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Dose distributions at extreme irradiation depths of gamma knife radiosurgery: EGS4 Monte Carlo calculations

J.Y.C. Cheung[a,b], K.N. Yu[b,*], C.P. Yu[a], R.T.K. Ho[a]

[a]Gamma Knife Centre (HK), Canossa Hospital, 1 Old Peak Road, Hong Kong, People's Republic of China
[b]Department of Physics and Materials Science, City Uiversity of Hong Kong, Tat Chee Avenue, Kowloon Tong, Kowloon, Hong Kong, People's Republic of China

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Abstract

The accuracy of the dose planning system (Leksell GammaPlan), used in Gamma Knife (type B) radiosurgery at extreme irradiation depths, was verified using the Monte Carlo technique. EGS4 Monte Carlo calculations were employed to calculate the dose distribution along the x, y and z axes for an irradiation relatively shallow in a spherical bony cavity water phantom. Two different sizes of the collimator helmets, 8 and 18 mm, of the Leksell Gamma Knife Unit were studied. The results of GammaPlan showed good consistency with the Monte Carlo results. Furthermore, small dose enhancements were observed in the skull bone where accurate dose measurements are difficult due to the presence of the air–phantom interface. Therefore, the results of this project can promote confidence to all Gamma Knife centres in the world when using the Leksell GammaPlan.

Keywords: Gamma knife; GammaPlan; Monte Carlo

1. Introduction

Stereotactic radiosurgery with the Leksell Gamma Knife is a non-invasive intracranial technique based on principles of the Leksell Stereotactic System for open deep brain surgery, invented and developed by Professor Lars Leksell. Gamma Knife radiosurgery allows precise external irradiation with a high dose and a sharp dose gradient to minimize the irradiation imparted to adjacent surrounding critical brain structures. In a single session, 201 separate converging beams of ionizing radiation are directed to the targeted lesion with an accuracy better than 0.3 mm (Elekta, 1992). The diameter of the gamma beams is defined by the collimator system and the size and the shape of the target can be varied by the exchange of collimator helmets. Standard collimator sizes are 4, 8, 14, and 18 mm.

Leksell GammaPlan is a powerful computer-based dose planning system specifically designed for the simulation and planning of stereotactic Leksell Gamma Knife radiosurgery and it is based on tomographical and projectional images, such as CT-scans, MR-scans, conventional X-ray or angiography. Dose calculations by the Leksell GammaPlan are based on interpolated empirical data (Elekta, 1996; Wu, 1992; Wu et al., 1990). Superposition of radiation distri-

* Corresponding author. Tel.: +852-2788-7812; fax: +852-2788-7830.
E-mail address: peter.yu@city.edu.hk (K.N. Yu).

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butions of all 201 gamma beams is used to calculate the dose at any point within the patient's skull. The dose contributed by an individual beam depends on the inverse square law, linear attenuation exponential formula and single beam profiles for gamma beams with different diameter.

In our study, an accurate Monte Carlo method is employed as an investigation tool to verify the results of GammaPlan at irradiation positions. Comparisons of dose distributions between GammaPlan and measurements at extreme positions were not reported by workers in previous studies.

2. Methodology

The Monte Carlo system employed is the PRESTA (Parameter Reduced Electron-Step Transport Algorithm) version of the EGS4 (Electron Gamma Shower) computer code. Detailed descriptions on the structure

