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Stereotactic dose planning system used in Leksell Gamma Knife model-B: EGS4 Monte Carlo versus GafChromic films MD-55

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Abstract

The accuracy of the dose planning system (Leksell GammaPlan) used in Gamma Knife (model-B) radiosurgery was verified using both the GafChromic films MD-55 (improved) and the EGS4 Monte Carlo technique. The Monte Carlo technique was employed to calculate the dose distribution along the *x*-, *y*- and *z*-axes when a single shot with opening of all 201 sources was delivered at the centre of a simulated water phantom with a diameter of 160 mm. Collimator helmets with different size of the Gamma Knife unit were verified. Good consistency (typical discrepancy less than 2%) was obtained between the results of Monte Carlo and GammaPlan. Small discrepancies, however, were obtained by GafChromic films. Discrepancies, as great as 10% when using the 4 mm collimator helmet, at the low percentage isodose curve along the *z*-axis of the measurement results were probably due to the small energy dependency of the GafChromic films. Significant discrepancies were not observed along *x*- and *y*-axes because such small discrepancies were easily over-washed by other gamma beams coming from the *x*- and *y*-directions. Similar results showing the discrepancies between the GafChromic films and GammaPlan were obtained when using the 8, 14 and 18 mm collimator helmets. However, the discrepancies along the *z*-axis became smaller as scattering effect increased when using larger collimator sizes. We suggest that the Monte Carlo technique should also be applied in stereotactic dose planning system verification as it is an ideal and reliable computational technique. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Gamma Knife; GammaPlan; EGS4; Monte Carlo; GafChromic film

1. Introduction

The Leksell Gamma Knife is a radiosurgical instrument used to treat deep-seated intracranial tissues, benign or malignant tumours, which are inaccessible or unsuitable for conventional invasive surgery. The Gamma Knife delivers a single dose of ionizing radiation exiting from 201 ^{60}Co sources. Each individual beam is mechanically focused on the target and the precision at the target (individual beam deviation from

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the centre less than 0.3 mm) makes the Gamma Knife ideal for treating critically located structures.

Different beam diameters, 4, 8, 14 and 18 mm, can be varied by the exchange of collimator helmets. This allows lesions of different size and shape to be treated. A steep dose gradient creates a region with sharply circumscribed boundaries, providing precise eradication of the target while sparing surrounding tissues by strictly respecting the boundaries of the target. There are no moving parts during treatment, and therefore, recalibration is not necessary between treatments. The accuracy is thus highly reproducible (micro-switches guarantee error of couch position less than 0.1 mm) and reliability is guaranteed.

Leksell GammaPlan is a UNIX-based dose planning system specifically designed for the simulation and planning of stereotactic Leksell Gamma Knife radiosurgery. Dose calculations by the GammaPlan are based on empirical data and interpolation is employed (Wu et al., 1990; Wu, 1992; Elekta, 1996). The dose contributed by an individual beam relies on the inverse square law, the exponential attenuation formula and the single beam profiles of different diameters of the gamma beams. In this study, comparisons of the Monte Carlo results and the GafChromic film measurements were made to verify the results of Leksell GammaPlan. GafChromic film dosimetry is a physical verification system whereas Monte Carlo technique is a computation technique to verify the accuracy of the dose planning system.

2. Materials and methods

The Monte Carlo modeling of particle transport problems in medical radiation physics offers significant advantages over other techniques. Experiments can be performed without having to set up the physical situation. Actual results are obtained with no perturbation introduced. The Monte Carlo system employed was the PRESTA (Parameter Reduced Electron-Step Transport Algorithm) version of the EGS4 (Electron Gamma Shower) computer code. The EGS4 code allows a more flexible geometrical simulation than other Monte Carlo codes. Detailed descriptions of the structure of the EGS4 code can be found from Jenkins et al. (1988).

A spherical water phantom of 160 mm in diameter was used to simulate the patient's head. Each source was modeled by a cylinder of 1 mm in diameter and 20 mm in length. The ^{60}Co sources were arranged in a sector of a hemispherical surface with a radius of about 400 mm. They were distributed along five parallel circles separated from each other by an angle of 7.5° (Elekta, 1992). All 201 gamma beams 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 which were 4, 8, 14 and 18 mm. A single isocentre was delivered at the centre (unit centre point: $x = 100$ mm, $y = 100$ mm, $z = 100$ mm) of the simulated water phantom using different size of collimator helmets.

Scoring bins with dimensions $0.5 \times 1 \times 1$ mm were defined along the x-, y- and z-axes for the 14 and 18 mm collimator helmets. For the 4 and 8 mm collimator helmets, the dimensions of the scoring bins were $0.25 \times 0.5 \times 0.5$ mm.

