose-response. However, in the energy range of 50 kVp to 10 MVp, this indication is diminished [13]. Borca et al. came to the conclusion that the field size affected the calibration curve of the EBT Gafchromic film [14]. The study's findings highlighted the significance of penumbra in smaller field sizes by demonstrating that the ratio of penumbra width to field size falls as field size increases.

The methods used in this study are EGSNRC MC simulation and measurement. The researchers performed MC simulations for source characterization [6, 15, 16], beam characterization, and dose calculations on the Gamma Knife Perfexion™ using the Sun Nuclear 457 Solid Water phantom [17]. The measurements were performed on Gafchromic EBT3 film. The novelty of this research is the stepwise and detailed MC simulation on the Gamma Knife Perfexion™ device, including: Producing a study/verification of the Cobalt-60 file output that is the same as the Gamma Knife Perfexion™ output in the source section. This is possible because the cobalt-60 source model enclosed in a capsule is exactly the same as the Gamma Knife Perfexion™ device. The cobalt-60 source designed in this study is in the form of a spectrum; previous researchers only used monoenergetic sources to determine the beam output on the cobalt-60 source belonging to the Gamma Knife Perfexion™. Produces a more accurate study/verification of the Cobalt-60 spectrum beam by considering the geometric shape and material aspects used in the Gamma Knife Perfexion™ collimation system. This is aimed at achieving precision and accuracy in irradiation. Previous research [17, 8] used EGS4 to study photon scattering on collimators with diameters of 4, 14, and 18 mm on a Gamma Knife Model B machine. The MC simulations that the researchers conducted were different from those of the above two researchers, both in the radiotherapy machine equipment used and the software used. In addition, this research involved a study/verification of dose calculations on the Sun Nuclear 457 Solid Water phantom to achieve dosimetric precision and accuracy. Previous research used EGS-4 to simulate the Gamma Knife Model B and Gafchromic MD-55 film. The results showed that there was a 10% difference between the simulation results and the measurements. Other studies used the GEANT4 program to determine the dose distribution on the Gamma Knife Perfexion™ [19]. Further research used the FLUKA program to calculate the MC output factor of each collimator row for the Gamma Knife Perfexion™ [20]. Based on the above explanation, it can be seen that previous researchers calculated the Gamma Knife Perfexion™ dose using software that was not the same as the one used by the author.

The originality of this research lies in the use of the Cobalt-60 source spectrum in the simulation. The source spectrum used in the EGSNRC Monte Carlo simulations on the Gamma Knife Perfexion™ was designed by the author himself in the EGSNRC code. One of the advantages of EGSNRC Monte Carlo is that the source energy can be modeled in terms of spectral energy and monoenergetic energy. The variation of the light beam through the variable collimator is the second originality produced in this research. The precise and accurate calculation of the dose on the phantom is the third originality produced.

Materials and Methods

The Leksell Gamma Knife Perfexion™ may target a particular part of the brain with radiation. Compared to its predecessors, the radiation unit in the Perfexion™ Model has been rebuilt. The beam collimation technology in earlier Gamma Knife models was made up of two distinct components: interchangeable collimator elements housed in hemispherical exterior helmets and internal collimators implanted within the shield in a hemispherical pattern. The lack of the external component of the collimation mechanism is the most obvious distinction between Perfexion™ and its predecessors [21]. The collimator size (beam size) range for the Perfexion™ system is different from that of the earlier Gamma Knife variants. There are now just three collimator sizes available: 4, 8, and 16 mm.



(a) (b)

Figure 1. Shows the collimator and radiation unit for the Leksell Gamma Knife Perfexion™.(a) The Perfexion radiation unit's cross-section. (b) A close-up of the sectors. Each sector can be moved independently of other sectors to set a collimator size or block beams, and each sector houses 24 cobalt-60 sources.

24 sources are moved over the chosen collimator set to automatically adjust the beam size for each sector. The previous model's laborious manual collimator installation is no longer necessary thanks to the automatic selection of built-in collimation. There are eight movable sectors with 192 sealed sources of Co-60, with 24 sources per sector. A distinct SSD for each ring, ranging from 374 to 433 mm, is produced by the source arrangement, which is significantly different from the earlier hemispherical arrangements [21, 22, 23]. Figure 1 shows a comprehensive representation of the Perfexion™ collimator system.The Perfexion™ unit may have certain limitations. A manual treatment mode is no longer feasible due to the design of the system. Given the thorough testing, this is most likely a relative constraint, but overall, the device's dependability is impressive.

The American Association of Physics in Medicine (AAPM) TG-10 recommends comparing simulation results with measurement results. The results of the Monte Carlo simulation are implemented under the same conditions as the measurements. Measurements on the Gamma Knife Perfexion™ device were performed using a Gafchromic EBT3 film in Siloam Hospital, Lippo Karawaci, Tangerang, Banten, Indonesia. The data was collected on 29 June 2024 under the supervision of Elia Soediatmoko, S.Si, FM, as a medical physicist at Gamma Knife Center Indonesia.

The Gafchromic EBT3 film is designed to measure the absorption dose due to exposure to ionizing radiation with perfect spatial resolution [24, 25]. This film is designed to operate in a dosage range of 0.2 to 10 Gy. The structure of the film is shown in Figure 2. The structure consists of an active layer 27 µm thick and two protective layers made of polyester. The active layer will blacken when exposed to radiation. Darkness occurs due to the reaction between radiation and the polymer in the material. The same thickness between the top and bottom layers of the active layer can avoid scanning errors due to the film's position on the scanning device.

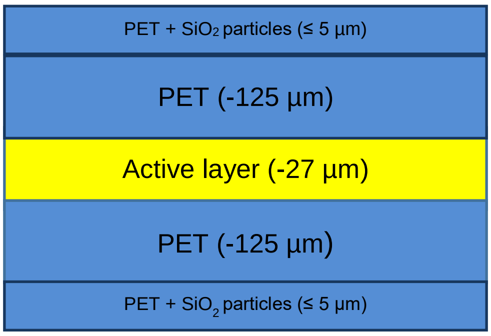


Figure 2. Film Gafchromic EBT 3 Structure

Figure 3. Gamma Knife Perfexion™ device

The density of the film is close to the density value of body tissue. This condition represents the absorption of radiation by the film in the body tissues. The film material consists of 42.37% carbon, 40.85% hydrogen, 16.59% oxygen, 0.01% nitrogen, 0.10% lithium, 0.04% chlorine, 0.01% potassium, and 0.01% bromine [27]. The Gafchromic film is cut to size (40 × 50 mm). The size was chosen because it takes into account the largest collimator of the Gamma Knife Perfexion™ device, as shown in Figure 3. The film's marking is done by making a hole in the length of the film as an attachment of the film to the phantom. Under the standard condition, 192 16 mm collimator emission beams are sent to the spherical phantom center, as shown in Figure 4.

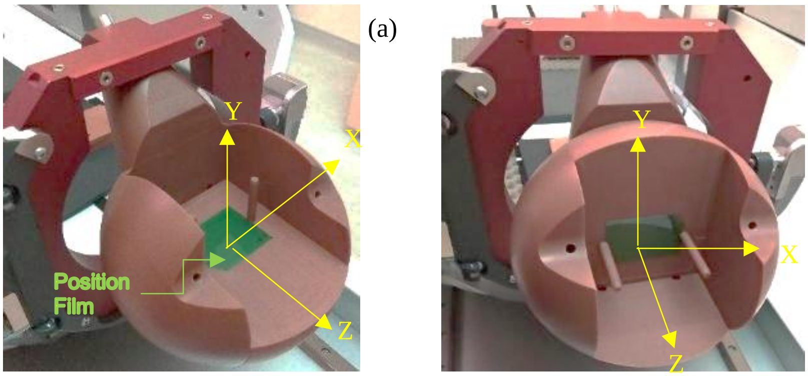


Figure 4. (a) Gafchromic EBT3 film on XZ orientation, (b) XY orientation.