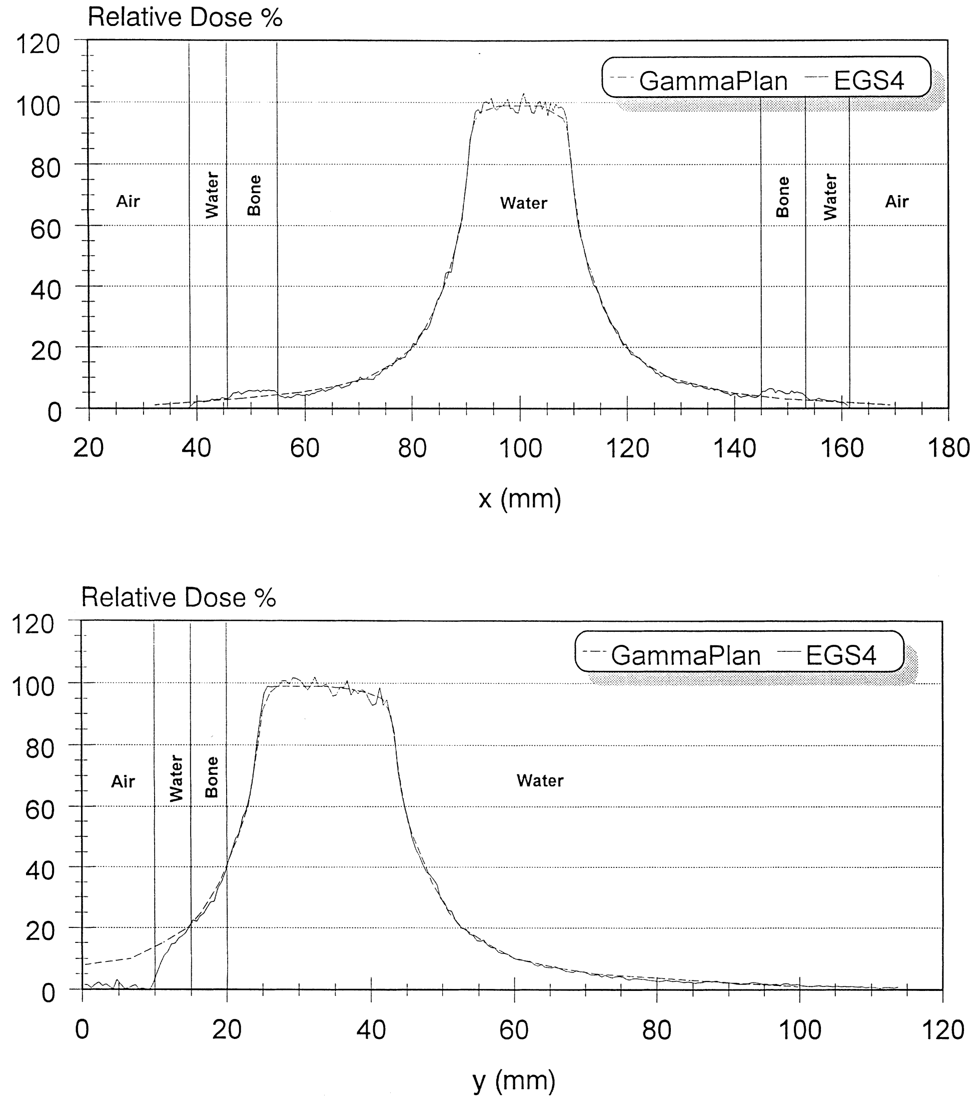

Fig. 1. (a) Comparison of the relative dose vs. x-axis between GammaPlan and EGS4 Monte Carlo when using 18-mm collimator helmet at position (100, 34, 100). (b) Comparison of the relative dose vs. y-axis between GammaPlan and EGS4 Monte Carlo when using 18-mm collimator helmet at position (100, 34, 100). (c) Comparison of the relative dose vs. z-axis between GammaPlan and EGS4 Monte Carlo when using 18-mm collimator helmet at position (100, 34, 100).

of the EGS4 code can be found from Jenkins et al. (1988). For the simulation, the patient's head was modeled by a spherical bony cavity water phantom. The skull bone, density 1.85 g/cm^3, was 5 mm in thickness and was 5 mm below the surface of the phantom. The diameter of the overall phantom was 180 mm.

Each 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, modeled by a cylinder 1 mm in diameter and 20 mm in length.

The Co-60 sources are arranged in a sector of a hemispherical surface with a radius of about 400 mm. They are distributed along five parallel circles separated from each other by an angle of 7.5° (Elekta, 1992). The 201 radiation beams pass through the opening of the collimators to the target point. The diameters of the radiation beams at the focus are confined by the size of the collimator.

