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Original Article

Evaluation of the Effects of Inhomogeneities on Dose Profiles Using Polymer Gel Dosimeter and Monte Carlo Simulation in Gamma Knife

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Abstract

Introduction
Polymer gel dosimeters offer a practical solution to 3D dose verification for conventional radiotherapy as well as intensity-modulated and stereotactic radiotherapy. In this study, EGSnrc calculated and PAGAT polymer gel dosimeter measured dose profiles from single shot irradiation with 18 mm collimator of Gamma Knife in homogeneous and inhomogeneous phantoms were compared with each other.

Materials and Methods
The head phantom was a custom-built 16 cm diameter plexiglas sphere. Inside the phantom, there were two cubic cutouts for inserting the gel vials and inhomogeneities. Following irradiation with the Gamma Knife unit, the polymer gel dosimeters were scanned with a 1.5 T MRI scanner. For the purpose of simulation the simplified channel of 60Co source of Gamma Knife BEAMnrc and for extracting the 3D dose distribution in the phantom, DOSXYZnrc codes were used.

Results
Within high isodose levels (>80%), there are dose differences higher than 7%, especially between air inserted and PTFE inserted phantoms, which were obtained using both simulation and experiment. This means that these values exceed the acceptance criterion of conformal radiotherapy and stereotactic radiosurgery (i.e., within some isodose levels, less than 93% of prescription dose are delivered to the target).

Conclusion
The discrepancies observed between the results obtained from heterogeneous and homogeneous phantoms suggest that Leksell Gamma Knife planning system (LGP) predictions which assume the target as a homogeneous material must be corrected in order to take care of the air- and bone-tissue inhomogeneities.

Keywords: Dose Profile, Gamma Knife, Inhomogeneity, Monte Carlo, Polymer Gel Dosimeter

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1. Introduction

Stereotactic Gamma Knife radiosurgery plays an important role in managing small intracranial brain lesions. For patient treatment, a stereotactic frame is attached to the patient's head which establishes a three-dimensional (3D) coordinate system for the determination of the precise target location with imaging techniques. All 201 ^{60}Co beams intersecting at the unit center point (UCP) and four helmets with different sized collimators form four standard clinical beam sizes (18, 14, 8, and 4 nominal diameters) [1, 2].

The treatment planning system (TPS) of Gamma Knife assumes that the target is a homogeneous material and in dose calculations does not consider the presence of inhomogeneities (e.g., bony structures and sinuses) which may lead to considerable dose disturbances [3, 4].

In the investigation of dose perturbations produced by heterogeneities, Monte Carlo (MC) has proved to be a useful tool, because it adequately accounts for the lack of electron equilibrium close to interfaces. The degree of accuracy that can be attained by this method is determined mostly by the accuracy of the cross-section data, the radiation beams with respect to energy and angular distribution, the statistical accuracy of the MC calculation method, and how the phantom geometry and tissue properties are related to the radiation interactions that are modeled. The EGSnrc based BEAMnrc and DOSXYZnrc from the National Research Council of Canada (NRCC) group were used in this study [5]. The EGSnrc was developed from the EGS4 code [6]. The EGS (Electron–Gamma–Shower) system of computer codes is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several hundreds of GeV [7].

Moreover, polymer gel dosimetry is still the only dosimetry method for directly measuring three-dimensional dose distributions. These dosimeters are tissue equivalent and can act as a phantom material [8, 9]. Polymer gel dosimetry is a technique that can map absorbed radiation dose distributions in three dimensions with a high spatial resolution and also offer a number of advantages over the traditional dosimeters such as ionization chambers, thermoluminescent dosimeters (TLDs), and radiographic films. The advantages include independence of radiation direction, radiological soft tissue equivalence, integration of the dose for a number of sequential treatment fields, and perhaps most importantly, evaluation of a complete volume at once.

Several studies have been performed for investigating the effects of inhomogeneities on dose distribution using MC simulation and conventional dosimeters [4, 10-12]; however, studies related to polymer gel dosimetry along with simulation are rare [9, 13-15].

