Investigating the impact of collimator size variation on the single beam radiation of Gamma Knife Perfexion™ based on Monte Carlo simulation

Junios¹, Irhas¹, Novitrian¹, E Soediatmoko², F Haryanto¹, Z Su’ud¹, and A.L. Fielding³

¹Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesha 10 Bandung 40132, Indonesia
²Gamma Knife Centre Indonesia, Siloam Hospital Lippo Karawaci, Tangerang, Banten 15811, Indonesia
³Science and Engineering Faculty, Queensland University of Technology, Brisbane Qld, 4001, Australia

* Email: junios@s.itb.ac.id

Abstract. The Gamma Knife Perfexion™ (Elekta Oncology Systems) is a specialized stereotactic radiotherapy device that uses 192 Cobalt-60 radioactive sources. A dynamic collimator system enables three circular field sizes of 4 mm, 8 mm, and 16 mm diameter to be delivered. This study investigates the dosimetric characteristics of the three different sized collimated beams using Monte Carlo (MC) simulations. The MC simulation made use of previously calculated phase space from a Monte-Carlo model of the encapsulated Cobalt-60 sources. The collimators were modelled using the FLATFILT component module of the BEAMnrc user code. The output of the single beam radiation was stored in a circular scoring plane with a radius of 1.4 cm at source surface distance (SSD) 17.20 cm in the phase space file. The simulation parameters were used 2.1 x 10⁹ particles, electron cut off energy (ECUT) of 0.7 MeV, and photon cut off energy (PCUT) of 0.01 MeV. To investigate the physical full width at half maximum (FWHM) and penumbra width (80-20%), the single beam profiles and mean energy were obtained using BEAMnrc/BEAMDP code. Based on the results that there was an increase of the full width at half maximum (FWHM) with the size of the collimator on the beam profile and the mean energy. The FWHM of the energy fluence profile for the collimator sizes 4, 8, and 16 mm are 2.22, 3.90, and 7.80 mm, respectively. The FWHM of the fluence profile for the collimator sizes 4, 8, and 16 mm are 1.87, 3.87, and 7.80 mm. The FWHM of mean energy as a function of position for the collimator sizes 4, 8, and 16 mm are 2.56, 4.20, and 7.94 mm, respectively. The maximum mean energy for the collimators decreases as much as 0.0185 MeV.

1. Introduction
The Gamma Knife Perfexion™ (Elekta Oncology Systems) delivers a highly focussed dose of ionizing radiation from 192 Cobalt-60 radioactive sources. This technique is known as stereotactic radiosurgery (SRS), which is typically used to irradiate cranial tumours and functional abnormalities with high geometric precision while conserving normal tissue [1, 2]. The collimated beam from each source is focused on an isocentre, with a precision of better than 0.2 mm, making the Gamma Knife ideal for...
treating small targets close to critical structures [3]. A mechanical collimator system made of tungsten is organized into eight sectors of 24 beams that are spherically arranged around the isocentre.

The collimator system allows circular field sizes of 4, 8, or 16 mm diameter to be delivered. The resulting spherical dose distribution at the intersection of the radiation beams creates a region with steep dose gradients, providing precise coverage of the target volume while sparing nearby surrounding tissue. Patients are positioned so that the target volume is at the isocentre using a robotic couch, with the positioning accuracy being reported as better than 0.1 mm [4].

A number of Monte-Carlo studies of Cobalt-60 external beam radiotherapy systems have been performed using the EGSnrc Monte-Carlo system. The work of Han et al. concluded that the observed increase in output of the machine with increasing field size was caused by scattered photons from the primary definer and the adjustable collimator [5]. Mora et al. [6] modelled the famous Eldorado system and simulated narrow and broad Cobalt-60 beams using the EGS/BEAMnrc Monte Carlo code to calculate the relative air-kerma output factors as a function of field size. They showed that the variation of the output factor is almost entirely due to scattered photons from the fixed and adjustable collimators and that the influence of the geometry of the collimation system on the photon spectra on-axis is shown to be small but finite. Rogers et al. [7] describe BEAM, a general-purpose Monte Carlo user code to simulate the radiation beams from radiotherapy units, including high-energy electron and photon beams, Cobalt-60 beams and orthovoltage units. This simulation presents a variety of calculated results to demonstrate the code’s capabilities. The calculated dose distributions in a water phantom irradiated by electron beams from the NRC 35 MeV research accelerator, a Varian Clinac 2100C, a Philips SL 75-20, an AECL Therac 20 and a Scanditronix MM50 are all shown to be in good agreement with the measurement at the 2 to 3% level. Mahmoudi et al. [8] calculated the penumbra width of a single and all 201 beams for different collimator sizes of the Gamma Knife 4C using the EGSnrc/BEAMnrc codes. The results from this study showed that the ratio of the penumbra width to the field size decreases with increasing field size, which emphasizes the importance of penumbra in smaller field sizes.

In this current study, we investigate the use of Monte-Carlo simulation for modelling the source and collimator of a Gamma Knife Perfexion™ for the three collimator sizes of 4, 8, and 16 mm. Furthermore, because of the mechanical design of the collimator system, it is not possible to deliver a single beam from a single source, the simplest irradiation that can be delivered is a single sector using 24 sources. MC simulation, however, does allow the determination of the beam profiles and spectra of an individual source.

