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GEANT4 BASED DOSIMETRY EVALUATION FOR GAMMA KNIFE USING DIFFERENT PHANTOM MATERIALS

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ABSTRACT. This study examines the dose difference for a variety of phantom materials that can be employed for "Leksell Gamma" Knifes. These materials resemble human tissue by not including the skull bone. Geant4 was utilized in the analysis of the dose distributions for collimator helmet sizes of 4mm and 8mm. The phantom is illustrated with a radius of 80mm. Water, brain, Poly-methyl methacrylate (PMMA) and polystyrene were being considered as the main material types. Results proved that there is no considerable differences for radiation dosimetries depending on the material types. In addition, the polystyrene and PMMA (phantom is also quite appropriate in terms of evaluating the dose profiles of the Gamma Knife unit.

1. INTRODUCTION

Gamma Knife device developed in 1950s, was first presented in 1967 using 179 Co-60 sources. Early Acoustic Neuroma patient, was treated by Leksell in1969. In 1975 the second gamma knife device was established under the Karolinska Institute and Brain Surgery service. The third and fourth units were used in Buenos Aires, Argentina and Sheffield, UK. It was initially applied to functional neurosurgery patients and then to some benign tumors and small sized malignant tumors in the 1980s. The primary 201 Cobalt-60 sources Gamma Knife was founded in the USA in 1987 and later sophisticated the Model C followed by 192 Cobalt-60 sources Leksell Gamma Knife Perfexion. Gamma Knife Icon is the sixth and recent generation of the Leksell Gamma Knife technology [1].

Keywords. Geant4, simulation, gamma knife, dosimetry

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Radiosurgery, a conformational treatment method, involves directing target bunches of beams from a number of different angles, resulting in rapid dose droping in normal tissues outside the target, while high doses are achieved in the confluence of the rays.

Leksell Gamma Knife radiosurgery comprises no institutionary surgical cuts for brain surgery operations [2]. The principle of Gamma Knife radiosurgery is incomplex. GammaPlan studies a tissue equivalent material, with a coefficient of attenuation, namely, "μ =0.0063 mm-1 at the energy 1.25 MeV", in all calculations deprived of the existing of a skull bone. Furthermore, in repetitive quality assurance programs of the Gamma Knife unit, a spherical polystyrene phantom is studied to provide dose distributions with the opening of all 201 "^{60}Co" sources. This phantom might not be completely tissue equivalent. Consequently, compatibility of these dose distributions is complicated [3]. In the proposed study, Geant4 is employed to compute the radial dose distributions obtained from a single radiation beam of 4 mm and 8 mm collimator helmet in variant phantom materials.

The source of radiation received in radiotherapy can be particle-based as well as gamma [4,5]. Different sources of radiation cause different reactions within the target [6]. Simultaneously, the increasing importance of radiation-related applications in our lives has increased the importance of measuring the amount of radiation received by living organisms or any material exposed to radiation [7].

Geant 4 is a Monte Carlo simulation software with a large library of physics, including tools that can simulate absolutely the interaction of the particles with the target. Geant name, "it was created using the geometry and Tracking words. While the major goal of the software growth is high energy physics experiment simulations, it is so used in many areas such as nuclear physics, medical and astrophysics today owing to the success and requirements of detector simulations. Also, the The Turkish Accelerator and Radiation Laboratory in Ankara, abbreviated as the TARLA facility, is proposed as the first facility of Turkish Accelerator Center (TAC) project where such detector simulations are made in Turkey. The main target of the TARLA facility is to build up a user facility to open up recent opportunities for interdisciplinary scientific research and applications, as materials science, medicine, nanotechnology, life sciences, etc [8,9].

There are several ways to get a Geant4 simulation for a particular problem. The easiest is to use a ready-made application or tool that provides the essential qualifications to create an installation or detector adapted to the field of application and to measure the observables. At the basis of Geant4 software, a category scheme is needed for the designed detector structure to be able to determine both geometric and physical phenomena and read the results. Starting from the root of the scheme and moving upwards, the essential structures and procedures for the simulation are performed, so that a subaltern structure of the simulation operation in a certain order and order is created [10].