In this study, effects of inhomogeneities on those distributions have been investigated using both EGSnrc calculation and PAGAT (PAG (PolyAcrylamide Gel) And THPC anti-oxidant) polymer gel dosimeter and dose profiles in three-dimensional (3D) coordinate system have been investigated.

2. Materials and Methods

2.1. Gel fabrication

PAGAT polymer gel dosimeter was fabricated according to composition proposed by Venning et al who noted that using MRI, the formulation to give the maximum change in the transverse relaxation rate R2 was determined to be 4.5% N,N'–methylene-bis-acrylamide (bis), 4.5% acrylamide (AA), 5% gelatine, 5 mM THPC, 0.01 mM hydroquinone (HQ), and 86% H2O.

For fabricating the gel dosimeter, the De Deene et al. [16] proposed method has been used in which for the nPAG gels containing crosslinker, the acrylamide and crosslinker N,N'-methylene-bis-acrylamide were first dissolved in 40% total water volume by heating to 45 °C and the gelatin solution was then cooled down to 35 °C before it was mixed with the monomer solution. The antioxidant was added to the solution under heavy stirring just before filling the test tubes [17].

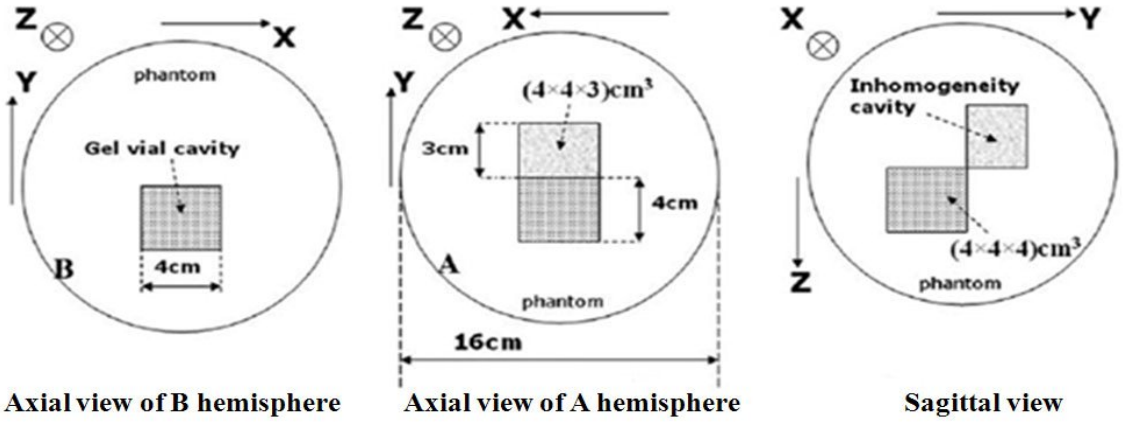

Figure 1. Schematic view of the phantom in three spatial coordinates. The location of the cubic cutouts for the gel vial and inserting the air and bone inhomogeneities are depicted.

2.2. Design and irradiation of the phantom

Phantom in this study was a 16 cm spherical plexiglas in which there was a cubic cutout for inserting the gel cubes (4×4×4 cm^3) and another cutout (4×4×3 cm^3) for inserting the air and/or a bone equivalent material (Poly-tetra-fluoro-ethylene (PTFE)), with density of 2.2 gr/cm^3).

Figure 1 shows a schematic view of the phantom in three spatial coordinates. In this view, the location of the cubic cutouts for the gel vial and inserting the air and bone inhomogeneities are also depicted.

Figure 2 shows the phantom placed in a Gamma Knife unit (model 4000C) for single-shot irradiations with 18 mm collimator to the maximum dose of 40 Gy.

The calibration tubes were irradiated using the Theratron ^{60}Co machine using especial water filled container (15×30×10 cm^3) in which the calibration vials could be placed horizontally at a depth of 5 cm. The calibration vials were irradiated from 0 to 45 Gy with steps of 5 Gy. Post manufacture irradiation time was 24 h.