2. Materials and methods

The source geometry to be simulated is built up from a series of predefined BEAMnrc component modules (CMs). The CMs define the geometry of the source volume and the volume around the source. The Cobalt-60 source is cylindrical with a diameter of 1 mm, packed in stainless steel capsules, with a physical density (ρ) of 8.9 x10-3 Kg/m3. Capsules are made from materials with a composition of 0.67 Fe, 0.133 Ni, 0.2 Cr, and 0.012 Mo with a density of 7.95 x10-3 Kg/m3. The output of this simulation is stored in the scoring plane at a distance of 3.1 cm [9]. Furthermore, the phase space output at a distance of 3.1 cm is used as input to the simulation for each collimator. The collimator is designed to be 4 mm, 8 mm, and 16 mm in diameter, modelled just below the source. The collimator is also designed using the BEAMnrc. The size and compilation of the collimator materials are obtained from Elekta AB, with a binding confidential agreement. Figure 1 explains the form of the model used in this study.
Figure 1. Collimator simulation. (a) 16 mm diameter, (b) 8 mm diameter, and (c) 4 mm diameter.

The collimator is modelled using the FLATFILT component module of the BEAMnrc code [10]. The output of this simulation is stored in a phase space file at a scoring plane located 17.20 cm from the source. The scoring plane is circular in shape with a radius of 1.4 cm.

Figure 2. Source surface distance and scoring plane

The Electron cut off energy (ECUT) was 0.7 MeV, and photon cut off energy (PCUT) was 0.01 MeV. Each simulation used 2.1 x 10^9 gamma particle histories to achieve statistical uncertainties below 1%. The phase-space files contained the necessary information for the determination of the beam fluence profile and mean energy.

BEAMDP [11] was used to derive the energy fluence (MeV/cm^2/incident particle) and fluence (incident particle/cm^2) a function of lateral location across the scoring plane and also the mean energy of gammas as a function of lateral location across the scoring plane.

3. Result

The following characteristics of the Gamma Knife Perfexion™ collimated beams were derived from Monte-Carlo simulations of the Gamma Knife source and collimator system, 1) Full-width half maximum (FWHM) of the energy fluence profile and fluence profile across the collimated beam, and 2) Penumbral width of the collimated beam (80-20%).

3.1. Beam profile

The calculated energy fluence profiles for the three collimated field sizes of 4, 8, and 16 mm are shown in Figure 3.
Figure 3. Beam profile at 17.20 cm from the source

Figure 3 shows the characteristics of the energy fluence profile as a function of location across the scoring plane for the three collimator sizes. The FWHM with collimator size (4 mm, 8 mm, and 16 mm diameter) is 2.22 mm, 3.90 mm, and 7.80 mm. Penumbra width (80-20%) is 0.15 mm, 0.10 mm and 0.42 mm for each collimator.

Figure 4. Fluence profile for the three different field sizes

Figure 4 shows the characteristics of the particle fluence profile as a function of location across the scoring plane for the three collimator sizes. The value of the max fluence for each collimator (4 mm, 8 mm, and 16 mm) increases in proportion to the greater size of the collimator. The ratio is 44%, 48%, and 100%. The FWHM with collimator size is 1.87 mm, 3.87 mm, and 7.80 mm. Penumbra width (80-20%) 0.31 mm, 0.31 mm and 0.62 mm for each collimator.

3.2. Mean energy
The mean energy of the gamma’s as a function of lateral location across the scoring plane is shown in Figure 4 for the three collimator sizes.
5. Discussion

4.1. Beam profile
In Figures 3 and 4, there are two factors that influence the profiles, one is the energy of the gammas, and the other is a number of particles. All gammas begin with narrow energy with energies 1.17 MeV, and 1.33 MeV are produced, before interactions in the source, it’s encapsulation and scattering in the collimator reduce the gamma energy. The result is a broader spectrum of gamma energies. This phenomenon is causing the mean energy to decrease due to the scattered gammas with their lower energies. At a particular location on the scoring plane, there will be a primary fluence, gamma's that have travelled directly from the source (high energy) and scattered fluence (lower energy). The ratio of primary and scattered fluence will change with collimator size; primary fluence should be independent of collimator size as, by definition, it hasn't interacted with anything.

The FWHM of the profiles is, for the 4 mm diameter collimator is 2.22 mm, while for 8 mm collimator is 3.90, and 16 mm collimator is 7.80 mm.

The penumbral width (80-20%) in collimators with a diameter of 4 mm is 0.15 mm, while 8 mm is 0.16 mm, and 16 mm is 0.42 mm. The greater the collimator diameter, the greater the penumbral width (80-20%). Based on these results, it can be concluded that the penumbral width (80-20%) is influenced by the size of the collimator diameter. The increase in fluence energy is linear with the increase in collimator diameter size.

4.2 Mean energy
In Figure 5, it is shown that the mean energy of the smallest field (4 mm diameter) is highest, and the largest field (16 mm diameter) has the lowest mean energy, showing that more scattered photons with lower energies are included for larger fields. The horns in the curves are caused by the collimator effect (geometry and material of collimator). The collimator will serve as a source that generates more scattered photons with increasing field size, caused by the increased visible area of the collimator for

Figure 5. Mean energy at 17. 20 cm.
the photons to interact with. These photons are also more forward-directed than the scattered photons scored in the centre of the field. The horns in Figure 3.3 are the result of the photons scattered in small angles containing higher energies than photons scattered in large angles toward the centre of the field.

5. Conclusion
In this study, we presented investigating the impact of collimator size variation on the single beam radiation of Gamma Knife Perfexion™ based on Monte Carlo simulation. A model of the Gamma Knife Perfexion™ has been built using the Monte Carlo package BEAMnrc. The FWHM of the profiles is, for the 4 mm diameter collimator is 2.22 mm, while for 8 mm collimator is 3.90, and 16 mm collimator is 7.80 mm, and penumbra width (80-20%) is 0.15 mm, 0.10 mm and 0.42 mm for each collimator. The mean energy decreases in each collimator size of the as much as 0.0185 MeV.

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