During the irradiation process, the film is placed so that it does not move inside the phantom. It was fixed on the phantom using two holes at the end of the film. The dose value given was 5 Gy at a maximum point. Each film will be exhibited with collimator sizes of 4, 8, and 16 mm.

The film is scanned with the same parameters as for the creation of the calibration curve. The result of the scan is the degree of darkness of each pixel. To determine the distribution of the doses to be analyzed, the image data extraction into digital results was carried out. The calibration curve equation converts the value of the degree of darkness into a dose value. When processing the dose distribution data, normalization is performed on the measurement results against the maximum value. The calibration procedure is described by the publisher of the Film QA Pro 10 software [28]. It took twenty-four hours between irradiation and scanning using the Epson Perfection V700 10000 XL scanner. It is important to keep the film's orientation and position constant throughout the scanning procedure to eliminate longitudinal variations in the scanner itself.

In Figure 5, there are two stages in the simulation. In the first stage, the Gamma Knife source and collimator system are simulated with BEAMNRC to produce particle information records in the phase space file document. Then the phase space file is reused in the DOSXYZNRC code to irradiate the spherical phantom. The application will produce a dose distribution for each voxel.

The preconfigured BEAMNRC component modules (CMs) form the basis of the source geometry to be simulated. The source volume's geometry and the volume surrounding it are specified by the CMs. The cylindrical, 1 mm-diameter Cobalt-60 source is enclosed in stainless steel capsules and has a physical density (ρ) of 8.9 x 10^{-3} kg/m³. Materials with a density of 7.95 x 10^{-3} kg/m³ and compositions of 0.67 Fe, 0.133 Ni, 0.2 Cr, and 0.012 Mo are used to make capsules. At a distance of 3.1 cm, the simulation's output is saved in the scoring plane. Previous research has performed this simulation [15]. Additionally, each collimator's phase space output at a distance of 3.1 cm is sent into the simulation. The collimator is modeled directly beneath the source and has a diameter of 4 mm, 8 mm, and 16 mm. The BEAMNRC is also used in the design of the collimator. Elekta AB is the source of the collimator materials' size and compilation, subject to a legally binding confidentiality agreement. The form of the model employed in this investigation is explained in Figure 6 and Figure 7 [29].

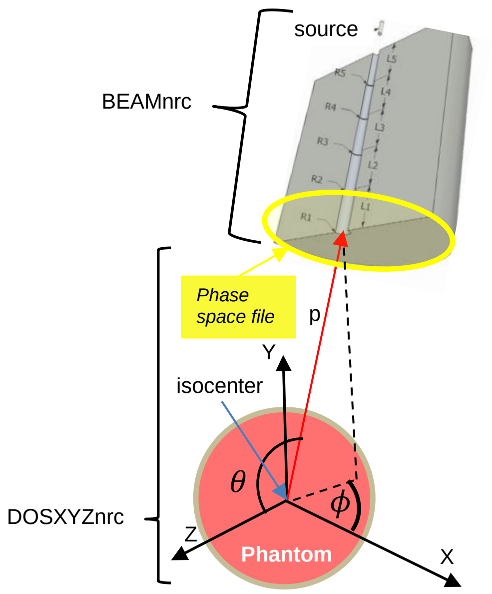


Figure 5. Source and collimator simulation with collimator size (R1-R5) and collimator thickness (L1-L5) different for each ring. The collimator leads to the isocenter point. ϕ, θ, and p are the spherical coordinate parameters.

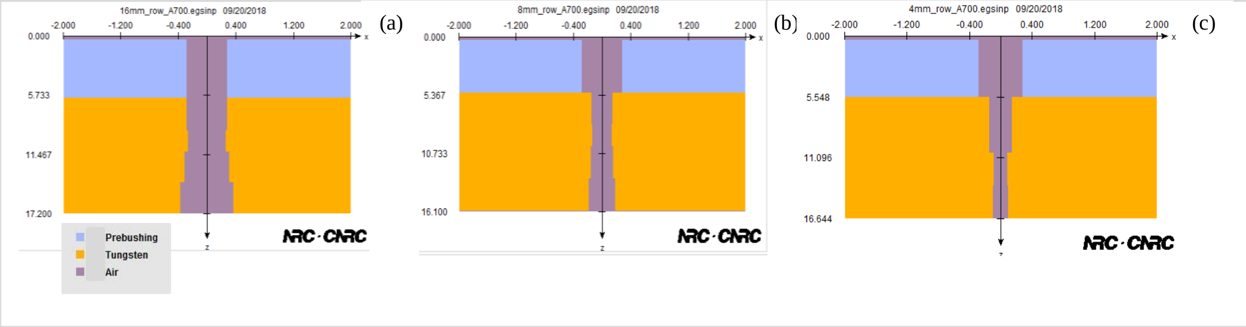


Figure 6. Collimator simulation. (a) 16 mm diameter, (b) 8 mm diameter, and (c) 4 mm diameter.

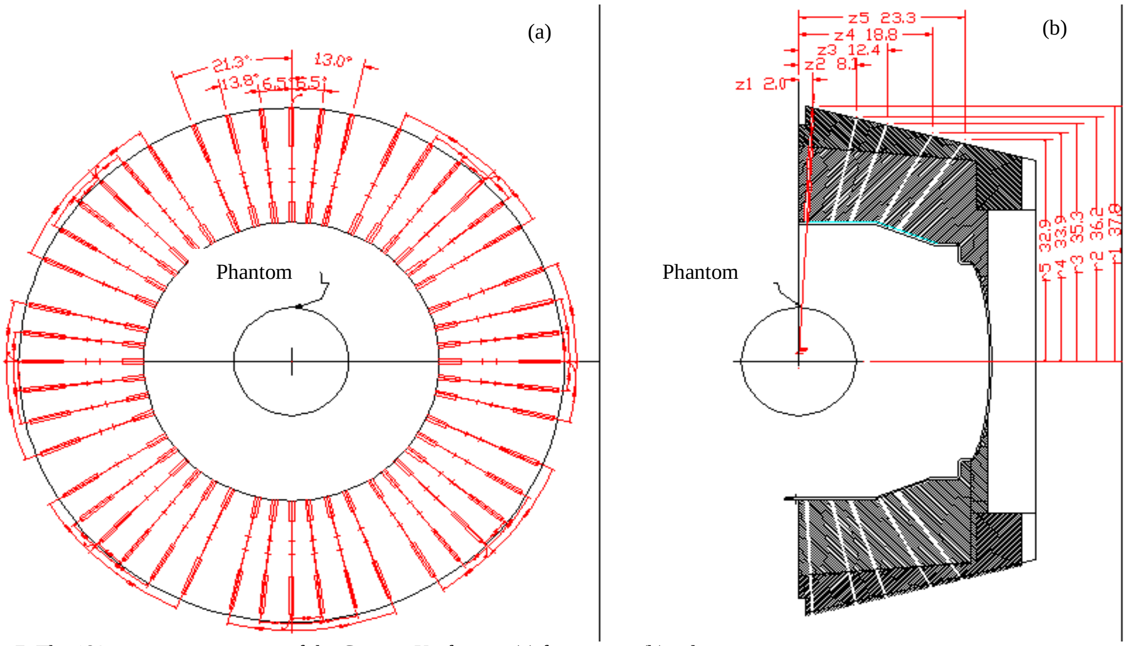


Figure 7. The 192-source arrangement of the Gamma Knife unit: (a) front view; (b) side view.

The phantom is spherical with homogeneous material. The phantom has a diameter of 160 mm. Homogeneous material in the phantom has a density of $1.03x10^{-3}$ kg/m^3. Phantom material is made from Solid Water RMI-457. Phantom is made from materials with a composition of 0.081 H, 0.672 C, 0.2 N, 0.001 Cl, and 0.023 Ca.

The majority of the elements making up phantom are carbon (67%). Phantom density has a difference of only 3% when compared to the density of water. Phantom material can be used as a substitute for water. For the sake of simulation, phantom imagery is taken with the Computerized Tomography (CT) scan modality. The image results have a digital image format and communication in medicine (DICOM). Measurement will use this phantom and will be directly exposed.