2.3. Evaluation of gel dosimeter

The evaluation of the polymerized dosimeter was performed on a 1.5 T clinical Siemens scanner in the transmitter/receiver head coil. A multi-echo sequence with 32 echoes was used for the evaluation of irradiated polymer-gel dosimeters. The parameters used for the sequence were as follows: TR=3000 ms, TE=22–640 ms, slice thickness=1 mm, FOV=128 mm, matrix size=256×256, pixel size=0.5×0.5 mm^2, and one acquisition. The R2 (spin-lattice relaxation rate, 1/T) was computed using modified radiotherapy gel dosimetry image processing software coded in MATLAB. The R2 matrix was subsequently converted into a relative dose matrix normalized to the maximum prescribed dose of 40 Gy.

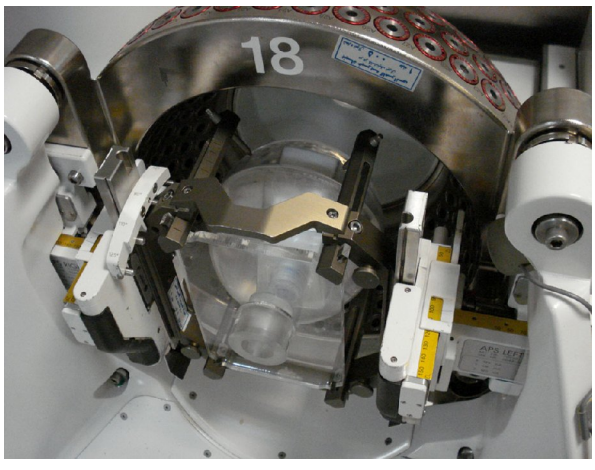

Figure 2. The Leksell Gamma Knife stereotactic frame attached to the spherical plexiglas head phantom.

Figure 3 shows the R2-dose response curve obtained from PAGAT polymer gel dosimeter in which the R2-dose sensitivity from 0-20 Gy and 20-40 Gy were 0.09±0.01 $^{s^{-1}}Gy^{-1}$ and 0.08±0.01 $^{s^{-1}}Gy^{-1}$, respectively.

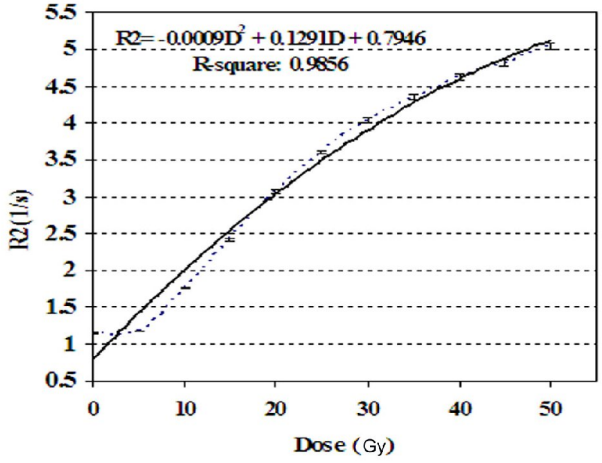

Figure 3. R2-dose curve obtained from PAGAT polymer gel dosimeter.

2.4. Monte Carlo modeling

The EGSnrc-based BEAMnrc code [18, 19] was used to simulate the geometry of the simplified Gamma Knife source channel, and outputs phase-space data (phase-space files), which include all the particle information (i.e., the charge, position, direction, energy, and history tag for each particle).

Previous studies have shown that this simplified geometry allows a significant reduction of the simulation time, without loss of accuracy in the doses delivered to the phantom [20].

Another general-purpose MC EGSnrs user code DOSXYZnrc [19, 21] was employed to model the 201 ^{60}Co sources of Gamma Knife unit. For performing this modeling, the "Phase-space source from multiple directions", source type of DOSXYZnrc code was used. This code was also employed to obtain the 3D dose distributions in the phantom which considers the phantom divided in a large number of small volume elements, or voxels.