In this study, dosimetry calculations were made for different phantom materials that can be employed for Leksell Gamma Knife device. Water, brain, PMMA and polystyrene were used as the phantom material types. Solid water, brain, PMMA and polystyrene phantom taken into consideration and the design of the skull and device source was made with the Geant-4 computer-based program, and the target doses were determined.

The rest of the paper is structured as follows: Section 2 describes the material and the method employed in our study, followed by Section 3 where findings are presented and discussed. Finally, the paper is concluded in Section 4.

2. Material and Method

In the study, a Gamma Knife device, brain phantom was simulated using Geant4. The Gamma Knife Device (GK) used was the 4C model with 201 sources. Phantoms are materials that are equivalent to human tissue and which are used to examine dose distributions in tissue. Studies with these phantom in the medical fields have been popular lately. For example, in dentistry, tissue-equivalent phantom was used to calculate dose rates of tumors at different depths with proton therapy.

This study mainly proposes to employ Geant4 platform, using Monte Carlo algorithms, to compute the radial dose distributions obtained from a single radiation beam of 8 mm and 14 mm collimator helmet in altered phantom materials. The material compositions of these phantom obtained from ICRP [11] are shown in Table 1.

Table 1. Phantom materials used in the analysis.

Component Name	**Chemical Formula**	**Density**
PMMA	$(C_5O_2H_8)_n$	1,18 g/ml
Polystyrene	$(C_8H_8)_n$	0.96–1.05 g/ml

In this study, a 80 mm radius phantom was used. As a phantom material are selected solid water, brain, PMMA (poly-methyl methacrylate) and polystyrene.

Geant4 is a modern Monte Carlo simulation program that emerged in 1993 with the work of scientists at CERN (European Organization for Nuclear Research), which can simulate particles interacting with matter. The name Geant is derived from the words "GEometry ANd Tracking" [12].

In Geant4 application, firstly, the preparation of geometry such as materials to be simulated, volumes and locations; description of related physics such as particles, physical processes, models and production threshold energy; formation mechanism of primary particles; display of prepared geometry and particle traces; adding user User Interface (UI) commands; During the simulation, necessary information must be collected [13].

For the simulation application of the Gamma Knife device, a new modular design was made by using the documentation of the existing system and taking its technical features. The aim here is to define the gamma beam profile and to reveal the most appropriate and useful structure for obtaining beam profile by using existing irradiation-collimator materials.

In the Geant4 simulation program, while preparing the simulation software of the Gamma Knife system, four basic steps were taken into consideration: 1) Defining the general structure, 2) creating the physical geometry, 3) defining the physics events and 4) simulation process and calculations.

3D models of Gamma Knife design were prepared and preliminary graphic models for simulation were created in computer environment. The 3D designs of the source are shown in Figure 1 below [14].

The shapes forming three basic geometric structures as World, Target and Tracker are defined with codes in Geant4 software. According to this definition, the world; A room with an indoor environment of 400x400 cm^2 air represents the position in the modeling and the model of the environment where the experiment will take place.

Target was defined as 90 × 90 × 90 mm voxel detector plate. Other materials were also defined as similarly. These definitions; While creating the basic geometric structure, the collimator head and dimensions that ensure the exact fit of the model are defined. Geometric definitions of other objects are made similarly [16].

In the last step of the simulation study; It includes simulation processes and physical calculations in a way that is exactly appropriate for the model. The Gamma knife device consists of a hemispherical iron-coated unit containing 201 co-60 sources.