A phantom is a photoperiod object in a DOSXYZnrc simulation. Phantom uses data from CT scan acquisition. Phantom data for simulation needs converting image results into EGSphant data, as in Figure 3. The user code used is ct-create. Before the conversion is done, the boundaries of the coordinates and the midpoint of the phantom are observed with an open-source DICOMpyler application. The midpoint of the phantom has coordinates 1.71 mm, -192.31 mm, and -171 mm.

The midpoint of phantom coordinates is entered in EGSINP on the CT-Create code. The limit of each axis is 80 mm from the center point. The voxel matrix is set 1.5 mm × 1.5 mm × 1.5 mm and has a number of voxels (107 × 107 × 106). The maximum number of matrices that can be generated is 128×128×128. Therefore, the smallest possible matrix size to cover ghosts with a diameter of 160 mm is 1.5 mm.

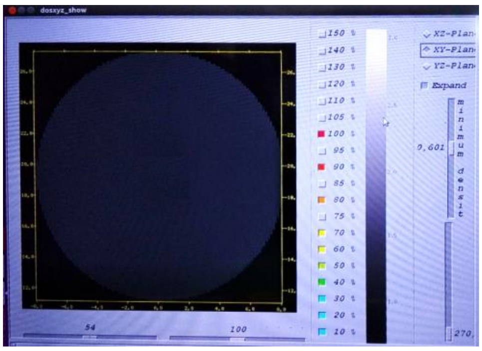


Figure 8. Phantom from CT created.

Figure 8 shows the document with the egsphant extension used as phantom data in the DOSXYZNRC user code. Each collimator is simulated by multiplying the number of sources according to the number of collimators for each ring at a certain angle. Phantom has certain characteristics that are round and homogeneous in distribution. Collimator simulations were carried out for each ring for each collimator size with 192 beams.

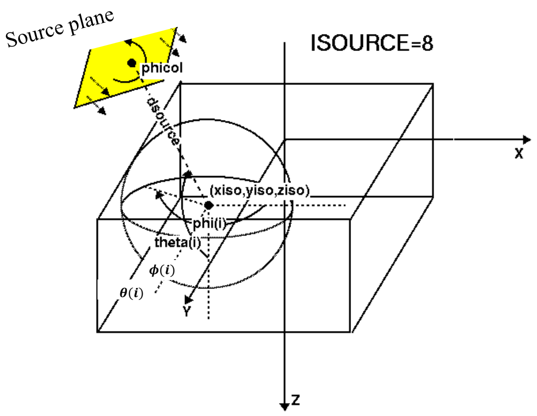


Figure 9. Source coordinate system of *ISOURCE* 8.

Figure 9 visualizes the source placement (ISOURCE = 8) leading to the phantom center. The magnitude of phicol has no effect in this study because of the circular collimator's cross-section. The values of x-iso, y-iso, and z-iso are adjusted to the phantom coordinates because the Gamma Knife therapy system is an object-to-source. This therapy system will adjust the target position on the phantom to the position of a fixed beam meeting point against the collimator. This point is obtained from observing the maximum dose point distribution of the TPS dose. In accordance with observations at the meeting point of the file, the values of x-iso, y-iso, and z-iso are set to 0.17 cm, -19.23 cm, and -17.1 cm.

Transformation of cylindrical coordinates into spherical coordinates is used (ISOURCE = 8), and the matrix equation used is

$$\begin{bmatrix}\hat{p}\\ \hat{\phi}\\ \hat{\theta}\end{bmatrix} = \begin{bmatrix}\sin(\theta) & 0 & \cos(\theta)\\ 0 & 1 & 0\\ \cos(\theta) & 0 & -\sin(\theta)\end{bmatrix}\begin{bmatrix}\hat{r}\\ \hat{\phi}\\ \hat{z}\end{bmatrix} \quad (1)$$

Where the angle θ is determined by

$$teta = \cos^{-1}\left(\frac{r}{p}\right) \quad (2)$$

And the p-value (radius) in spherical coordinates is determined by

$$p = \sqrt{r^2 + z^2} \quad (3)$$

Simulations will be performed on each ring. The phase space file data is adjusted to the ring being simulated. The d-source distance uses the distance of the collimator tip to the midpoint of the phantom. The large d-source value is the difference in the value of the radius on the spherical coordinates (p) and the thickness of the collimator on each ring. The angle θ is the angle formed by the Z axis and the direction of the source, while the angle ϕ is the angle formed by the positive X axis and the direction of the source. The angle θ and the d-source distance on each ring have a fixed value. In implementing source parameters, the θ-ϕ group is used. This input can increase the number of collimators in each ring according to the varied value ϕ. The ϕ value defined is position 1, position 8, and the number of collimators is 8, with the same probability for each position.

0.7 MeV was the electron cut-off energy (ECUT), and 0.01 MeV was the photon cut-off energy (PCUT). To achieve statistical uncertainty below 1%, 2.1 x 10^9 gamma particle histories were used in each simulation. The information required to determine the mean energy and beam fluence profile was available in the phase-space data [29, 31].

The cobalt-60 beam output measurement on the Gamma Knife Perfexion™ device uses three sizes of the collimator with diameters of 4, 8, and 16-mm. Table 1 shows the exposure time of the Cobalt-60 beam to the dose value. Gafchromic EBT3 film measuring 35 × 43 cm² is then cut to 4 × 5 cm².

Gafchromic film irradiation with photon energy spectrum. Energy spectra have 1.17 MeV and 1.33 MeV, using a dose range of 0-10 Gy. The dose rate measured by the ionization chamber detector at the point of isocenter is 1675.78 ± 28.62 mGy/min. There is a 0.65% deviation from the dose rate at TPS. The resulting deviation is even smaller than the AAPM number 54 recommendation regarding SRS. The measured dose rate value is used to calculate the exposure time of each film.

The analysis was performed to determine the relationship between Net-OD and photon energy dose to obtain the response curve of EBT3. Net-OD is used as a parameter to analyze the characteristics of the EBT3 film, according to equation (4).

$$netOD = log_{10}\left(\frac{PV_{un}}{PV_{ex}}\right) \quad (4)$$

PV_{un} is the film's pixel value without irradiation, and PV_{ex} is the pixel value of the film after being irradiated with photon energy. The exposure time of Gafchromic EBT3 film with certain values is shown in Table 1.

Table 1. The exposure time of the film with a certain dose

Dose (Gy)	Time (minutes)	Description
0	-	As a reference
1	0.601	
2	1.201	
3	1.802	
4	2.402	
5	3.003	Dose distribution
6	3.604	
7	4.204	
8	4.805	
9	5.405	
10	6.006	