3. Results

Figure 4 (a-f) compares the relative dose profiles in three spatial coordinates for PAGAT polymer gel dosimeter and MC simulation.

Figure 5 compares simulation with measurements in three spatial coordinates. Table 1 shows dose differences between homogeneous and inhomogeneous phantoms and Table 2 shows comparison between measurements and the simulation.

Because of the especial phantom geometry and also isocentre within gel cubes, the correct dose distribution using gel dosimeter could only be obtained at the –Y direction. Therefore, in order to compare dose profiles only the negative direction of Y axis was considered.

Table 1. Dose differences (DDs) for MC simulation and PAGAT polymer gel dosimeter. Homogeneous vs. air inserted phantom (DD(H-A)%), Homogeneous vs. PTFE inserted phantom (DD(H-P)%), and air inserted vs. PTFE inserted phantom (DD(A-P)%), in three coordinate axes.

MC simulation			
Axes	DD (H-A)%	DD (H-P)%	DD (A-P)%
X	4.08±1.46	2.72±1.01	7.00±1.60
Y	4.94±1.45	2.95±1.35	7.82±1.84
Z	3.64±1.16	2.98±2.10	6.48±2.01
PAGAT gel dosimeter			
Axes	DD (H-A)%	DD (H-P)%	DD (A-P)%
X	3.23±2.45	5.73±1.88	8.39±3.37
Y	3.10±1.84	6.91±1.72	7.87±2.50
Z	4.27±2.45	3.26±2.14	7.27±3.05

Table 2. Dose differences (DDs) for MC simulation vs. PAGAT polymer gel dosimeter in air inserted, homogeneous and PTFE inserted phantoms along the three coordinate axes.

Axes	Air inserted phantom	Homogeneous phantom	PTFE inserted phantom
X	4.16±2.83	1.20±1.13	2.74±0.79
Y	3.39±2.39	1.66±1.01	2.68±1.16
Z	2.32±2.42	3.13±2.06	2.49±1.65

