Two Dimensional Verification of the Dose Distribution of Gamma Knife Model C using Monte Carlo Simulation with a Virtual Source

Tae-Hoon Kim[a], Hyun-Tai Chung[b,*], Yong-Kyun Kim[a], Cheol Ho Lee[a], Jaebum Son[a], Sangmin Lee[a], Dong Geon Kim[a], Joonbum Choi[a], Jae Yeong Jang[a]
[a] *Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul(04763), Korea*
[b] *Department of Neurosurgery, Seoul National University College of Medicine, 101 Daehang-no Jongno-gu, Seoul (03080), Korea*
[*] *Corresponding author: htchung@snu.ac.kr*

1. Introduction

The LekSell Gamma Knife® (GK, Elekta AB, Stockholm, Sweden) is a minimally-invasive stereotactic radiosurgery (SRS) device that delivers lethal radiation to intracranial lesions by directing many collimated ^{60}Co gamma rays to a single focal point [1]. Gamma Knife model C contains 201 ^{60}Co sources located on a spherical surface, so that each beam is concentrated on the center of the sphere.

In the last work, we simulated the Gamma Knife model C through Monte Carlo simulation code using Geant4 [2]. Instead of 201 multi-collimation system, we made one single collimation system that collects source parameter passing through the collimator helmet. Using the virtual source, we drastically reduced the simulation time to transport 201 gamma circle beams to the target.

To confirm the validity of simulation using the virtual source method, we implement 2-D dose comparison using a gamma index method which was introduced by Low et al [3]. Gamma index has been widely used to compare two dose distributions in cancer radiotherapy. Gamma index pass rates were compared in two calculated results using the virtual source method and the original method and measured results obtained using radiocrhomic films.

2. Methods

In the original simulation system using Geant 4.10, we prepared a beam transport system along a single direction and rotated it to the 201 angles which are defined as the source direction of the Gamma Knife Model C. Because we neglected simultaneous decays of the source and simulated photons one by one, this serial rotation along 201 directions is equivalent to the single set of 201 sources.

The virtual source file, i.e, a phase space file, was obtained by accumulating the particles passing through a spherical shell of inner radius 8 cm and thickness 0.1 mm around the center of a Gamma Knife. Just like the original method, the phase space file was obtained only in a single direction. When we generated a particle from the virtual source, firstly we read a particle type, energy, and direction from the phase space file, and secondly rotated the particle along a randomly chosen direction of the Gamma Knife sources as shown in Figure 1.

The dose distributions in the XY-plane of an 18 mm collimator of a Gamma Knife Model C were obtained by calculating energies obtained in small voxels of $0.508 \times 0.508 \times 0.508$ mm^3 at the center of a sphere of water of radius 8 cm.

In order to measure the dose distribution in the XY-plane, we set a GafChromic MD-V3 film at the center of a commercial solid water phantom (Elekta AB, Stockholm, Sweden) and irradiated it up to 60 Gy at the maximum point. The irradiated films were scanned and analyzed along a standard film handling procedure [1].

In order to compare two 2-D dose distributions, Gamma index method was used. Gamma index pass rate is an index that represents how the two distributions are equivalent. The gamma value is obtained by using the equation (1) [5].

$$\Gamma(\vec{r}_e, \vec{r}_r) = \sqrt{\frac{\delta^2(\vec{r}_e,\vec{r}_r)}{\Delta D^2} + \frac{r^2(\vec{r}_e,\vec{r}_r)}{\Delta d^2}} \quad (1)$$

where $\vec{r}_e$, $\vec{r}_r$ is evaluated and reference positions. ΔD, Δd is dose difference criterion and DTA criterion. The δ value means the dose difference between evaluated position and reference position and the r value means the spatial distance between evaluated and reference dose points. To find the Gamma index for one reference pixel, this number had to be computed in all surrounding calculated pixels. Then the lowest value

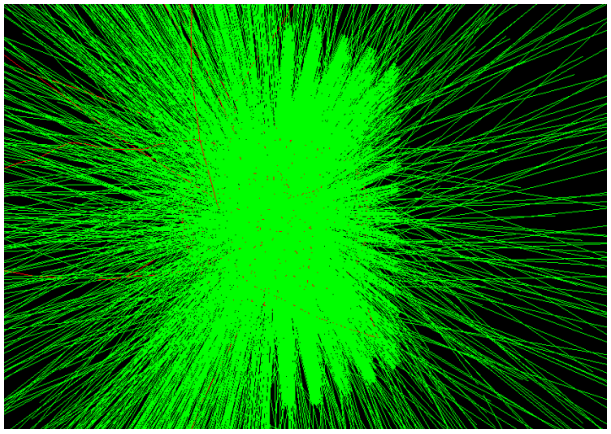

Fig. 1. Simulation with virtual sources rotating 201. directions randomly. Green line represents gamma particle track history, Red line means secondary electron

