Monte Carlo N-Particle Transport Code Simulation of Leksell Gamma Knife Using Disk Sources of Polystyrene, PMMA, Plastic Water and Head Phantom

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Stereotactic Radiosurgery (SRS) has become a standard modality for the treatment of benign and metastatic brain lesions that were deemed medically unsuitable for surgery. The Leksell Gamma Knife (LGK), a type of SRS that was used in this study, has 201 Cobalt-60 sources distributed in a hemisphere whose radiation intersects at the isocenter. The relative dose at the isocenter was verified using Monte Carlo N-Particle Simulation (MCNP). This study uses disk sources, an alternative for the full geometry collimator system of the LGK, to simulate a 160-mm water phantom made of different materials: polystyrene, plastic water, and PMMA (Polymethyl methacrylate). In addition, the simulation of a head phantom was also included in this study. Relative dose distributions were calculated and were compared to the relative dose distributions from the cited literatures. As a result, no significant differences have been found. In conclusion, the use of disk sources provides a simpler method of simulating the LGK instead of using the full geometry collimator system in the MCNP Visual Editor.

INTRODUCTION

Stereotactic Radiosurgery (SRS) is one of the treatment modalities used to treat benign and metastatic brain lesions. It is a specialized technique where a uniform dose, with highly conformal radiation, is delivered to the target.

The type of SRS that was used in this study was the Leksell Gamma Knife (LGK). LGK was developed by Swedish neurosurgeon Lars Leksell and Physicist Borje Larson. The LGK, manufactured by Elekta Instruments Inc., uses 201 Co-60 sources distributed on a hemisphere. The diameter of the beams of the ionizing radiation was defined by the collimator system and the shape of the target can be varied by changing the size of the collimator helmets: 4 mm, 8 mm, 14 mm and 18 mm.

The Co-60 sources are arranged on a hemispherical surface with a radius of 400 mm. These sources are represented by a set of 12 to 20 Co-60 pellets that are cylindrical in shape with 1 mm diameter and 1 mm length distributed along a five radii separated by an angle of 7.5 degrees (Trnka & Kluson 2006). In this study, the Co-60 sources are represented as disk sources with its energy set to 1.25 MeV, the average of the two gamma energies that Co-60 emits.

MCNP is a powerful tool to calculate dose given by LGK. From the study of Yipeng, the possibility of modeling the sources of LGK as a point and disk sources was explored.

Key words: External beam radiotherapy, Leksell Gamma Knife, MCNP, relative dose distribution, treatment planning

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The main goal of this study was to obtain and determine the relative dose distribution using disk sources for the LGK. The internal geometry of collimator system consists of cylinders and cones, in order to simplify this in MCNP, a disk source was used to represent the Co-60 sources and its collimator system. The validation of the disk source simulation was done by creating and comparing the relative dose distribution at the center of the phantom with published results. The study considered the photons as parallel beams with uniform distribution that was emitted perpendicularly from the 201 disk sources. These disks sources correspond to the diameter of the outer aperture of the collimator helmet. In the simulation of the disk sources, a 160-mm water phantom, 160-mm water phantom made of different materials and head phantom were used. The resulting relative dose distributions in the x-, y- and z-axes were studied and compared to other publications (Trnka & Kluson 2006; Moskvin et. al 2002).

The location of the 201 sources, represented by a point, where first simulated to validate the position of the 201 sources (Cheung & Yu 2006). The point sources were arranged in a hemispherical surface with a radius of 400 mm. The sources are distributed along five radii separated by an angle of 7.5 degrees (Trnka & Kluson 2006).

The coordinates of the 201 sources were used to determine the direction of the particles biased towards the center of the phantom. The directions of the particles were calculated using direction cosines. The simulation of the 201 point sources contains a fewer specifications in the source definition (SDEF) card of MCNP.

After the verification of the location and direction of the 201 point sources, disk sources were simulated. The energy of the disk source was set to 1.25 MeV. This energy is the average of the two gamma energies that Co-60 emits. A figure of the adapted geometry for disk sources is presented in Figure 1.