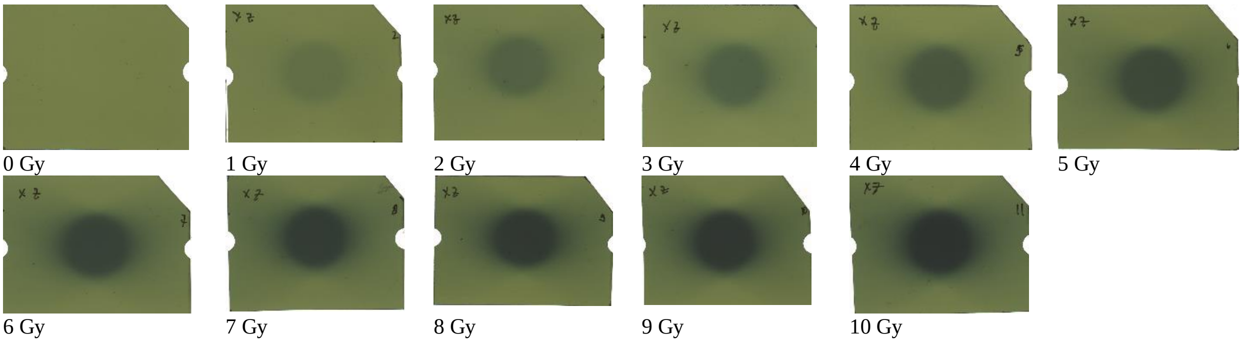


Figure 10. Gafchromic EBT 3 film by variation of the dose

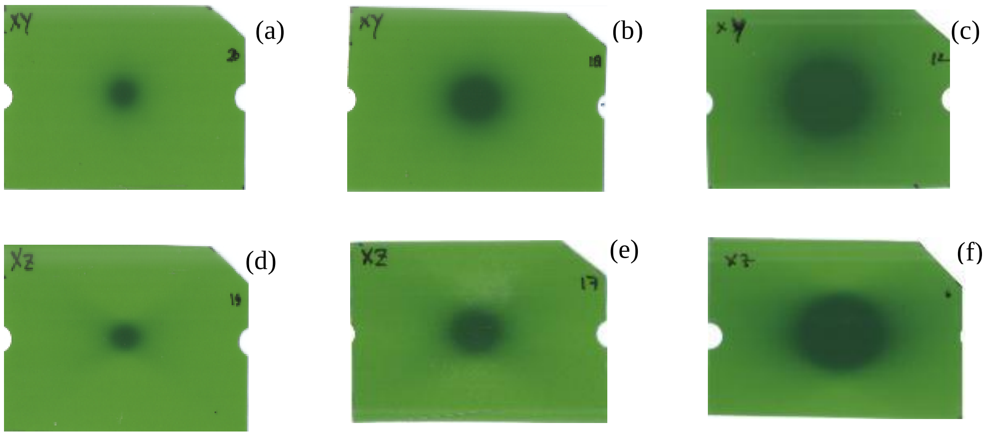


Figure 11. Gafchromic EBT3 Film Scanning Results on Field of XY: (a) 4 mm Collimator, (b) 8 mm Collimator, (c) 16mm Collimator, on Field of XZ (d) 4 mm Collimator, (e) 8 mm Collimator, (f) 16 mm Collimator

Based on the exposure time in Table 1, the dose value given to the film increases linearly with the exposure time. The dose value is the dose at the isocenter point. Therefore, the administered dose is the maximum film dose. The film with a 5 Gy dose will be analyzed for its dose distribution as a film resulting from a 16 mm collimator's exposure in the XZ plane.

Figure 10 is a Gafchromic EBT3 film that has been exposed to film calibration. The results of the analysis are processed with the ImageJ application. Calibration curves are used to convert OD values to dose distribution values. The film's center point (isocenter position) was determined, and indentations are used at the right and left ends of the film. A straight line will be drawn between these two curves as the X-axis. A line perpendicular to the X-axis at the center of the line will produce a Y-axis in XY orientation and a Z-axis in XZ orientation. The dose profile curve will be generated so that the one-dimensional dose distribution is known.

For other purposes, the Gafchromic film was scanned on the source through three collimators with a diameter of 4mm, 8mm, and 16mm, as shown in Figure 11.

The dose distribution of the Gafchromic EBT3 film will be seen in a certain area. The 4 × 5 cm Field of View (FOV) size is used as a region of interest (ROI), which is limited to 3.81 × 3.81 cm or the equivalent of 900 × 900 pixels. It is because at the end of the film, there is a film numbering marker that may interfere with the read result. The voxel size has been changed to 1.5 × 1.5 mm with the concept of averaging.

Dose distribution analysis was performed on a dose profile. Profile analysis will examine the distribution at the isocenter point. Profile analysis was used to determine the limits of the dose matrix used. The dose profile consists of nine graphs, where each collimator will be analyzed on each axis. The full half-maximum width (FWHM) parameters of the profiles for each method are compared.

Determination of Penumbra

Using MATLAB software, dose profiles in Figures 17 and 18 were computed in the head phantom at the isocenter depth for four collimator sizes of 4, 8, and 16 mm in order to establish the physical penumbra width of 192 beams (80–20% isodose lines) from simulation. Only X-profiles were evaluated due to their resemblance to Y-profiles. Measurement data were used to compute experimental penumbra widths. Lastly, the outcomes were compared using Origin software.

It is possible to estimate the Gamma Knife's single beam penumbra width using MC simulation and DOSXYZNRC in a Solid Water RMI-457 phantom. For 16 mm collimator sizes, voxel sizes along the X direction were 0.5 mm, and for 8 mm and 4 mm collimator sizes, they were 0.25 mm [32]. To accomplish the statistical errors of <1%, 2.1×10^9 incident particles were employed for voxel sizes of 0.5 and 0.25 mm, respectively. MATLAB was used to draw profiles along the X axis in order to calculate the physical penumbra widths (80–20%).

Results

Calibration curve results

The calibration curve is generated by comparing the degree of darkness of each pixel of the exposed film reduced by the value of the degree of darkness of the reference film. Mathematically, it can be thought of as Equation 1. The results of the calibration curve are shown in Figure 12. The calibration curve describes the relationship between dose and net-OD. The calibration curve was generated with a value of $R^2 = 0.9963$.

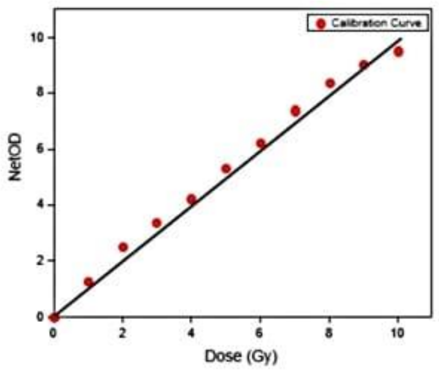


Figure 12. Calibration curve

Monte Carlo (MC) validation

All measured and MC-calculated profiles for 4, 8, and 16-mm collimator diameters were compared to verify the MC-simulation procedure. Origin software and MATLAB were used for validation. Figure 13's simulation and measurement profiles, as shown in Table 2 and Table 3 along the X and Z axes, demonstrated a good agreement (less than 1 mm).

Table 2. Measurement and MC calculated the FWHM of 192 beams along the X axis

Collimator size (mm)	MC simulation (mm)	Film measurement (mm)	difference (mm)
4	6.56	6.06	0.5
8	11.79	11.24	0.55
16	25.06	24.80	0.26

Table 3. Measurement and MC calculated the FWHM of 192 beams along the Z axis

Collimator size (mm)	MC simulation (mm)	Film measurement (mm)	Difference (mm)
4	5.10	4.95	0.15
8	10.11	9.58	0.53
16	17.99	17.02	0.97

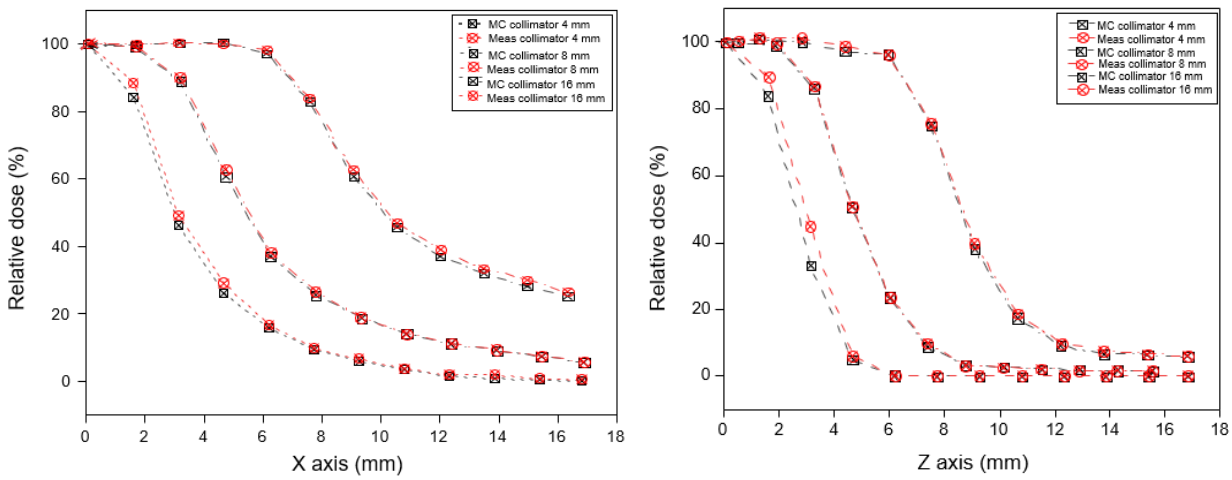


Figure 13. Comparison of measured and simulated profiles for three field sizes along the X axis and Z axis at the isocenter depth