User defined scoring bins with dimensions 0.5 mm $\times 1$ mm $\times$ 1 mm were made along the x, y and z axes for the 18-mm collimator helmet. For the 8 mm collimator helmet, the dimensions of the scoring bins were 0.25 mm $\times$ 0.5 mm $\times$ 0.5 mm. All scoring bins were faced tangential to the isodose distribution curves.

A total of 1.5×10^8 histories were acquired for the 8 and 18-mm collimator helmets. All history runs were divided into 30 batches for calculations of statistics and were large enough to give a standard error of less than 2% at the dose maximum region. The photon spectrum of Co-60 was taken from Amersham (Medical Radiation Sources Catalogue, 1982), containing two peaks, viz. 1.173 and 1.333 MeV. The cutoff energies for electrons and photons were set to be 0.521 and 0.01 MeV, respectively. Lowering the value of these cutoff energies resulted in no differences in the dose distributions. The latest collision and radiative stopping powers of ICRU 37 (ICRU, 1984; Duane et al., 1989; Rogers et al., 1989) were employed in the PEGS4 (pre-processor of EGS4) data file (Nelson, 1989). Rayleigh scattering was turned on in all simulations. Since all simulations required a huge number of history runs, a long sequence random number generators of James (1988) was used. This random number possesses a sequence length of about 10^{43}, effectively infinite for our calculation, and has about 10^9 independent sequences that can be selected from initial conditions.

In this project, single irradiations using collimator helmets 8 mm and 18 mm were delivered at relatively shallow positions. The coordinates were (100, 29, 100) and (100, 100, 25) for the 8-mm collimator helmet, (100, 34, 100) and (100, 100, 31) for the 18-mm collimator helmet. The dose distributions along the x, y and z axes of the target point are calculated using the Monte Carlo technique and the results are compared with those generated by GammaPlan.

3. Results

Fig. 1 (a–c) show the results of the relative dose against the x, y and z axes, respectively using the 18-mm collimator helmet at position (100,34,100), while

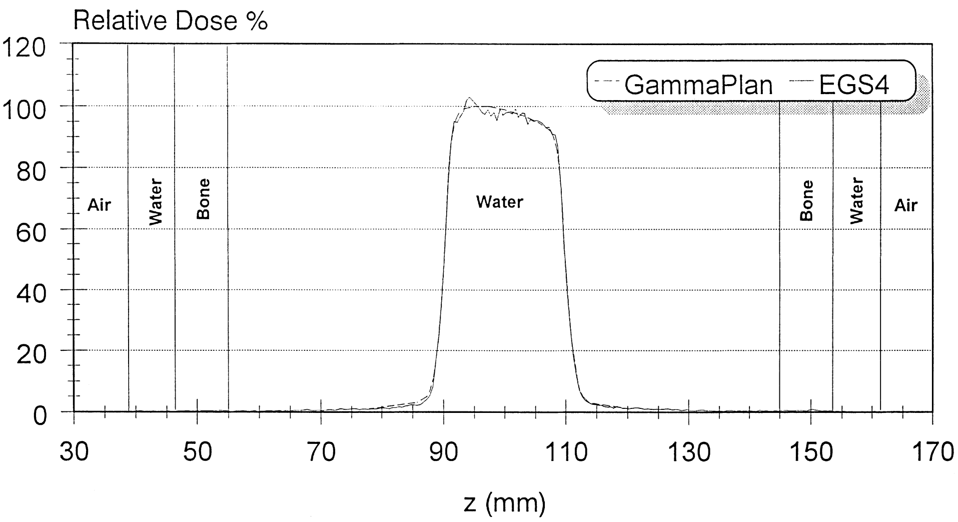

Fig. 1 (*continued*).

