

Monte Carlo Dosimetry for ^{125}I Eye Plaque Brachytherapy

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Abstract

In this study, Brachytherapy dose distribution is evaluated for a 12 mm COMS eye plaque loaded with model 6711- ^{125}I seeds. The dose rate constant, air kerma strength per contained activity (UmCi^{-1}) for the radioactive seed (model 6711) and air kerma strength to deliver 85 Gy in depth of 5 mm on central axis in water and homogenized eye were also calculated. Furthermore, comparison between MCNP4C and MCNP5 codes was done. Due to the Silastic carrier attenuation, PMMA carrier with lower effective atomic number has been studied as a substitute. The results show that the Silastic insert has significant effect on the dose reduction along the central axis of the eye plaque in comparison with PMMA insert. The isodose contours were plotted by considering lens and homogenized eye composition.

Keywords: MCNP; Eye plaque; Brachytherapy; Dosimetry

Introduction

Chroidal melanoma is the most common cancer among malignant eye tumors. Different modalities such as enucleation, X-ray teletherapy, proton beam therapy and eye plaque brachytherapy are employed for treatment of these tumors [1]. Eye plaque brachytherapy is the most popular method to treat eye melanoma because of its conformal dose distribution compared with EBRT [2] and more economical and accessible compared with proton beam therapy [3].

The standard design of eye plaque recommended by COMS protocol is made of a gold alloy backing with Silastic insert. There are some slots on Silastic that brachytherapy seeds place in. Depend on the size and stage of tumor; plaques are available in six standard sizes [4]. Implantation of seed was considered to deliver 85 Gy dose at 5 mm depth on the central axis for a treatment time of 100 hours [5]. ^{125}I brachytherapy seed model 6711 and 12 mm diameter COMS plaque were simulated. The air kerma strength, S_k , per contained activity (UmCi^{-1}) and dose rate constant, Λ , were obtained according to the TG-43U1 recommendations for a single seed [6]. In addition, Monte Carlo method was used to calculate required air kerma strength of each seed to deliver 85 Gy prescription dose by plaque at 5 mm depth (apex). Silastic with an atomic number of 10.7 causes a significant decrease in dose than water ($Z_{\text{eff}} \sim 7.4$), specially for the lower energy photons [7].

In this study use of PMMA carrier instead of Silastic was investigated. Since PMMA is a biocompatible medium it can be an appropriate substitute for Silastic. With respect to critical situation of eye, accurate dose calculation by applying reliable version of Monte Carlo code is inevitable. This study has been examined the potential of different cross section library used in MCNP5 versus MCNP4C and the effect of these different versions of MCNP code on calculation of dose.

Materials and Methods

^{125}I source description:

The information presented in the latest publication by Dolan et al. [8] was used to simulate the model 6711 ^{125}I Seed. The source has an effective active length of $L=2.8$ mm. The length of Ti capsule, inner and outer diameters were 4.55 mm, 0.5 mm and 0.8 mm, respectively. The source consists of a cylindrical silver core onto which a layer of ^{125}I

has been uniformly adsorbed. The thickness of radioactive layer was estimated about 2 μm .

Monte Carlo calculations:

The dose distributions were simulated by use of two versions of the Monte Carlo (MC) radiation transport code published by Los Alamos National Laboratory. The photon cross-section library of MCNP5 (MCPLIB04) is based on the ENDF/B-VI data [9] and the MCNP version 4C photon cross-section library (DLC-200) is based on Storm and Israel [10].

The dose rate distributions in water were calculated from the energy deposition averaged over a cell using the MCNP F6 tally in MeV/g particle and converted to absorbed dose by conversion factors. The photon energies and Photons per disintegration for ^{125}I were extracted from TG-43U1 [6].

According to TG43-U1 recommendation, the proposed formula for two-dimensional dose rate is:

$$\dot{D}(r, \theta) = S_k \wedge \frac{G(r, \theta)}{G(r_0, \theta_0)} g(r) F(r, \theta) \quad (1)$$

Where $\dot{D}(r, \theta)$ is the dose rate in water at the distance r in cm from a line source and θ denotes the polar angle specifying the point of interest, S_k is the air-kerma strength has unit of $U = \text{cGy cm}^2 \text{h}^{-1}$, Λ is the dose rate constant expressed in $\text{cGy h}^{-2.1} \text{U}^{-1}$; $\frac{G(r, \theta)}{G(r_0, \theta_0)}$ is the geometry factor; r_0, θ_0 are the reference position, $r_0 = 1$ cm and $\theta_0 = 90^\circ$, $g(r)$ is the radial dose function; and $F(r, \theta)$ is the anisotropy function.