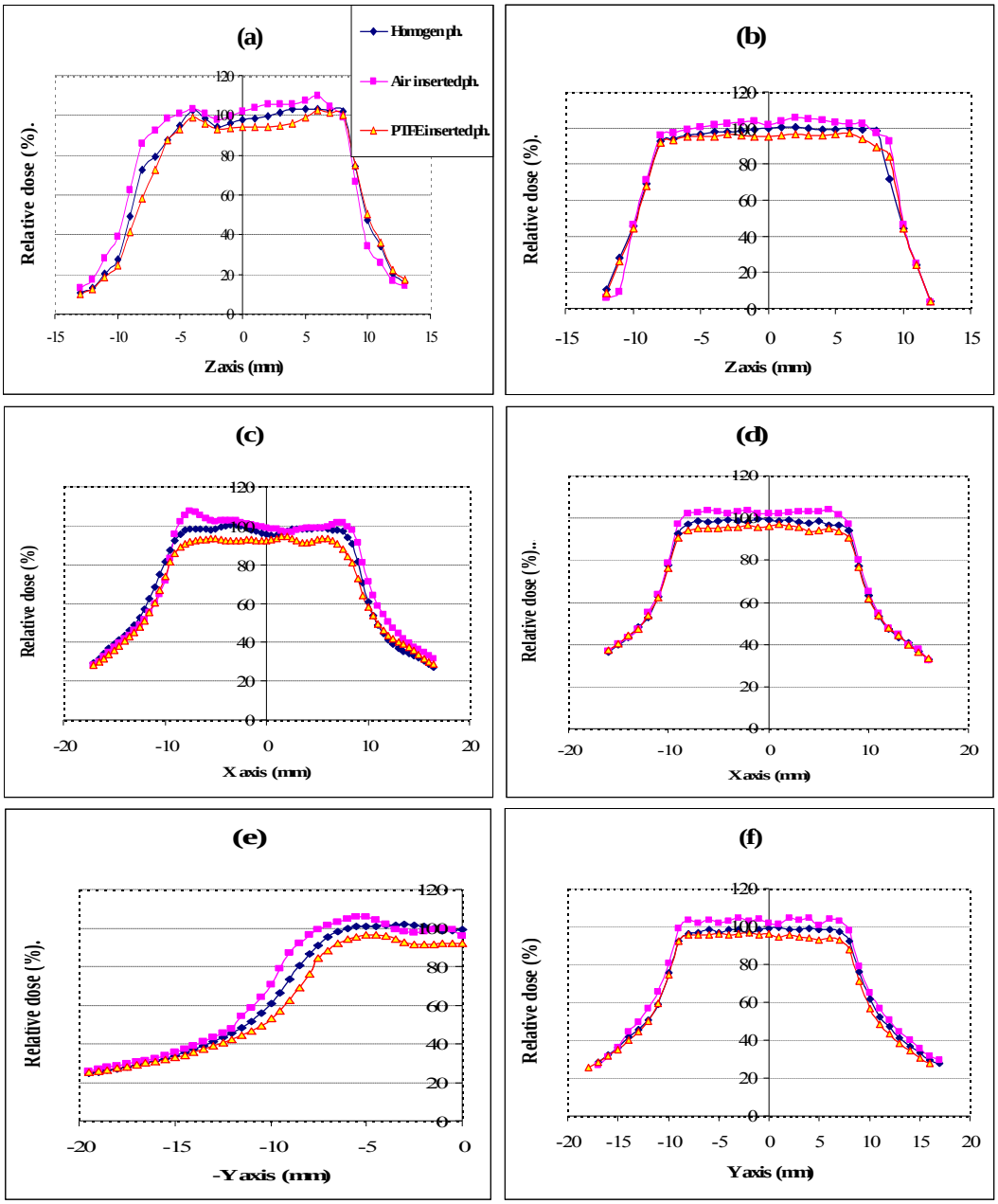

Figure 4. Comparing relative dose profiles along three coordinate axes (X, Y, and Z) for MC simulation (b, d, f) and PAGAT polymer gel dosimeter (a, c, e) in irradiation with 18 mm collimator.

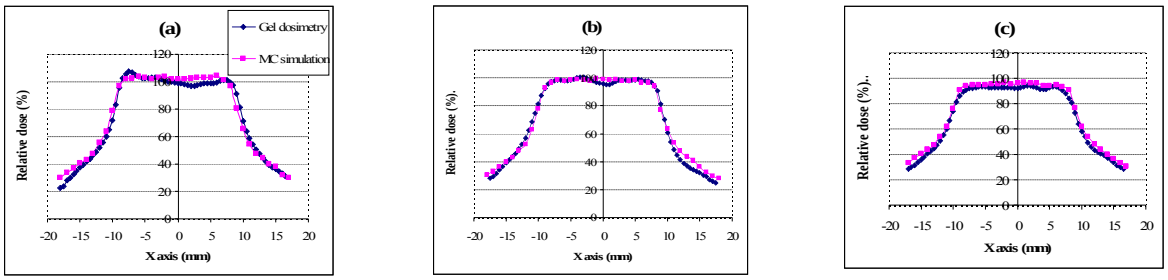

Figure 5. Comparing relative dose profiles along three coordinate axes (X, Y, and Z). MC simulation vs. PAGAT polymer gel dosimeter in a) air inserted, b) homogeneous, and c) PTFE inserted phantoms, in irradiation with 18 mm collimator.

4. Discussion

Regarding acceptance criteria for conformal radiotherapy, not more than 7% dose difference in delivered dose to the target is acceptable [22], and it is obvious that the Gamma Knife as a stereotactic radiosurgery unit must convey such a degree of accuracy. According to values of Table 1 within high isodose levels (>80%), there are dose differences higher than 7%, especially between air inserted and PTFE inserted phantoms, which were obtained using both simulation and experiment. This means that these values exceed the acceptance criterion of conformal radiotherapy and stereotactic radiosurgery (i.e., within some isodose levels less than 93% of prescription dose are delivered to the target). It seems that different linear attenuation coefficient of inserted materials within the phantom can cause such dose disturbances.