Histories of 10^8 simulations were performed for the 8 and 18 mm collimator helmets while histories of 3×10^7 and 6.2×10^7 were performed for the 4 and 14 mm collimator helmets, respectively. All history runs were divided into 20 batches for calculation of statistics and were large enough to give a standard error of less than 2% at the dose maximum region of the isodose curves. The primary photon spectrum of ^{60}Co was taken from Medical Radiation Sources Catalogue (1982), which contained two peaks, viz. 1.173, 1.333 MeV. The latest collisional and radiative stopping powers of ICRU 37 (ICRU, 1984; Duane et al., 1999; Rogers et al., 1989) were employed in the PEGS4 (pre-processor of EGS4) data file (Nelson, 1989). A long sequence random number generator of James (1988) was used for the huge number of history runs.

The type of the film employed in this experiment was GafChromic film MD-55 (improved) with CAT. NO. 37-041. It was manufactured by ISP Technologies. (The film is available from: Division of Victoreen, 100 Voice Road, P.O. Box 349, Carle Place, NY 11514-0349). The film is a multi-layer structure composed of a nominal 30 μm thickness of the sensitive material, sandwiched between two pieces of 75 μm thick polyester base material and two pieces of 13 μm laminated material, yielding a total thickness of 206 μm. The film is colorless and transparent before being exposed to ionizing radiation. The sensitive layer changes from colorless to blue by dye polymerization without processing, upon exposure to ionizing radiation. The darkness of the blue color depends on the absorbed dose and can be measured with a laser densitometer with a wavelength ranging from 610 to 675 nm. Operational characteristics of the GafChromic film MD-55 (improved) have been evaluated by Meigooni et al. (1996) who reported good sensitivity, linearity, reproducibility, uniformity, and energy and time dependence of the film response.

The dose distributions along the x-, y- and z-axes of the target point were measured using films with maximum dose of 120 Gy at a spherical polystyrene phantom. The maximum dose was high enough to minimize the measurement uncertainty to 9%. The optical density was converted into dose by a characteristic line which was made by irradiating the films with different dosages. The densitometer used was a Lumisys Lumiscan 150. The light source was a 632.8 nm laser (He–Ne laser) (Muench et al., 1991) with a 100 μm spot size. It has a linear CCD for detection and information is sent out in 12 bit format with optical density range from 0 to 3.5 OD. The spatial resolution was set to 0.3 mm.

One important factor when using this scanner was that the orientation of the films when placed in the scanner was the same for all films as the radiochromic film has a polarization. As the light source is a reflected He–Ne laser, the light source is polarised and thus the orientation of the film can affect the measured results. Finally, comparisons were made among the results from Monte Carlo, GafChromic films and the Leksell GammaPlan for detailed studies.

3. Results and discussion

Fig. 1 shows the comparison of the dose values against the x-axis when using the 4 mm collimator helmet. The plot of the relative dose against the y-axis was about the same as that against the x-axis. Good agreements between the results of GafChromic films and GammaPlan were observed along x- and y-axes, with typical discrepancies less than 2%.

Small discrepancies, however, were obtained by GafChromic films. In Fig. 2, discrepancies as great as 10% when using the 4 mm collimator helmet at the low percentage isodose curve of the measurement results were observed along the z-axis; these were probably due to the small energy dependency (Meigooni et al., 1996) of the GafChromic films. Significant discrepancies were not observed along the x-and y-axes because the discrepancies were sufficiently small to be over-washed by gamma beams coming along the x- and y-axes; there are no gamma beams coming along the z-axis. Similar results showing discrepancies between the GafChromic films and GammaPlan were obtained when using other collimator helmets. However, the discrepancies along the z-axis became smaller as scattering effect increased when using larger collimator sizes. The increase of scattering effect over-washed part of the discrepancies along the z-axis.

The GafChromic film measurement is a good measuring method but it may not be an ideal measuring technique to verify the stereotactic dose planning system, where steep dose gradients are of concern. To cope with this problem, the Monte Carlo technique was introduced. Accurate low percentage isodose distribution is important in Gamma Knife radiosurgery in preserving surrounding normal brain structures. The absorbed dose in low percentage isodose regions

