INTRODUCTION

Leksell GammaPlan® is a powerful computer-based dose planning system specifically designed for the simulation and planning of stereotactic Leksell Gamma Knife® radiosurgery based on tomographic and projection images. The Leksell Gamma Knife is a device for radiosurgery for brain lesions. It directs beams of cobalt-60 gamma radiation to a specific region, to treat patients whose brain tumors or lesions are so deeply buried that conventional surgery is not possible. In a single session, 201 separate converging beams of ionizing radiation are directed to the targeted lesion with an accuracy of better than 0.3 mm.1 This “cross firing” results in radiation dose being delivered to the point of interest with sparing of the adjacent normal brain tissues. The diameter of the gamma beams is confined by collimator systems and the size and shape of the target can be varied by the exchange of collimator helmets. Standard collimator sizes are 4, 8, 14, and 18 mm.

The total dose contributions to a point within a patient’s skull are the sum of dose contributions from the 201 sources.2 For each individual beam, the dose calculation at the point of interest requires definition of the patient’s skull configuration, the linear attenuation coefficient of Co-60 gamma rays in the skull, the transverse radiation dose profile (single-beam dose profile), and the dose rate at the reference point in a tissue equivalent phantom.3 Wu et al.4 verified the single-beam dose profiles experimentally. He blocked all but one collimator of the helmet. A piece of radiographic film was inserted in a special polystyrene cassette and placed at the center of an 8 cm radius spherical phantom to simulate the human skull. The film was irradiated and final results were obtained by subtraction of the radiation leakage from the 200 plugs. The single-beam dose profiles were measured using a scanning densitometer with a 1 mm aperture. However, such a method may not give accurate results, particularly in the regions of low relative percentage dose having low optical density. In our study, idealized experiments were performed using the Monte Carlo technique to verify the single-beam dose profiles provided by Elekta.

METHODS

The Monte Carlo system employed was the PRESTA (Parameter Reduced Electron-Step Transport Algorithm) version of the EGS4 (Electron Gamma Shower) computer code. Detailed descriptions on the structure of the EGS4 code can be found from Jenkins et al.5 For the simulation, the patient’s head was modeled by a water phantom 160 mm in diameter.

Each one of the 201 sources located in the radiation unit is composed of 20 Co-60 pellets 1 mm in diameter and 1 mm in length. Each source was therefore modelled by a cylinder 1 mm in diameter and 20 mm in length. The Co-60 source was positioned at a distance of 400 mm from the center of the phantom. The radiation beam passed through the opening of the collimators to the target point. The diameters of the
radiation beams at the focus were confined by the size of collimators. The modelled collimators gave the beam diameters of 4, 8, 14, and 18 mm at the focus.

Concentric cylinders were created as scoring bins around the center of the spherical phantom. The radial resolution of the scoring bins was 0.5 mm for the cases using 14 and 18 mm collimators and 0.25 mm for the cases using 4 and 8 mm collimators. The height of the scoring bins was 1 mm for the cases using 14 and 18 mm collimators and 0.5 mm for the cases using 4 and 8 mm collimators.

A total of $5 \times 10^7$ histories were performed for the cases using the 8 and 18 mm collimators, while $1.5 \times 10^7$ and $3.1 \times 10^7$ histories were performed for the cases using 4 and 14 mm collimators, respectively. All history runs were divided into 10 batches for calculation of statistics. The standard errors at dose maxima were all less than 1%. All simulations were performed using Pentium-133 PCs and compiled by the MS PowerStation FORTRAN Compiler version 4.0 working under the MS Windows 95. On average, the computational time took about 24 h for $2.5 \times 10^6$ histories.

The photon spectrum of Co-60 was taken from Amersham, containing two peaks, viz. 1.173 and 1.333 MeV. The threshold energies for discrete electron collision losses (AE) and radiation loss (AP) were set to 0.512 and 0.001 MeV, respectively. The cutoff energies for electrons (ECUT) and photons (PCUT) were set to 0.521 and 0.01 MeV, respectively. Lowering the values of the cutoff energies caused no difference in the calculated results. The employment of PRESTA in the simulation made the EGS4 Monte Carlo code select a suitable step length dynamically, which enabled fast simulation while still providing accurate physics. The latest collision and radiative stopping powers of ICRU 37$^{8-10}$ were employed in the EGS4 (pre-processor of EGS4) data file.$^{11}$ To avoid breaking down of the assumption about multiple scattering dominance for narrow beams, an improved bremsstrahlung photon angular sampling accompanied by a variance reduction technique of bremsstrahlung splitting$^{12}$ was used in the EGS4 code system. For more reliable results, Rayleigh scattering and photoelectrons angle selection$^{13}$ were turned on in all simulations. Since all simulations required a large number of history runs, the long sequence random number generator of James$^{14}$ was used. The random number sequences have a length of about $10^{43}$, effectively infinite for our calculations, and there are about $10^9$ independent sequences that can be selected from initial conditions.

RESULTS AND CONCLUSION

Figures 1–4 show the comparison results between the single-beam dose profiles of different collimator sizes pro-
vided by Elekta and those calculated by the Monte Carlo method. The Monte Carlo results were normalized with the Elekta profiles at the region of dose maximum. According to Wu et al., the dimensions of the 50% isodose or full-width-at-half-maximum (FWHMs) are 4.0, 8.4, 14.0, and 18.0 mm for the 4, 8, 14, and 18 mm collimator helmets, respectively. The Monte Carlo results were essentially consistent with these data. The profiles from Elekta GammaPlan were excellently consistent with the Monte Carlo results for the 4, 14, and 18 mm collimators. The maximum discrepancy was less than 3% at all radial distances. For the 8 mm collimator, the maximum discrepancy was 8% in relative dose in the radial distance range from 4.3 mm to 5.2 mm.

We calculated the dose profiles along x, y, and z axes for all four collimator sizes, using the Monte Carlo results, by summing over all 201 sources at different directions. Excellent agreements were observed between the cases using the Elekta default and the calculated Monte Carlo results for all collimator helmets, except for the 8 mm collimator helmet along z axis. Figure 5 shows the results summing over all 201 beams for the 8 mm collimator helmet along the z axis. Although such differences may be too small to give a clinical significance in Gamma Knife radiosurgery, these results can serve as references to all Gamma Knife physicists in the world.

Fig. 5. Comparisons of dose profiles for the 8 mm collimator helmet along the z axis (summing over all 201 sources), using the Elekta default and the Monte Carlo results.