Several studies have been performed for investigating the effects of inhomogeneities on dose distribution using MC simulation and conventional dosimeters [4, 10-12]; however, in the case of polymer gel dosimetry along with simulation only a few studies exist which will be reviewed in the following.

In one study [23], considerable differences were found between diameter of isodoses less than 80% between homogeneous and inhomogeneous phantoms using MAGIC gel dosimeter which is in contrast with our study. According to their study, the diameters of the 50% isodose curves differed 43% in the X axis and 32% in the Y axis. We found no reasonable answer for these differences between the two studies.

In another study [4], using conventional dosimeters and simulation (PENELOPE), it was found that the dose delivered to the target area away from an air-tissue interface may be underestimated by up to 7% by GammaPlan due to overestimation of attenuation of photon beams passing through air cavities. Their findings are somewhat similar to our findings in air inserted phantom.

Al-Dweri et al. [10] determined that dose distribution for heterogeneous phantoms including the bone- and/or air-tissue interfaces show non-negligible differences with respect to those calculated for a homogeneous one, mainly when the Gamma Knife isocentre approaches the separation surfaces. Their findings confirm an important underdosage (~10%) nearby the air-tissue interface. However, their study was in interfaces of bone-tissue and air-tissue and somewhat different from our goal of study.

Allahverdi Pourfallah et al. [15] in one study through investigating the dose-volume histograms using simulation and polymer gel dosimetry showed that in irradiation with 18 mm collimator of the Gamma Knife unit, 23.24% difference in DVH within 90%–100% relative isodose level for homogeneous and inhomogeneous phantoms exist. Furthermore, authors revealed that a significant part of the target (28.56%) received relative doses higher than the maximum dose, which exceeds the acceptance criterion. In another study [14], the authors showed that the presence of inhomogeneities in head phantom could cause spatial uncertainty higher than ±2 mm and dose uncertainty higher than 7% when measurement and simulation in homogeneous and inhomogeneous phantoms are used.

Regarding the results of comparison between simulation and measurement (Table 2), it is clear that the observed difference between them is within the acceptance criterion (<7%). However, some differences (at most 4.16±2.83% in air inserted phantom) were observed between the two which may be due to experimental uncertainty and parameters that can affect the accuracy of polymer gel dosimetry [24].

Imaging artifacts may affect the accuracy of gel dosimetry. Dosimetric imaging artifacts can be related to MRI machine or the dosimeter itself. Machine-related artifacts originate from imperfections in the scanning device while dosimeter-related artifacts are mainly attributed to a temperature drift during scanning or molecular self-diffusion.

In addition, MRI protocol with more acquisition or larger voxel size can improve signal to noise ratio. Noisy results can cause deviations between polymer gel measurements and MC plus LGP calculations. More studies may be necessary to answer these questions.

5. Conclusions

The discrepancies observed between the results obtained for heterogeneous and homogeneous phantoms suggest that LGP predictions which assume the target as a homogeneous material must be corrected in order to deal with the air-and bone-tissue inhomogeneities. These results suggest that algorithms considering the tissue differences in the head would calculate the delivered dose more accurately.

The aim of treatment using Gamma Knife unit is to cover the tumor or the lesion with the high isodose levels. However, ignoring tissue inhomogeneities can mislead accurate localization of dose levels. Clinically, this can cause underdose irradiation of the tumor in some regions or overdose irradiation of the normal tissue in an unwanted region.

It could also be concluded that the applied MC code, i.e., EGSnrc is a suitable tool for 3D evaluation of dose distribution in irradiation with Gamma Knife unit, which can be used as an important evaluation criterion for 3D dose distribution in clinical practice.

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