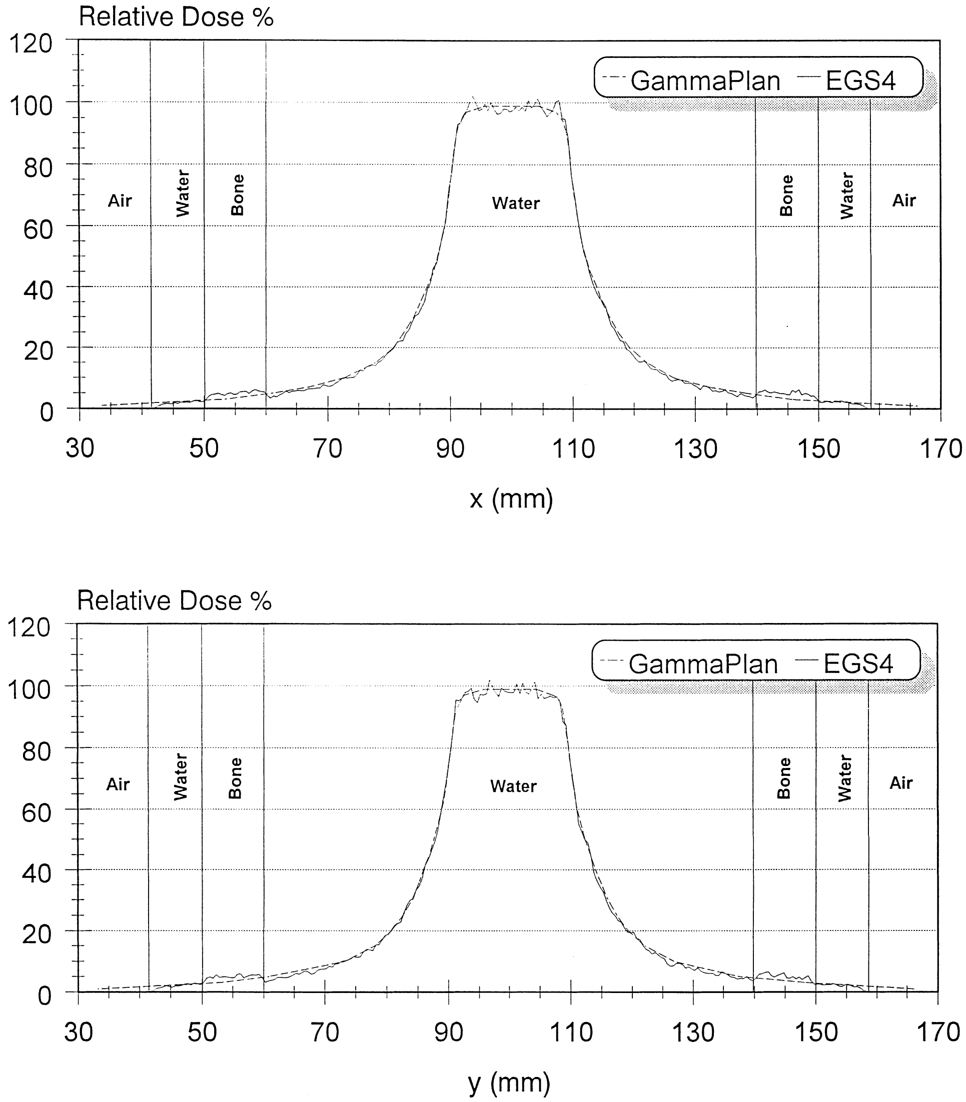

Fig. 2. Comparison of the relative dose vs. x-axis between GammaPlan and EGS4 Monte Carlo when using 18-mm collimator helmet at position (100, 100, 31). (b) Comparison of the relative dose vs. y-axis between GammaPlan and EGS4 Monte Carlo when using 18-mm collimator helmet at position (100, 100, 31). (c) Comparison of the relative dose versus z-axis between GammaPlan and EGS4 Monte Carlo when using 18-mm collimator helmet at position (100, 100, 31).

Fig. 2(a–c) show the corresponding at position (100, 100, 31). Similar results were obtained using the 8-mm collimator helmet. There is a good agreement between the GammaPlan results and the Monte Carlo results. Small dose enhancements were observed in the skull bone for the Monte Carlo results. However, no significant dose enhancement was noticed at the skull bone in Fig. 1(b), where the isocenter was closed to the skull bone, and therefore, beam attenuation becomes dominant over scattering.