Isodose Curve

The simulation was performed on DOSXYZNRC. The input of this simulation came from the output of the beam characteristics stored in the assessment field at a distance of 17.20 cm from the source. The output of this simulation was stored on a Phantom of the Sun nuclear 457 solid water at varying distances between 37−43 cm from the source. The output of DOSXYZNRC produced a three-dimensional dose distribution in Cartesian coordinates. The dose distribution is presented in .3ddose format data. The results of the dose distribution were processed using MATLAB and Origin programs. The results of the study are presented in 1-dimensional form in the form of a dose profile and in 2-dimensional form in the form of an isodose curve. At the end, the dose distribution of a single beam and 192 beams of Gamma Knife Perfexion™ on the X-axis is analyzed.

The results of the MC simulation in the 2D dose distribution in the form of isodoses are shown in Figure 14. The position of the midpoint of the beam is determined at the coordinates (0, 0, 0) or at voxels 54, 54, and 54. The planes intersecting the coordinate points are analyzed and then compared with the isodose curve of the measurement data using Gafchromic EBT-3 film.

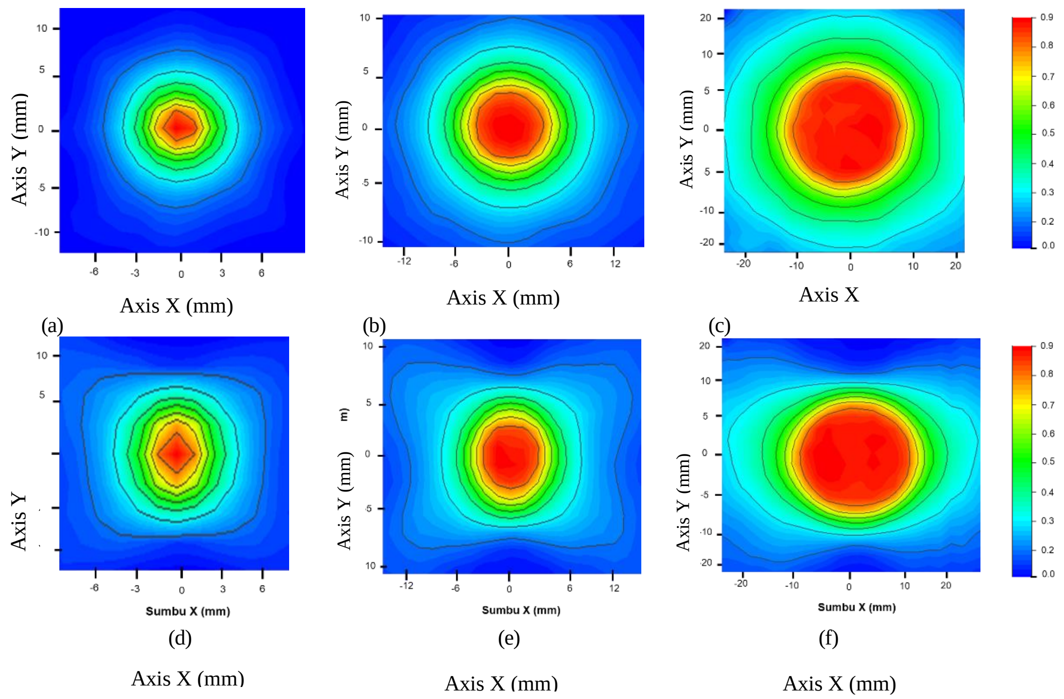


Figure 14. Isodose curves from simulation results are normalized (a) XY plane of 4 mm collimator, (b) XY plane of 8 mm collimator, (c) XY plane of 16 mm collimator, (d) XZ plane of 4 mm collimator, (e) XZ plane of 8 mm collimator, and (f) XZ plane of 16 mm collimator

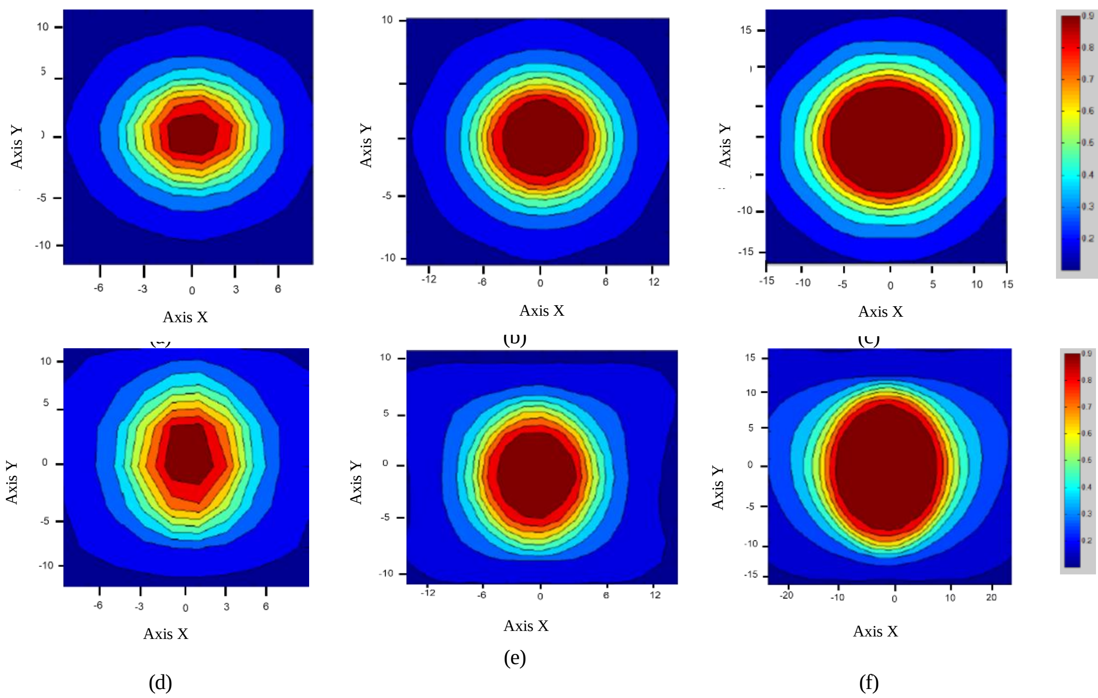


Figure 15. Gafchromic EBT3 film measurement isodose curves normalized (a) 4 mm collimator XY plane, (b) 8 mm collimator XY plane, (c) 16 mm collimator XY plane, (d) 4 mm collimator XZ plane, (e) 8 mm collimator XZ plane, and (f) 16 mm collimator XZ plane.

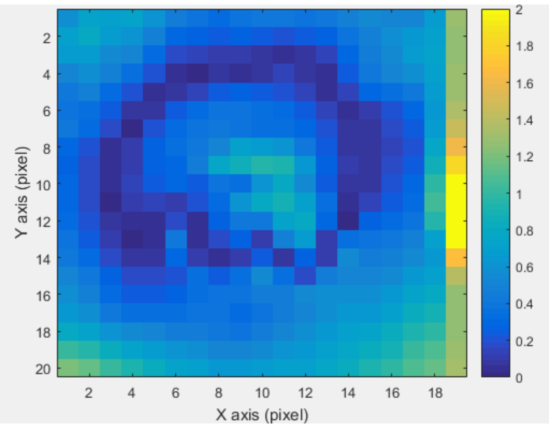
The results of the isodose curve of the Gafchromic EBT-3 film measurement shown in Figure 15 have an isodose curve shape similar to the isodose curve of the simulation results in Figure 14.

