Choice of phantom materials for dosimetry of Leksell Gamma Knife unit: A Monte Carlo study

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In calculations for the Leksell Gamma Knife, GammaPlan employs a tissue equivalent material without the presence of a skull bone, while dosimetry work is based on a polystyrene phantom. The compatibility of these dose distributions is uncertain. The Monte Carlo technique was employed to determine the radial dose distributions from a single 14 mm collimator helmet in 160 mm diam phantoms with different materials. The materials studied were polystyrene, perspex, water, and water with skull bone. Results showed no significant differences among the radial doses in different phantom materials for the 14 mm collimator helmet. The Monte Carlo simulation was repeated with the inclusion of all 201 sources. Again, no significant differences were observed. *© 2002 American Association of Physicists in Medicine.* [DOI: 10.1118/1.1508797]

Key words: Gamma Knife, GammaPlan, EGS4 Monte Carlo, phantom materials

Leksell Gamma Knife radiosurgery involves no traditional surgical incisions for brain surgery. No lengthy recuperation is required, and mortality risks from the procedures are much less.[1] The principle of Gamma Knife radiosurgery is simple.

For simplicity in dose calculations, GammaPlan employs a tissue equivalent material,[2] with an attenuation coefficient $\mu = 0.0063\ \text{mm}^{-1}$ at the energy 1.25 MeV, in all calculations without the presence of a skull bone. On the other hand, in routine quality assurance programs of the Gamma Knife unit, a spherical polystyrene phantom is employed to give dose distributions with the opening of all 201 ^{60}Co sources. This phantom may not be fully tissue equivalent. Therefore, compatibility of these dose distributions is uncertain. In the present study, we used the Monte Carlo method to calculate the radial dose distributions from a single radiation beam of 14 mm collimator helmet in different phantom materials. The studied materials were polystyrene (density $= 1.06\ \text{g/cm}^3$, 92.26% of carbon and 7.74% of hydrogen by mass), perspex (density $= 1.19\ \text{g/cm}^3$, 59.98% of carbon, 31.96% of oxygen and 1.19% of hydrogen by mass), water, and water with a skull bone (bone density $= 1.85\ \text{g/cm}^3$, 6.40% of hydrogen, 27.80% of carbon, 2.70% of nitrogen, 41.00% of oxygen, 0.20% of magnesium, 7.00% of phosphorus, 0.20% sulphur, and 14.70% calcium by mass).

The Monte Carlo system employed was the PRESTA (Parameter Reduced Electron-Step Transport Algorithm) version of the EGS4 (Electron Gamma Shower) computer code.[3,4] Employment of the PRESTA in the simulation allowed the EGS4 Monte Carlo code to select a suitable step length dynamically, which enabled fast simulation while still providing an accurate modeling of radiation transport. Detailed descriptions of the structure of the EGS4 code can be found in Jenkins *et al.*[5] In the simulation, the patient's head was modeled by a phantom of 160 mm in diameter. Phantoms with materials of polystyrene, perspex, water, and water with skull bone were employed in the simulation. The thickness of the skull bone was 5 mm for the water phantom with skull bone. ^{60}Co sources were modeled by cylinders of 1 mm in diameter and 20 mm in length. The sources were arranged in a sector of a hemispherical surface with a radius of 400 mm.

There are different strategies in simulating a collimator system. First, we simulated the whole single-beam channel, including the cylindrical double encapsulated stainless steel source, precollimator, lead collimator, and the interchangable final collimator. Second, each source was modeled as a cylinder without any source and capsule filtration. The beam was collimated by the internal diameters of the interchangeable final collimator. Radiation scattering due to the collimator system was ignored. Single-beam dose profiles were generated by these two strategies. Because of the larger source-to-target distance when compared to the source dimensions, no observable difference was obtained in the single-beam profiles. For simplicity, we employed the second strategy in simulating the collimator system.

In calculating the single-beam dose profile (Fig. 1) along its radial distance, concentric cylinders were created as scoring bins around the center of the spherical phantom. The radial resolution of the annular scoring bins was 0.5 mm for the 14 mm collimator. The depth of the scoring bins was 1 mm. A total of 1.55×10^7 histories were large enough for radial symmetrical geometry. All history runs were divided into five batches for the calculation of statistics. The standard errors at dose maximum were all less than 1%. Rayleigh scattering and photoelectrons angle selections[6] were turned on in all simulations. The primary photon spectrum of ^{60}Co was adopted from the Amersham Medical Radiation Sources Catalogue.[7]