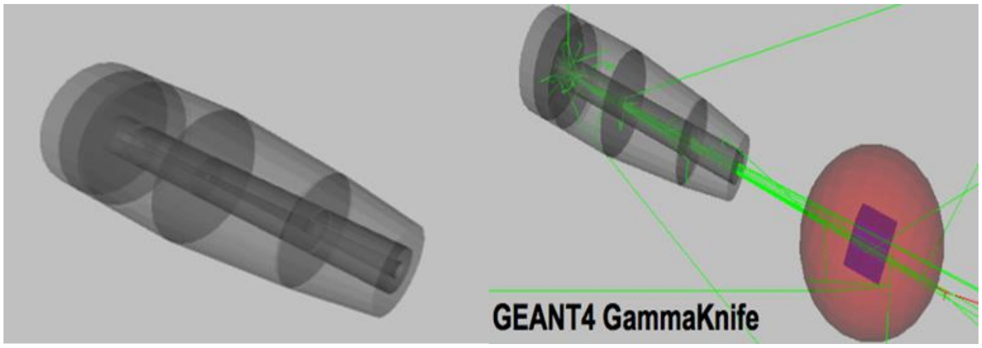

FIGURE 1. 3D resource design with Geant4 [15].

Gamma rays come from different directions and focus on the target.

Calculations were made for 4, 8 mm collimators. The stored energy was calculated at the end of the simulation in voxels divided into small 90x90x90 mm cubes using scoring mesh.

In the modeling study, firstly, instead of 201, the gamma ray originating from a single source was taken as a reference and calculations were made for 201 sources at different angles.

While modeling, the spherical water phantom having a radius of “80 mm”, the brain phantom taken from ICRU data, PMMA (Poly-methyl methacrylate) and polystyrene phantom were used in dosimetric measurements (ICRU). The distance between patient source is 401 mm. Two gamma rays of 1.17 MeV and 1.33 MeV are released from the Co-60 decay. The stored energy was plotted by normalizing the dose with the data taken from the simulations.

3. Results And Discussion

The simulation results were used to analyze the differences between varying embolization materials. The findings are described in the following.

The absorbed doses were compared in Table 2. The difference between the brain and the water phantom was observed as 12.5% and 7.9% for collimators with diameters of 4mm and 8 mm, respectively. The difference between the brain and the PMMA phantom was found as 12.6% when using a 4mm diameter collimator while it was 1.4% for the 8mm diameter collimator. The difference between the brain and the

Polystyrene phantom was observed as 6.2% and 3.6% for collimators with diameters of 4mm and 8 mm, respectively.

TABLE 2. Comparison of absorbed doses for different phantoms materials.

Collimator helmet size	**Mean peak dose Phantom (a)**	**Mean peak dose Phantom (b)**	**% difference ǀ(a-b)ǀ×100/a**
4 mm	Brain 0,8420	Water 0.9473	12.5
		PMMA 0.9481	12.6
		Polystyrene 0.8945	6.2
8 mm	Brain 0,9268	Water 0.8530	7.9
		PMMA 0.9399	1.4
		Polystyrene 0.8928	3.6

When Figures 2 and 3 are examined, it can be seen that the normalized dose curve expands as the collimator diameter increases. That is, as the collimator diameter increased, normal tissue received more doses. In addition, another observation is that as the collimator diameter increases, the margin of error decreases according to Table 2.

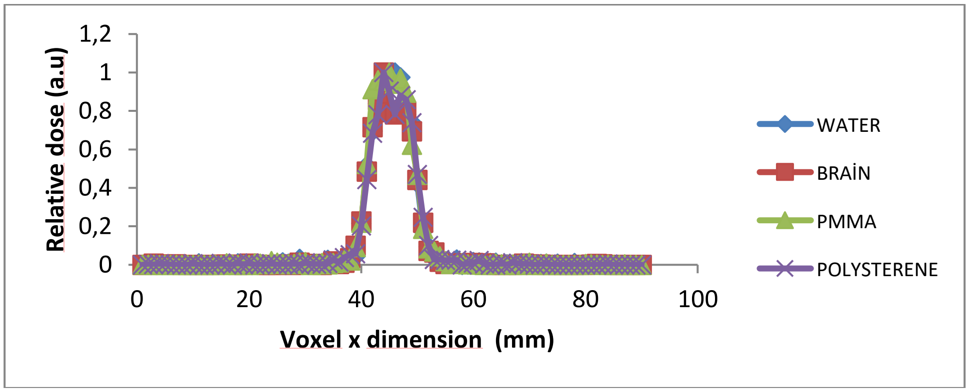

FIGURE 2. An evaluation graph of radial doses obtained from different phantom materials (4 mm collimator helmet of the “Leksell Gamma Knife”).