Gamma Index

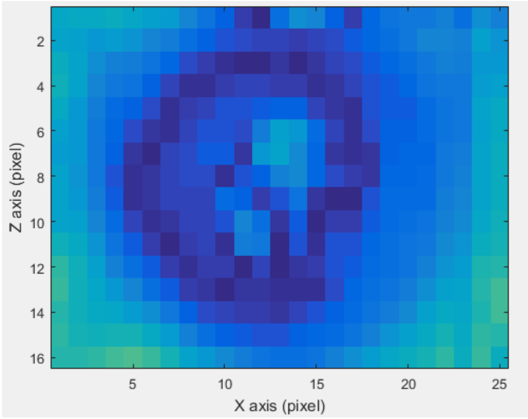
The distribution of gamma index values was carried out on a collimator diameter of 16 mm, as in Figure 16. Observation of the dose distribution was limited to a size of

37.5 × 37.5 mm. This limitation was made because of the selection of a pixel size of 1.5 mm. The dose distribution on the 16 mm collimator simulation and measurement of the Gafchromic EBT3 film produced a distribution of gamma index values. This dose distribution produces a difference that, if the difference occurs above a value of 1, then the observed pixel/position is different outside the tolerance.

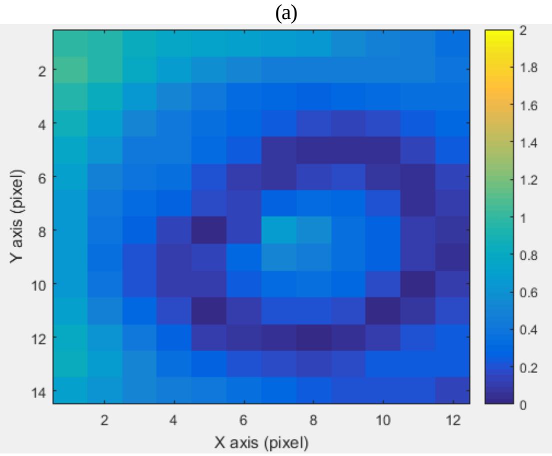
Based on Figure 16, the highest Gamma Index value is 1.1, which is seen in the green area, while in other areas it shows a Gamma Index value below 0.8. Overall, the majority of the gamma index distribution has a light blue to dark blue color. Based on the Gamma Passing Rate (GPR) value in Table 4, all orientations and collimator sizes have values above 97%. The minimum GPR value is found in the XZ orientation and 16 mm collimator, which is 98.24%. The number of pixels that have a gamma index value of more than 1 is 11 out of 625 observed voxels. Therefore, the simulation and measurement systems have a suitable dose distribution.



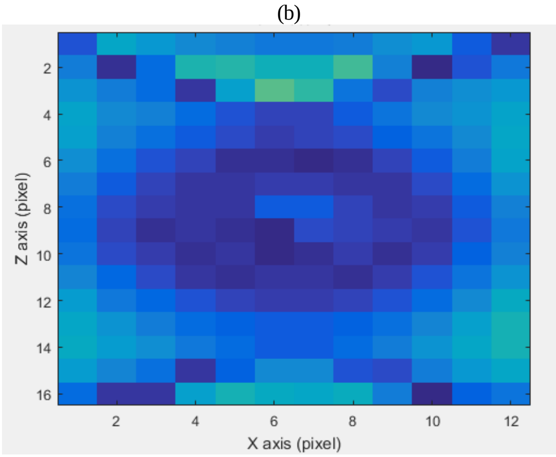
(a)



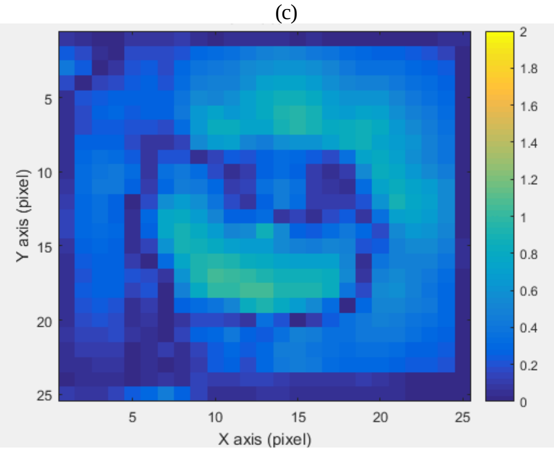
(b)



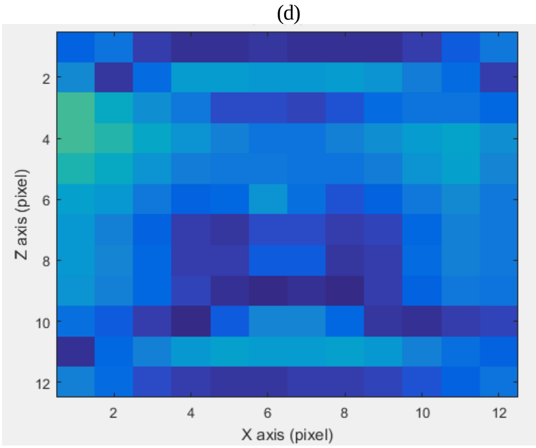
(c)



(d)



(e)



(f)

Figure 16. Distribution of Gamma Index (a). 16 mm collimator at isocenter on XZ plane, (b). XY plane. (c). 8 mm collimator at isocenter on XZ plane, (d) XY plane. (e). 4 mm collimator at isocenter on XZ plane, (f). XY plane.

Table 4. Gamma Passing Rate of Simulation and Measurement

Collimator Size	GPR (each collimator size (%))	
	XY	XZ
16 mm	98,24	98,25
8 mm	99,40	98,96
4 mm	99,33	98,61

Based on Table 4. In the XZ, the GPR is lower than the XY. Because in the Z axis, the dose degradation that occurs is quite sharp. The simulation still takes into account the low dose, while the Gafchromic EBT-3 film is unable to capture the radiation dose if it is below 0.1 Gy.

Beam Penumbra Width Determination

The discrepancies between the MC calculation and the film dosimetry measurement of the actual penumbra width (80–20%) of 192 beams along the X and Z axes are displayed in Table 5. It is discovered that the penumbra width rises as field sizes grow, which is consistent with prior studies. Additionally, the 4 mm collimator shows the largest discrepancy between the measured and MC-computed values. The issue of dosimetry in small fields is the cause of this. Furthermore, it is difficult to determine the experimental dosimetry of tiny fields due to the limitations of source size, absence of electronic equilibrium, and detector size. Even while current research on EBT3 films with miniature pinpoint chambers yields satisfactory results for Gamma Knife field widths of 8 and 16 mm, empirical data for fields smaller than 4 mm have an approximate inaccuracy of 11% in comparison to the simulation.

Therefore, it prevents these narrow domains from using empirical results. The accuracy of MC simulation in small-field dosimetry in comparison to other dosimetric techniques has been highlighted in numerous studies. The experimental data of fields 4, 8, and 16 mm can be utilized to validate small-field MC simulations concerning the permissible range of experimental measurements in small fields. However, it has been demonstrated in the majority of the literature that the most accurate field size is 16 mm.

The physical penumbra widths of 192 beams are greater than those of single beams because of penumbra overlap, as can be observed from the MC-simulated single-beam profiles of the Gamma Knife in Figures 17 and 18 and the physical penumbra values (80–20%) of beam profiles reported in Table 5. Using an 18-beam coplanar beam, Keller et al. [33] have demonstrated this phenomenon. The significance of the overlapping effect for higher field sizes is further demonstrated by the data from Table 5, column 4, which indicates that the difference between these values is larger for larger field sizes. The significance of penumbra in lower field sizes is shown by the data from Table 5, column 5, which indicates that the ratio of the penumbra width to the field size decreases with increasing field size. The source of this phenomenon is that the scatter contribution that results in increased penumbra is not proportional to the increase in field size in the range of tiny stereotactic fields.