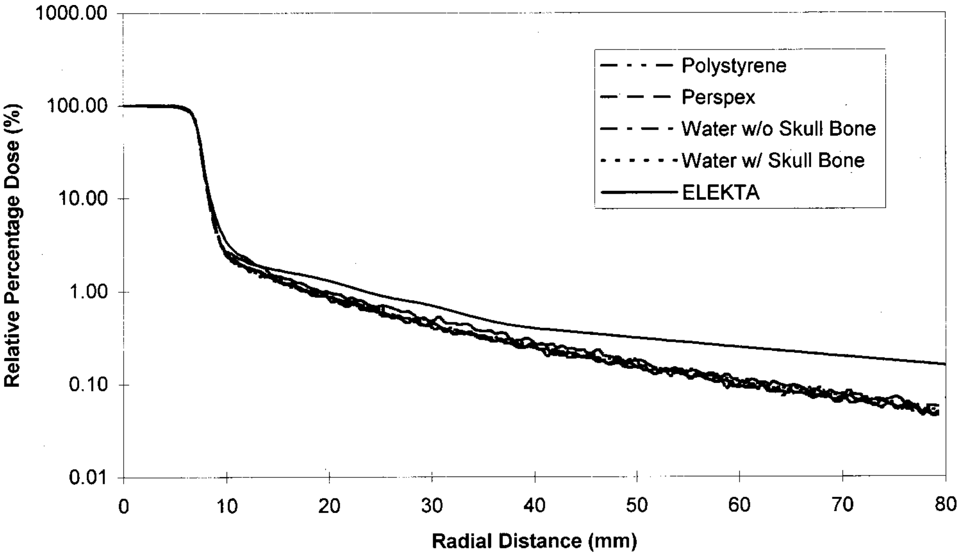

FIG. 1. A comparison of radial doses in different phantom materials from the 14 mm collimator helmet of the Leksell Gamma Knife. The curves for different phantoms are close to each other and differences cannot be discerned.

In order to calculate the dose distributions along the three principal axes with photons exiting from the 201 ^{60}Co sources, a second simulation was made. All the sources were distributed along five parallel circles separated from each other by an angle of 7.5°.[8] Scoring bins with dimensions $0.5\ \text{mm}\times 1.0\ \text{mm}\times 1.0\ \text{mm}$ were defined along the x, y, and z axes. All scoring bins were tangential to the isodose distribution curves. A total of 6.2×10^7 histories were generated. All history runs were divided into 20 batches for calculation of statistics. Average standard errors of less than 2% were obtained at the dose maximum of dose distribution curves. Single shots of 201 gamma beams were delivered at the center (unit center point: $x=100$ mm, $y=100$ mm, $z=100$ mm) of the simulated spherical phantom.

Figure 1 shows the comparison of radial doses among different phantom materials for the 14 mm collimator helmet of the Leksell Gamma Knife. All radial dose curves for different materials were normalized at 100%, as we needed to compare the shapes of the curves. The results show no observable differences among the radial doses in different phantom materials for the 14 mm collimator helmet.

The radial dose profile for different phantom materials, including the one provided by ELEKTA (Manufacturer of the Leksell Gamma Knife) in Fig. 1, were almost identical. In other words, there were no observable differences in dose distributions in different phantom materials along the three principal x, y, and z axes with the opening of all 201 ^{60}Co sources. Therefore, the GammaPlan can be used with confidence to calculate the dose distribution without the skull bone correction. Furthermore, the simulation was repeated using the water phantom with skull bone with diameters of 130 and 190 mm. Again, there were no observable differences in dose distributions along the three principal x, y, and z axes with the opening of all 201 ^{60}Co sources.

In addition, the polystyrene and perspex phantom are also suitable for measuring the dose profiles of the Gamma Knife unit. The noninclusion of skull bone in the patient's head gave no observable changes in the isodose distributions. For example, the presence of the skull bone only causes an underestimation of the absorbed dose at the target point by 1.75%, i.e.,

$$\frac{\Delta I}{I_o}\times 100\% = \left(\frac{I_o\cdot e^{-\mu_{\text{water}}x\cdot\rho_{\text{water}}} - I_o\cdot e^{-\mu_{\text{bone}}x\cdot\rho_{\text{bone}}}}{I_o}\right)\times 100\% = 1.75\%,$$

which is acceptable according to Hartmann.[9] The deviation in dosage should be less than 4%. Using pure water phantom to obtain the dose distribution is not necessary, as it is a difficult and expensive setup.

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[1] S. J. Goetsch, "Risk analysis of Leksell Gamma Knife Model C with automatic positioning system," Int. J. Radiat. Oncol., Biol., Phys. **52**, 869–877 (2002).

[2] Leksell GammaPlan Instructions for Use for Version 4.0—Target Series, Elekta, 1996.

[3] A. F. Bielajew and D. W. O. Rogers, "Electron step-size artefacts and PRESTA," in *Monte Carlo Transport of Electrons and Photons*, edited by T. M. Jenkins, W. R. Nelson, and A. Rindi (Plenum, New York, 1988), p. 115.

[4] A. F. Bielajew and D. W. O. Rogers, PRESTA: The *Parameter Reduced Electron-Step Transport Algorithm for Electron Monte Carlo Transport*, NRC-CNRC, 1988.

[5] T. M. Jenkins, W. R. Nelson, and A. Rindi, *Monte Carlo Transport of Electrons and Photons* (Plenum, New York, 1988).

[6] A. F. Bielajew and D. W. O. Rogers, "Photoelectron angular distribution in the EGS4 code system," National Research Council Canada PIRS-0058.

[7] Medical Radiation Sources Catalogue, Amersham International Ltd., 1982.

[8] Leksell Gamma Unit—User's Manual 1, Elekta, 1992.

[9] G. H. Hartmann, *Quality Assurance Program on Stereotactic Radiosurgery—Report From a Quality Assurance Task Group* (Springer-Verlag, Berlin, 1995).