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The dose rate constant, Λ , for the ⁶⁷¹¹-¹²⁵I seed was calculated as the ratio of the dose to water at 1 cm from the seed along the transverse axis, to the source's air-kerma strength, S_k , at distance r from the source center. The air-kerma strength was calculated using the recommended equation below [11]:

$$S_k = \dot{K}_\delta(r)r^2 \quad (2)$$

Due to the low energy of the photons from ¹²⁵I, it was assumed that in the Monte Carlo calculations all electrons generated by the photon collisions are absorbed locally, so the dose is equal to kerma at all points of interest [12,13]. The air-kerma rate, $\dot{K}_\delta(r)$, of the seed was estimated by calculating the dose in 1 mm-thick air-filled rings in a vacuum. The rings were bounded by 86° and 94° conics and defined with a radial increment of 5 cm to 150 cm along the transverse axis of the source to find the S_k that is independent to distance. The dose distributions were calculated from the energy deposition averaged over a cell tally F6 in MeV/g/source photon. The geometry function, $G(r, \theta)$, takes into account the effect of the distribution of radioactive material inside the capsule on the dose distribution [14]. In this study the geometry function was calculated for a line source using the MCNP F4 tally, particle fluence (1/cm²) with the mass densities of all materials within the entire computational geometry set equal to zero so there were no interaction through the seed and phantom geometry [15,16].

The dose distributions were calculated from the energy deposition averaged over a cell tally F6 in MeV/g/source photon. For the simulations, the titanium characteristic K-Xray production was suppressed by using a cut-off energy δ of 5 keV [6].

In Radiation transport calculations, 1.5×10^8 and 3×10^8 starting particles were used for air kerma strength and for dose rate in water, respectively. This amount of starting particles produced statistical uncertainty below 0.1% in both air and water.

COMS plaque simulation

The 12 mm diameter COMS eye plaque with 8 seeds was modeled in this study. The eye plaque is consisted of 0.5 mm thick gold alloy backing with inner and outer radius of curvature 15.05 mm and 12.3 mm, respectively. The seed carrier insert was modeled for the both Silastic and PMMA materials. The plaque positioned on a spherical eyeball, 24.6 mm in diameter by considering lens and homogenized eye materials according to ICRU 46 (Figure 1) [17]. In order to consider the effect of backscatter photons the plaque and eyeball were simulated in a 30 cm diameter spherical water phantom.

The seeds copied and translated into the various plaque geometries with the cell transformation card, TRCL [9]. Depth dose was calculated along the central axis of the eye plaque in water using tiny cylindrical voxels from outer sclera to 10 mm inside the eye. The dimensions of cylinders were 0.05 mm radius and 0.01 mm thick. The dose rate was calculated by converting MeV/gr to Gy, dividing this number by the air kerma strength per contained activity (UmCi⁻¹) for one seed and multiplying by the number of the seeds and the air kerma strength per seed, ${}_{source}S_k$ [18,19]. The air kerma strength of each seed was calculated to deliver 85 Gy to a central axis depth of 5 mm. The total dose delivered during a treatment is then determined by integrating over the treatment time, 100 h, taken into account the decay factor of the source [17,18]. For the simulation by using LAT card, the dose values were determined in $0.5 \times 0.5 \times 0.5$ mm³ voxels inside the eye on bisecting transverse plane and the isodose contours were plotted.

Results and Discussion

For the model 6711, dose rate constant, ${}_{MC}\Lambda$, and air kerma strength, s_k , per contained activity values were calculated to be 0.935 cGy h⁻¹U⁻¹ and 0.712 UmCi⁻¹, respectively (Table 1). The MCNP simulation method in this work was benchmarked with the ⁶⁷¹¹-¹²⁵I in the TG-43U1. The comparison of calculated values in this study, with the previously published data [16,18], demonstrates the accuracy of our simulation method (Table 1).

The air kerma strength per seed, ${}_{source}S_k$, required to obtain a prescription dose of 85 Gy at the tumor apex for a 100 hours was calculated 4.656 U/seed in water; there is a -1.2% difference in comparison with Melhus et al. result. This parameter was also scored 4.829 U/seed by employing homogenized eye and lens material.

