Monte Carlo calculations and GafChromic film measurements for plugged collimator helmets of Leksell Gamma Knife unit

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The Monte Carlo technique and GafChromic films were employed to verify the accuracy of the dose planning system (Leksell GammaPlan®) used in Gamma Knife (type B) radiosurgery when plugged collimator helmets were used. The EGS4 Monte Carlo code was used to calculate the dose distribution along the x, y, and z axes when a single shot was delivered at the center point (unit center point: x = 100, y = 100, z = 100) of a spherical polystyrene phantom, with gamma angle of 90°. Two different sizes of the plugged collimator helmets, 4 and 18 mm, were studied. Two typical plugged patterns, 51 plugs and 99 plugs along the y direction, were examined. The results of our Monte Carlo trials showed good consistency with GammaPlan calculations and GafChromic film measurements. Furthermore, the Monte Carlo results showed that radiation leakage from the plugs was too small to affect the overall isodose curve distribution even when the heavily plugged pattern of up to 99 plugs was employed. The results of this project provide confidence to all Gamma Knife centers using the Leksell GammaPlan treatment planning system. © 1999 American Association of Physicists in Medicine. [S0094-2405(99)02207-5]

Key words: Gamma Knife, GammaPlan, plug pattern, Monte Carlo, GafChromic film

I. INTRODUCTION

Stereotactic radiosurgery with the Leksell Gamma Knife® is a closed intracranial surgery based on the 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 high dose and a sharp dose gradient to minimize radiation doses given to adjacent 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.1 The diameter of the gamma beams is defined by a system of collimator arrays. The size and shape of the delivered dose distribution can be varied by combining and/or exchanging these collimator helmets. Standard collimator sizes are 4, 8, 14, and 18 mm. Some critical structures, such as the brain stem, intracranial nerves, and optic lenses can be protected by modifying the shape of the isodose distribution curves. Such modifications are implemented by plugging some of the collimator apertures on each of (or the largest beam diameter) helmets used for a particular patient’s treatment.

Leksell GammaPlan® is a powerful computer-based dose planning system specifically designed for simulation and planning of stereotactic Gamma Knife radiosurgery based on tomographical and projectional images, such as CT scans, MR scans, conventional x-ray imaging or angiography. Dose calculations of the Leksell GammaPlan® are based on some empirical data and interpolation is employed.2–4 The technique of superposition of radiation distributions from all gamma beams is used to calculate the dose at any point within the patient’s skull. The dose contributed by an individual beam relies on the inverse square law, linear attenuation exponential formula, and single beam profiles for gamma beams of different diameter.

In this study, an accurate Monte Carlo method was employed as a main investigational tool to verify the results of GammaPlan with plugged patterns. Heavily plugged patterns are often employed in Gamma Knife radiosurgery as a means of implementing the concept of conformal radiosurgery. Therefore, computed GammaPlan dose distributions arising from the use of such plugging were performed. The results were further compared with measured results using GafChromic films (Type MD-55) available from Nuclear Associates (Division of Victoreen, Inc., 100 Voice Road, PO Box 349, Carle Place, NY 11514-0349). The films were mounted inside a spherical polystyrene phantom in the orientations of the x–y plane (transaxial cut), y–z plane (sagittal), and x–z plane (coronal cut). Therefore, the dose profiles along three main principle axes x, y, and z, passing through the center of the spherical phantom, could be obtained. Figure 1 provides a brief description of the coordinate system for the Gamma Knife. The maximum dose delivered was 120 Gy, which was
high enough to minimize the measurement uncertainty down to 9%. The optical density was then converted to dose using a calibration curve which was made by irradiating the films using different dosages.

II. MONTE CARLO

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 in Jenkins et al.5 For the simulation, the patient’s head was modeled by a spherical polystyrene phantom, with a diameter of 160 mm.

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 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°.1 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 defined by the size of the collimator apertures.

Scoring bins with dimensions 0.5 mm×1 mm×1 mm were defined along the x, y, and z axes for the 18 mm collimator helmet. For the 4 mm collimator helmet, the dimensions of the scoring bins were 0.25 mm×0.5 mm×0.5 mm. All dimensions of scoring bins were small enough to give a high resolution of the dose profiles and were large enough to give good statistical results. All scoring bins were faced parallel to the isodose distribution curves.