The simulation of the 201 disk sources has a similar SDEF card with the simulation of point sources except for the addition of “RAD” in the SDEF card of the disk sources. “RAD” was used to specify the different collimator sizes of the collimator system: 2.5 mm outer aperture was used in a 4 mm collimator helmet, 5.0 mm for 8 mm, 8.5 mm for 14 mm, and 10.6 mm for 18 mm (Moskvin et al. 2002). Different diameter of the disk sources corresponds to the different collimator sizes of LGK which are 4 mm, 8 mm, 14 mm and 18 mm. Table 1 summarizes the SDEF card for the simulation using point and disk sources.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
<th>Point Sources</th>
<th>Disk Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>“POS”</td>
<td>Location of the 201 sources</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>“ERG”</td>
<td>Set to 1.25 MeV, the average of the energies that the Co-60 emits</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>“DIR”</td>
<td>Set to 1, the particles are emitted in one side of the source (towards the center of the phantom)</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>“VEC”</td>
<td>Direction cosines of the coordinates of the sources</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>“RAD”</td>
<td>The outer aperture of the collimator of LGK</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>
All simulations for the different materials using disk sources have the same SDEF card and the upper energy limit for detailed photon physics treatment set to 2 MeV, photons will not produce electrons, no occurrence of coherent scattering, no photonuclear collisions and Doppler energy broadening will not occur. The number of particles to be plotted was set to $2.01 \times 10^8$ particles.

The relative dose distributions were generated by placing spherical detectors of radius 0.1 mm at the x-, y- and z-axis of all the phantoms. *F8 tally was used according to equation 1 to convert the energy deposited to dose in rad. The energy deposited is divided by the mass and then multiplied to a constant, $1.602 \times 10^{-8}$. The constant was used for the easier conversion of MeV (energy deposited) to dose in rad (Shultis et al. 2004).

$$Dose(\text{rad}) = \frac{\text{F8 tally}}{\text{mass}} \times 1.602 \times 10^{-8} \quad \text{Equation 1}$$

The doses obtained from the simulations were used to calculate for the relative dose distribution along x-, y-, and z-axes by means of equation 2.

$$\text{Relative dose} = \frac{\text{Dose in each detector}}{\text{Maximum dose}} \quad \text{Equation 2}$$

RESULTS

Figure 2 shows that the highest dose obtained in the verification step of the simulation, checking the correct positioning of the 201 point sources, is obtained at the center of the phantom.

After the verification of the location and direction of the 201 point sources, disk sources were then simulated. The relative dose obtained for 4 mm and 18 mm collimator helmet are presented in Figure 3. The scattered radiation increases as the diameter of the collimator increases.

To determine the relative dose for different materials, head phantom was also simulated. Figure 4 shows the relative dose of head phantom for 4 mm and 18 mm collimator helmet.

DISCUSSION AND CONCLUSION

The simulation of 201 point sources verifies that the location and direction of the particles in the MCNP simulation was correct. The highest dose was found to be at the center of the phantom (Fig. 1). This is in line with the relative dose seen in literatures (Cheung & Yu 2006; Moskvn et al. 2002; Xiong et al. 2007).

The resulting relative dose distributions using disk sources
for different phantom materials were used to compare with other studies (Cheung 2006; Trnka & Kluson 2006; Moskvin 2002; Xiong 2007). It was confirmed that our results were similar to the results of other studies where the highest dose obtained from the simulation were at the center of the phantom. For 4, 8, 14 and 18 mm collimator, the area of significant dose increases as the collimator sizes increases (Fig. 3a and 3b).

The presence of scattered radiation also increases as the diameter of the collimator helmet increases (Fig. 4). No scattered photons contribution higher than 20% of the maximum relative dose in the region of interest for the head phantom has been observed. This is due to the geometry construction of the head phantom in the MCNP visual editor. However, the results for the simulation of the head phantom showed that no observable differences can be observed in the simulation results with respect to the water phantom, as reported in the results (Zhu 2011).

The good agreement among the Monte Carlo simulations done in this study of different phantom materials is expressed by having the same region of highest dose. The results prove that the disk sources simulation was capable of simulating the LGK Co-60 sources and that these results hold for the materials used in this study. In this work, MCNP simulation using disk sources has been successfully implemented.

In conclusion, the simulation of LGK using disk sources provides a simpler method in obtaining and calculating the relative dose distributions for water phantoms with 1 cm thick shell made of different materials and head phantom, with the highest dose at the center of each phantom.

REFERENCES