According to the quality assurance program on stereotactic radiosurgery (Hartmann, 1995), the output of the computerized treatment planning needs to be verified by measurement. The experimental and the hypothetical dose distribution normalized to dose maximum are compared by measuring the width at the

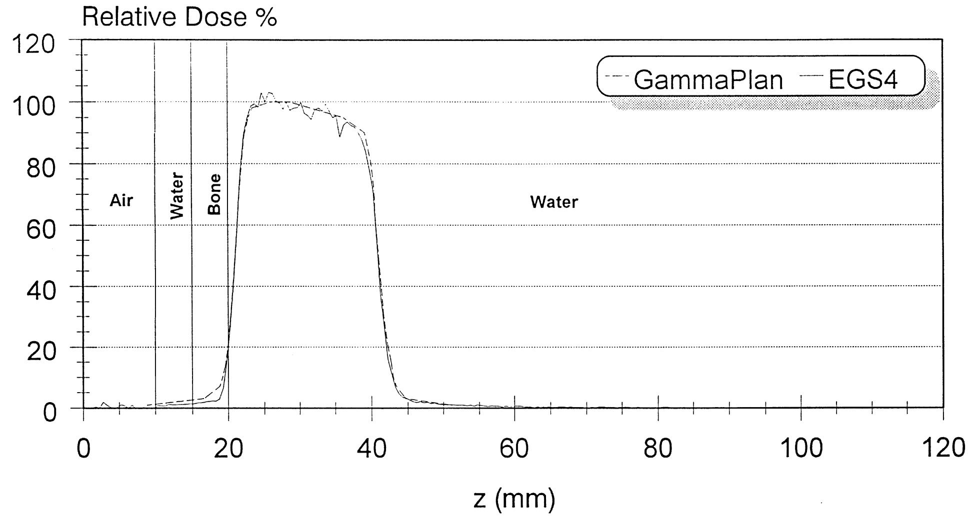

Fig. 2 (*continued*).

50% level. The measured width must agree within 1 mm with that of the corresponding calculated profile.

In our findings, the width at the 50% level agrees well within 1 mm with the results of Monte Carlo and GammaPlan even at extreme shot positions.

4. Conclusions

Monte Carlo simulations have successfully verified the performance of GammaPlan under relatively extreme conditions, providing a firm foundation for clinical use of the software.

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References

Duane, S., Bielajew, A.F., Rogers, D.W.O., 1989. Use of ICRU-37/NBS collision stopping power in the EGS4 system. National Research Council of Canada Report PIRS-0173.

Elekta, L., 1992. Gamma Unit: User's Manual 1. Elekta.

Elekta, L., 1996. GammaPlan instructions for use for version 4.0 — target series. Elekta.

Hartmann, G.H., 1995. Quality assurance program on stereotactic radiosurgery — report from a quality assurance task group. Springer.

ICRU, 1984. Stopping Powers for Electrons and Positrons, Report No. 37. U.S. Government Printing Office, Washington, DC.

James, F., 1988. A review of pseudorandom number generators. CERN-Date Handling Division, Report DD/88/22.

Jenkins, T.M., Nelson, W.R., Rindi, A., 1988. Monte Carlo Transport of Electrons and Photons. Plenum, New York.

Medical Radiation Sources Catalogue, 1982. Amersham International Ltd., Buckinghamshire.

Nelson, W.R., 1989. Lecture-9 on PEGS4: datasets for different media. In: Course on Electron and Photon Transport Using the EGS4 Monte Carlo System, 25–28 September. National Physical Laboratory, Teddington, UK.

Rogers, D.W.O., Duane, S., Bielajew, A.F., 1989. Use of ICRU-37/NBS radiative stopping power in the EGS4 system. National Research Council of Canada Report PIRS-0177.

Wu, A., 1992. Physics and dosimetry of the gamma knife. Neurosurgery Clinics of North America 3, 35–50.

Wu, A., Lindner, G., Maitz, A.H., Kalend, A.M., Lunsford, L.D., Flickinger, J.C., Bloomer, W.D., 1990. Physics of gamma knife approach on convergent beams in stereotactic radiosurgery. Int. J. Radiat. Oncol. Biol. Phys. 18, 941–950.