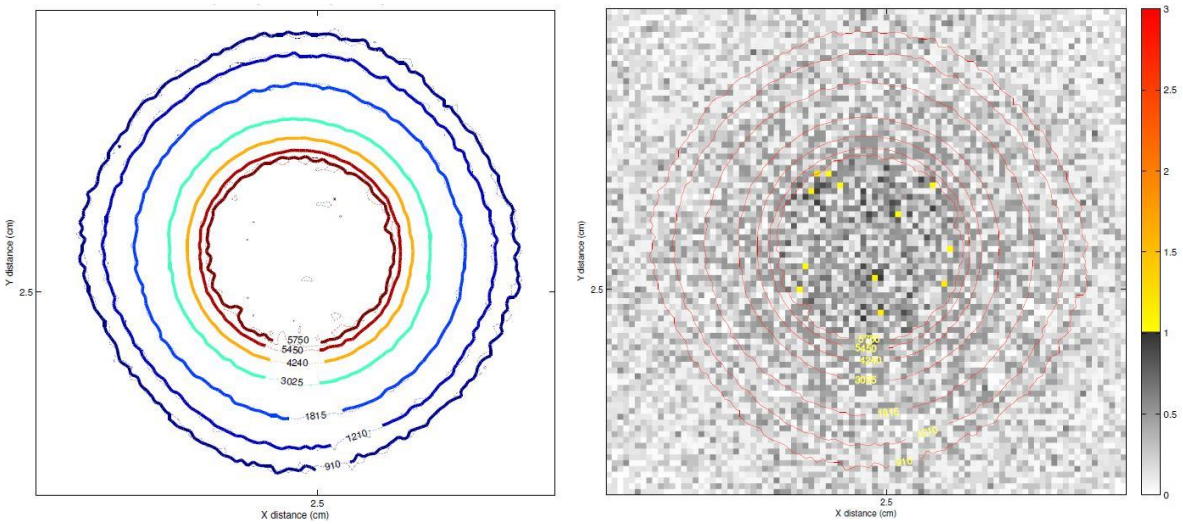

Fig 2. Comparison of 2-D dose distribution with simulation using the virtual source method (thick solid) and using the original method (thin dashed) contours at the centor of the 8cm water phantom (left). Gamma index distribution with 99.7% passrate using DTA/Dose difference criteria of 1mm/3% (right). Gray color of Gamma index distribution means Gamma value in less than <1.

surrounding reference pixel sets the Gamma index. In the each pixel, Gamma index is set and the measured pixel would "pass" the gamma evaluation if it is 1 or less. For ordinary intensity modulated radiation therapy, using the standard quality assurance of 3mm/3% (DTA/Dose difference criteria) Gamma Index shows ordinary pass rates of 90% for a given treatment plan [4].

3. Results

We compared the iso-dose lines of the two calculated dose distributions, the original method and the virtual source method, as given in Figure 2. The simulation with original method was implemented by 14 billion photons and the simulation with the virtual source method was implemented by generating 2 billion virtual source particles at collimator positions that corresponds to 44 billion original photons. Two simulations were normalized on the basis of the radiochromic film before the comparison. The average dose value of the radiochromic film is 59.1 Gy in 1cm×1cm at the center of the film. The Gamma Index pass rate between the two calculated dose distribution was 99.7% using DTA/Dose difference criteria 1mm/3%. The Gamma Index pass rate between the dose distribution of the simulation using virtual sources and radiochromic film was 93.8% using DTA/Dose difference criteria 1mm/3%.

4. Conclusions

A virtual source method significantly reduces simulation time of a Gamma Knife Model C and provides equivalent absorbed dose distributions as that of the original method showing Gamma Index pass rate close to 100% under 1mm/3% criteria. On the other hand, it gives a little narrow dose distribution compared to the film measurement showing Gamma Index pass rate of 94%. More accurate and sophisticated examination on the accuracy of the simulation and film measurement is necessary.

REFERENCES

[1] Jae Pil Chung, SeWoon Oh, Young Min Seong, Kook Jin Chun, Hyun-Tai Chung, An effective calibration technique for radiochromic films using a single-shot dose distribution in Gamma Knife® , Physica Medica 32 368–378, 2016.
[2] Tae-Hoon Kim, Hyun-Tai Chung, Yong-Kyun Kim, A virtual source method for Monte Carlo simulation of Gamma Knife Model C, Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, 0309-141, May 12-13 2016.
[3] Xuejun Gu, Xun Jia, and Steve B. Jiang, GPU-based fast gamma index calculation, Physics in Medicine and Biology
[4] Heng Li, Lei Dong, Lifei Zhang, James N. Yang, Michael T. Gillin, and X. Ronald Zhu, Toward a better understanding of the gamma index: Investigation of parameters with a surface-based distance method, Medical Physics, Vol. 38, No. 12, December 2011
[5] MOBIUS MEDICAL SYSTEMS, LP, DOSELAP User Manual, Version 6.7.0 Rev 1.0, AUGUST 19, 2015