The EBT3 film for 2D dosimetry was one of the study's shortcomings. In all axial, sagittal, and coronal sections, gel dosimetry works better as a 3D dosimeter to achieve dosage distributions. Furthermore, exposed films need to be scanned 48 hours after exposure, and film readout is not an online procedure. This may produce potential errors and alter the scanning circumstances.

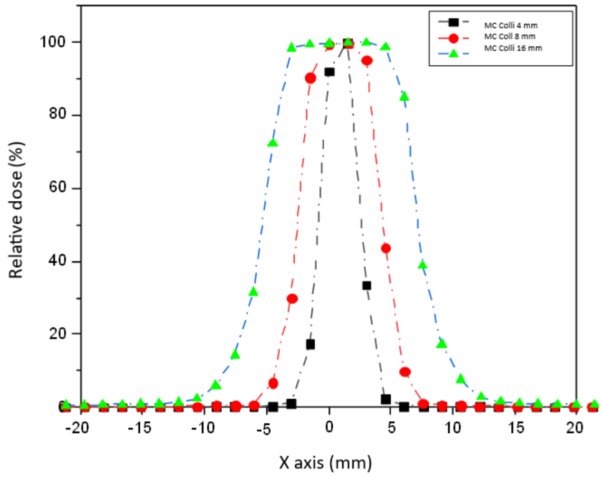


Figure 17. Simulated single beam profile for 4, 8, and 16 mm collimator sizes along the X axis at isocenter depth

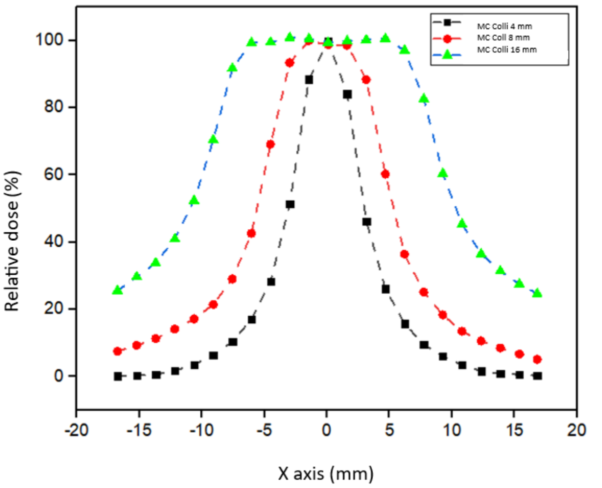


Figure 18. Simulated 192 beam profiles for 4, 8, and 16 mm collimator sizes along the X axis at isocenter depth

Table 5. Results of calculating the penumbra width (80-20%) of a single beam and 192 beams on the X axis

Collimator size (mm)	MC simulation on single beam (mm)	MC simulation on 192 beams (mm)	Difference (mm)	The ratio of penumbra to field size	
				Single beam	192 beams
4	0.75	2.60	1.85	0.06	0.20
8	0.77	4.80	4.03	0.02	0.09
16	0.87	8.70	7.83	0.00	0.04

Discussion

To verify the correctness of the MC simulation, all measured and simulated profiles for collimator diameters of 4, 8, and 16 mm were compared in Figure 13. The simulated and measured findings (differential dose (DD) = 2% and distance to agreement (DTA) = 2 mm) agreed well, and for all field sizes, the Gamma Index value (a combination of DD and DTA) was less than 1. These results demonstrate the validity of our MC simulation procedure for Gamma Knife equipment and are consistent with previous studies, which have also reported good agreement (<3%) between Monte Carlo simulations and film dosimetry for small stereotactic fields [26,17].

The isodose curves of the simulation results for collimators with diameters of 4, 8, and 16 mm in both the XY and XZ planes closely matched the Gafchromic EBT3 film measurements, further supporting the reliability of the model. Similar findings have been observed in other validation studies using radiochromic films and ionization chambers, reinforcing the reproducibility of MC-based dose calculations across different measurement methods.

Based on the dose distribution in Figure 14, the distribution in 192 collimator beams showed distinct patterns across field sizes. In the XY plane, the isodose curves maintained a regular circular shape due to the circular symmetry of the cone beams.

In the XZ plane, the incoming beams converged from around the isocenter of the X and Y axes, producing an area above the center that was relatively spared from irradiation. Clinically, this region often corresponds to organs at risk (OAR), suggesting that the beam arrangement of the Gamma Knife system inherently provides a degree of protection for critical structures.

Analysis of penumbra values (Table 5) revealed differences between single beams and the composite 192 beams of Gamma Knife Perfexion™, with the differences becoming more pronounced for larger collimator sizes. This effect reflects the overlapping contribution of multiple beams, which broadens the penumbra for larger fields. Conversely, the ratio of penumbra width to field size decreased as field size increased, indicating that the influence of scatter on penumbra broadening is proportionally greater in smaller stereotactic fields. These findings align with previous reports that highlight the critical role of penumbra characteristics in high-precision stereotactic treatments, particularly for small lesion sizes.

Nevertheless, this study has several limitations. The use of Gafchromic EBT3 film, although widely adopted, has limitations in spatial resolution and dosimetric accuracy compared to high-resolution detectors. Furthermore, simulations were performed in a homogeneous phantom, which does not fully account for tissue heterogeneity encountered in patient treatments. Future studies should therefore extend validation to heterogeneous phantoms and patient-specific geometries and ideally include direct comparisons with commercial treatment planning systems (TPS), such as Leksell GammaPlan, to further establish clinical applicability.

Conclusion

The BEAMNRC code was used to simulate the Gamma Knife head, and the DOSXYZNRC code and EBT3 film dosimetry were used to calculate the profiles and determine the penumbra width. The EBT3 film is suitable for a variety of field-size dosimetry, including small fields, due to its many unique properties, including good spatial resolution, water-equivalent material, linear response, energy independence, and dose-rate independence. This is especially true for penumbra determination of the Gamma Knife Perfexion™.

To enhance the treatment plan and gain a better understanding of radiation doses to vital organs, penumbra width specifications are necessary. Physical penumbra sizes for single-beam and 192-beam profiles were investigated using MC simulation and EBT3 measurement. The results indicated that although the measured and simulated penumbra widths differ, they fall within a reasonable range. The findings recommend using MC simulation for radiosurgery field penumbra evaluation, particularly for a 4-mm collimator size, in order to increase precision in the penumbra region with a high dose gradient. Additionally, a new study on beam penumbra reduction of this Gamma Knife machine model might be considered based on the penumbra width specification and its significance, particularly for the 4-mm collimator size.

Acknowledgment

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References

1. Junios J. Hubungan Kuadratik Jumlah Dan Letak Seed Dengan Distribusi Dosis I-125 Brachyseed Pada Model Kanker Prostat Menggunakan Dose Volume Histogram. J Sainstek IAIN Batusangkar. 2012;4(1):26–35. doi: 10.31958/js.v4i1.54.
2. Nabavi M, Nedaie HA, Salehi N, Naderi M. Stereotactic Radiosurgery/Radiotherapy: A Historical Review. Iran J Med Phys. 2014;11(1). doi: 10.22038/ijmp.2014.2621.
3. Tyler M, et al. Characterization of small-field stereotactic radiosurgery beams with modern detectors. Phys Med Biol. 2013;58(21):7595–608. doi: 10.1088/0031-9155/58/21/7595.
4. Pipek J, Novotný J, Novotný Jr J, Kozubíková P. A modular Geant4 model of Leksell Gamma Knife Perfexion™. Phys Med Biol. 2014;59(24):7609–23. doi: 10.1088/0031-9155/59/24/7609.