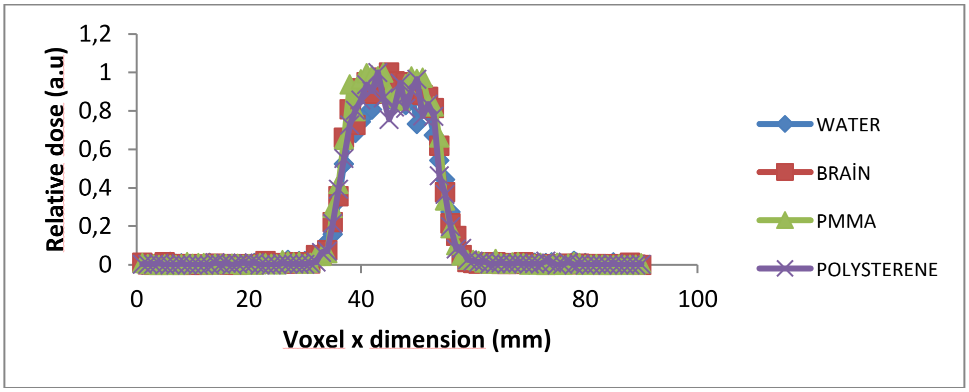

FIGURE 3. An evaluation graph of radial doses obtained from different phantom materials (8 mm collimator helmet of the "Leksell Gamma Knife").

Table 3 shows the results of the t-test performed to find out whether there are significant differences in the dose difference computed for different embolization materials. The simulations were run 10 times and the dose accumulations are compared. From the results, one can conclude that there are significant differences between water and brain while the differences of PMMA and Polystyrene were not found to be statistically significant.

TABLE 3. Statistical evaluation of dose differences of phantom materials with brain t-test.

	Water	**PMMA**	**Polystyrene**
"t Stat"	4.031180	-0.277680	1.120481
"P(T<=t) one-tailed"	0.000713	0.392812	0.141391
"t critical , one tailed"	1.770933	1.770933	1.770933
"P(T<=t) two-tailed"	0.001426	0.785624	0.282782
"t critical , two tailed"	2.160369	2.160369	2.160369

4. CONCLUSIONS

The correct determination of the radiation dose given to the patient is critically important. Therefore, phantoms are used that are equivalent to human tissue and examine the dose distribution in the tissue.

Our results show that the differences between the dose values using Geant4 for solid water phantom, brain, PMMA and polystyrene are remarkable. The percentage difference of Table 1 indicates some differences; however, these differences were not found to be statistically significant when the t-test was applied. Furthermore, these differences in statistical terms are not larger than the acceptable range (< 3%) prescribed by the stereotactic radiosurgery. Results reveal different radiation dosimetries based on the material types. Besides, the polystyrene and PMMA phantoms are also appropriate for determining the dose profiles of the Gamma Knife unit as can be seen in [17].

Dose distribution in Leksell Gamma Plan (LGP) was calculated based on a homogeneous phantom. Different results can be obtained when materials of different densities are involved into the experimental process. Result encourage authors to adapt Geant4 simulations to investigate further problems regarding SRS [18].

Author Contribution Statements O.D. and E.B. designed the model and the computational framework and analysed the data. O.D. carried out the implementation and performed the calculations. O.D. and E.B. wrote the manuscript with input from all authors. H.E., G.K., F.E. and M.S.G. conceived the study and were in charge of overall direction and planning. In addition, all authors discussed the entire study and approved the final version.

Declaration of Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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