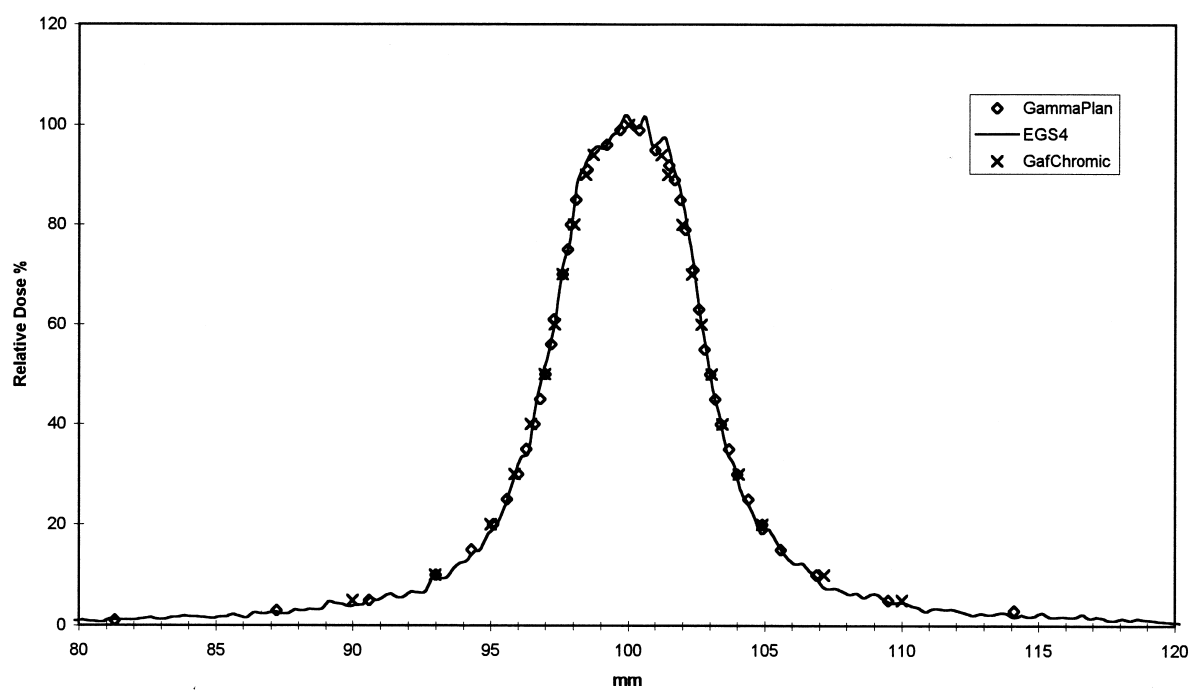

Fig. 1. Comparison of the dose values versus x-axis among the results of GammaPlan (outlined rhombuses), GafChromic films (crosses) and EGS4 Monte Carlo (solid line) when using 4 mm collimator helmet.

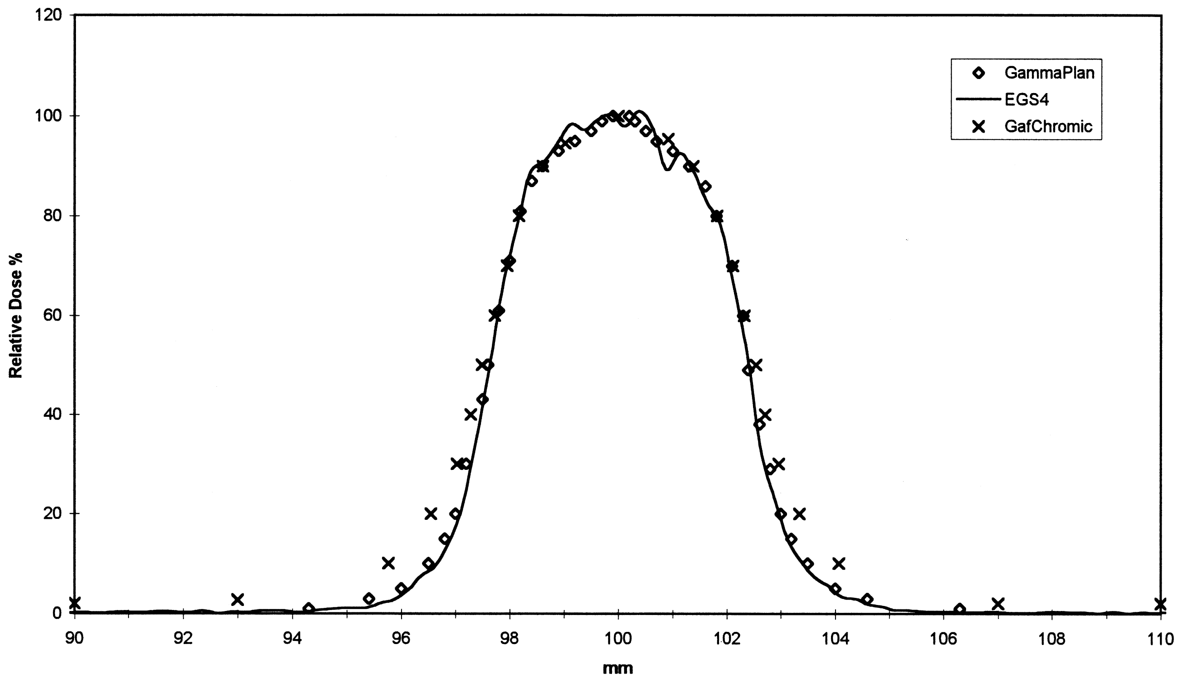

Fig. 2. Comparison of the dose values versus z-axis among the results of GammaPlan (outlined rhombuses), GafChromic films (crosses) and EGS4 Monte Carlo (solid line) when using 4 mm collimator helmet.

becomes more significant when a high radiation dose is given at the maximum. An example is to preserve the optic chiasma in the treatment of pituitary adenoma with endocrinopathy. The optic chiasma is right above the pituitary along the z-axis. A high dose of 35 Gy delivered at 50% isodose curve is usually necessary, which gives 70 Gy at the maximum. The chiasma in the low percentage isodose region should receive less than 8 Gy and this was calculated by the GammaPlan.

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