5. Niranjan A, Novotny Jr J, Bhatnagar J, Flickinger JC, Kondziolka D, Lunsford LD. Efficiency and Dose Planning Comparisons between the Perfexion and 4C Leksell Gamma Knife Units. Stereotact Funct Neurosurg. 2009;87(3):191–8. doi: 10.1159/000222663.
6. Junios J, Kariman D, Susanti E, Haryanto F. Investigating the effect of the material absorber of gamma knife Perfexion™ source based on Monte Carlo simulations. Presented at: The 4th International Conference On Mathematics And Sciences (The 4th IcmsC): The Roles of Tropical Science in New Capital Nation Planning; 2024; Samarinda City, Indonesia. doi: 10.1063/5.0205474.
7. Dosimetry of Small Static Fields Used in External Beam Radiotherapy. Technical Reports Series, no. 483. Vienna: International Atomic Energy Agency; 2017. Available from: https://www.iaea.org/publications/11075/dosimetry-of-small-static-fields-used-in-external-beam-radiotherapy.
8. Cheung YC, Yu KN, Ho RTK, Yu CP. Stereotactic dose planning system used in Leksell Gamma Knife model-B: EGS4 Monte Carlo versus GafChromic films MD-55. Appl Radiat Isot. 2000;53(3):427–30. doi: 10.1016/S0969-8043(99)00285-7.
9. Manik JT, Okselia A, Junios J, Margaretha A, Haryanto F. Evaluation of 6 MV photon beam characteristics on Varian Clinac iX: a Monte Carlo study. Int J Adv Appl Sci. 2025;14(1):227. doi: 10.11591/ijaas.v14.i1.pp227-234.
10. Novotny J, et al. Dosimetric comparison of the Leksell Gamma Knife Perfexion and 4C. J Neurosurg. 2008;109(Supplement):8–14. doi: 10.3171/JNS/2008/109/12/S3.
11. Cho Y, Van Prooijen M, Jaffray DA, Islam MK. Verification of source and collimator configuration for Gamma Knife® Perfexion™ using panoramic imaging. Med Phys. 2010;37(3):1325–31. doi: 10.1118/1.3327458.
12. Mahmoudi A, Geraily G, Shirazi A, Bakhshi M. Study the effect of source to diaphragm distance (SDD) on beam penumbra width of Gamma Knife machine model 4C using Monte Carlo simulation. Iran J Med Phys. 2018;15 (Special Issue-12th Iranian Congress of Medical Physics). doi: 10.22038/ijmp.2018.13027.
13. Donmez Kesen N, Cakir A, Okutan M, Bilge H. A comparison of TPS and different measurement techniques in small-field electron beams. Med Dosim. 2015;40(1):9–15. doi: 10.1016/j.meddos.2014.07.001.
14. Borca VC, et al. Dosimetric characterization and use of GAFCHROMIC EBT3 film for IMRT dose verification. J Appl Clin Med Phys. 2013;14(2):158–1. doi: 10.1120/jacmp.v14i2.4111.
15. Junios J, et al. Characterization of Gamma Knife Perfexion™ source based on Monte Carlo simulation. Radiol Phys Technol. 2020;13(4):398–404. doi: 10.1007/s12194-020-00590-3.
16. Junios J, Haryanto F, Su'ud Z, Novitrian. The effect of radiation source distance to the scintillation detector based on Monte Carlo simulation. J Phys Conf Ser. 2020;1493(1):012012. doi: 10.1088/1742-6596/1493/1/012012.
17. Mahmoudi A, Shirazi A, Geraily G, Hadisi Nia T, Bakhshi M, Maleki M. Penumbra width determination of single beam and 201 beams of Gamma Knife machine model 4C using Monte Carlo simulation. J Radiother Pract. 2019;18(1):82–7. doi: 10.1017/S1460396918000407.
18. Cheung JYC, Yu KN. Study of scattered photons from the collimator system of Leksell Gamma Knife using the EGS4 Monte Carlo Code. Med Phys. 2006;33(1):41–5. doi: 10.1118/1.2143138.
19. Pipek J, Novotný J, Novotný J, Kozubíková P. A modular Geant4 model of Leksell Gamma Knife Perfexion™. Phys Med Biol. 2014;59(24):7609–23. doi: 10.1088/0031-9155/59/24/7609.
20. Battistoni G, et al. FLUKA Monte Carlo simulation for the Leksell Gamma Knife Perfexion radiosurgery system: Homogeneous media. Phys Med. 2013;29(6):656–61. doi: 10.1016/j.ejmp.2012.07.005.
21. J. Novotny, J. P. Bhatnagar, M. A. Quader, G. Bednarz, L. D. Lunsford, and M. S. Huq, "Measurement of relative output factors for the 8 and 4-mm collimators of Leksell Gamma Knife Perfexion by film dosimetry," Med. Phys., vol. 36, no. 5, pp. 1768–1774, May 2009, doi: 10.1118/1.3113904.
22. Cho Y-B, Van Prooijen M, Jaffray DA, Islam MK. Verification of source and collimator configuration for Gamma Knife® Perfexion™ using panoramic imaging: Verification of source and collimator using panoramic imaging. Med Phys. 2010;37(3):1325–31. doi: 10.1118/1.3327458.
23. Nabavi, M., Nedaie, H. A., Salehi, N., Naderi, M. Stereotactic Radiosurgery/Radiotherapy: A Historical Review. Iranian Journal of Medical Physics, 2014; 11(1): 156-167. doi: 10.22038/ijmp.2014.2621.
24. Novotny J, Bhatnagar JP, Quader MA, Bednarz G, Lunsford LD, Huq MS. Measurement of relative output factors for the 8 and 4 mm collimators of Leksell Gamma Knife Perfexion by film dosimetry: Perfexion relative output factors measured by film. Med Phys. 2009;36(5):1768–74. doi: 10.1118/1.3113904.
25. Khan FM, Gibbons JP. The Physics of Radiation Therapy. 5th ed. 2014.
26. Tajiki S, et al. Penumbra Measurements and comparison of In-house and standard circular cones by Gafchoromic film, PinPoint ion chamber and MCNPX Monte Carlo simulation. Iran J Med Phys. 2018;Online First. doi: 10.22038/ijmp.2018.32356.1387.
27. Das IJ. Radiochromic Film: Role and Applications in Radiation Dosimetry. 1st ed. Boca Raton, FL: CRC Press, Taylor & Francis Group; 2017. doi: 10.1201/9781315154879.

28. Noname N. Efficient Protocols for Accurate Radiochromic Film Calibration and Dosimetry [Internet]. Available from: http://www.gafchromic.com/documents/Efficient Protocols for Calibration and Dosimetry.pdf.
29. Junios J, et al. Investigating the impact of collimator size variation on the single beam radiation of Gamma Knife Perfexion™ based on Monte Carlo simulation. J Phys Conf Ser. 2020;1505(1):012013. doi: 10.1088/1742-6596/1505/1/012013.
30. Kurniati F, Krisna FP, Junios J, Haryanto F. The Dose Distribution from Iridium-192 Source on Cervical Cancer Brachytherapy by Manchester System Using Monte Carlo Simulation. At Indones. 2021;47(3):205. doi: 10.17146/aij.2021.1102.
31. Krisna FP, Yani S, Junios J, Atiqah N, Asmawan MD, Haryanto F. A Study of the Dose Distribution from Ir-192 Source on Inhomogeneous Phantom by Monte Carlo Simulation. J Phys Conf Ser. 2020;1505(1):012051. doi: 10.1088/1742-6596/1505/1/012051.
32. Guerrero M, Li XA, Ma L. A technique to sharpen the beam penumbra for Gamma Knife radiosurgery. Phys Med Biol. 2003;48(12):1843–53. doi: 10.1088/0031-9155/48/12/312.
33. Keller BM, Pignol J, Presutti J, Beachey DJ. Intermediate energy photons to improve dose gradient, conformality, and homogeneity: Potential benefits for small field intracranial radiosurgery. Med Phys. 2009;36(1):33–9. doi: 10.1118/1.3026588.