Histories of $4.5 \times 10^7$ were performed for the 4 mm collimator helmet and histories of $1.5 \times 10^8$ were performed for the 18 mm collimator helmet. All history runs were divided into 30 batches for calculation 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,6 containing two peaks, viz. 1.173 and 1.333 MeV. The cutoff energies for electrons and photons were set to be 0.521 MeV (rest mass of electron + 0.01 MeV) and 0.01 MeV, respectively. High cutoff energies shortened the simulation time at the expense of reliable results. In our study, further lowering these cutoff energies caused no observable differences of the output results.

In this study, a single shot was delivered at the center of a spherical polystyrene phantom, with gamma angle of 90°. Selected beam channels were closed to stimulate the plug patterns, as in Figs. 2(a) and 2(b). The composition of the plug is 18.1% of Si, 1.1% of K, 0.5% of Mn, 0.6% of Fe, 5.8% of Ni, 2.1% of Cu, 71.7% of W, and 0.2% of Se. Radiation leakage from an individual plug could be enabled or disabled mathematically. When using the plug patterns as in Figs. 2(a) and 2(b), no difference in isodose curve distribution was observed with and without including the radiation leakage from the plugs for the 4 and 18 mm collimator helmets.
Fig. 3. Comparison of the relative dose vs $x$ axis between GammaPlan, EGS4 Monte Carlo, and GafChromic films when using a 4 mm collimator helmet with 51 plugs.

Fig. 4. Comparison of the relative dose vs $y$ axis between GammaPlan, EGS4 Monte Carlo, and GafChromic films when using a 4 mm collimator helmet with 51 plugs.

Fig. 5. Comparison of the relative dose vs $z$ axis between GammaPlan, EGS4 Monte Carlo, and GafChromic films when using a 4 mm collimator helmet with 51 plugs.
**Fig. 6.** Comparison of the relative dose vs. $x$ axis between GammaPlan, EGS4 Monte Carlo, and GafChromic films when using a 4 mm collimator helmet with 99 plugs.

**Fig. 7.** Comparison of the relative dose vs. $y$ axis between GammaPlan, EGS4 Monte Carlo, and GafChromic films when using a 4 mm collimator helmet with 99 plugs.

**Fig. 8.** Comparison of the relative dose vs. $z$ axis between GammaPlan, EGS4 Monte Carlo, and GafChromic films when using a 4 mm collimator helmet with 99 plugs.
III. RESULTS

Figures 3, 4, and 5 show the results of the relative dose against the \(x\), \(y\), and \(z\) axes, respectively, using the 4 mm collimator helmet with 51 plugs, while Figs. 6, 7, and 8 show the results of the relative dose against the \(x\), \(y\), and \(z\) axes, respectively, using the 4 mm collimator helmet with 99 plugs. Similar results were obtained using the 18 mm collimator helmet. Good agreement was obtained between the results of Monte Carlo, GammaPlan, and GafChromic films, although the maximum measurement uncertainty when using GafChromic films was found to be 9% (close to the dose maximum region).

According to the Quality Assurance Program on Stereotactic Radiosurgery\(^7\) the output of 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 50% level. The measured width must agree within 1 mm with that of the corresponding calculated profile. The employment of plugged collimators is however not mentioned. In this study, both the technique of Monte Carlo and GafChromic film measurements successfully verified the GammaPlan output when using heavily plugged collimators. The results calculated by GammaPlan were therefore proved to be reliable and accurate enough to predict the changes of the isodose curves after plugging. By measuring the width at the 50% level, they all agreed within 1 mm when comparison was made between the results of GammaPlan, Monte Carlo, and GafChromic films. Leakage from the plugged collimators was too small to affect the overall isodose distributions. The changes in shape of isodose curves after plugging, particularly in the low percentage dose regions, can protect organs at risk during Gamma Knife radiosurgery.

\(^6\)Medical Radiation Sources Catalogue (Amersham, Buckinghamshire, England, 1982).