Figure 2 shows the comparison between the calculated dose values in this study and those obtained by Melhus et al. [18] along the central

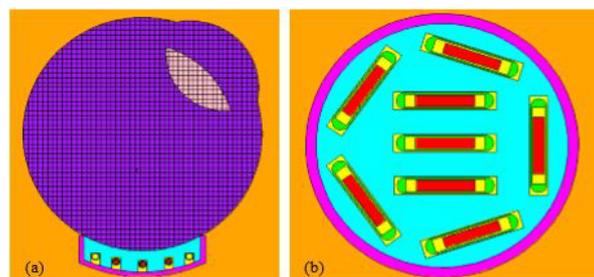


Figure 1: a) A cross section of the eye phantom with a 12 mm diameter COMS eye plaque used in the MCNP calculations. The dose values were determined in $0.5 \times 0.5 \times 0.5$ mm³ voxels inside the eye, b) the ⁶⁷¹¹-¹²⁵I seeds arrangement in the eye plaque.

	sk/A (U/mCi)	MCA(cGy h ⁻¹ U ⁻¹)	${}_{source}S_k$ (U)
$\dot{\gamma}$ (mcnp5)	0.712	0.935	4.656
$\dot{\gamma}$ (mcnp4c)	0.716	0.85	5.22
Melhus et al. [18]	0.712	0.921	4.738

Table 1: Comparison of air kerma strength per contained activity, dose rate constant and air kerma strength per seed needed to provide 85 Gy prescription dose at the tumor apex using MCNP4C and MCNP5 with similar work.

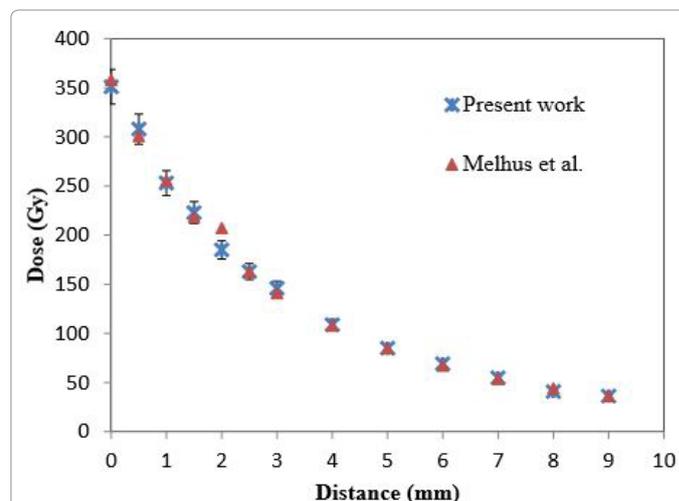


Figure 2: Calculated central axis depth-dose distribution for the 12 mm COMS plaque fully loaded with ⁶⁷¹¹-¹²⁵I seeds in comparison with Melhus et al. [11].

axis for a 12 mm diameter COMS plaque fully loaded with ¹²⁵I seeds in water. The differences are less than 4%. Using different database for extracting energies and abundances can justify these differences [6,20-28].

Table 1 compares the calculated air kerma strength per contained activity by MCNP4C and MCNP5 codes with Melhus et al. [18] results. In Table 2, the calculated dose rate values on central axis are compared for different carrier materials. The comparison shows that the attenuation of PMMA carrier is significantly less than Silastic carrier.

Table 3 shows relative errors of the dose rate per mCi on central axis in the water by applying MCNP4C and MCNP5 codes. MCNP4C code demonstrated large discrepancies compared with MCNP5. A difference about 10% was observed at prescription point (Apex) and external sclera (-1 mm).

Table 4 presents the comparison of MCNP4C and MCNP5 for evaluating the differences in the dose rate values at points of interest for a plaque located midway between posterior pole and equator temporal to eye globe by employing homogenized eye and lens material. The results showed 6.5% underestimation of dose in center of lens and 8.6% in macula by using MCNP4C. Also the absolute dose values in critical organs by employing required air kerma strength to deliver 85 Gy at the tumor apex in 100 hours are tabulated in Table 4.

Table 5 shows dose distribution along the central axis by using water and eye compositions. According to the table, the differences between dose values in water phantom and eye phantom are less than 5.5% but for accurate dosimetry it's recommended to consider the eye phantom in the simulations.

Figure 3 presents two dimensional isodose curves using fully loaded 12 mm COMS plaque applying ¹²⁵I seeds. The isodose curves values have been normalized to the maximum dose value. By increasing the distance from the plaque (Along the z coordinate) the dose is reduced and the reduction is about 20% at the apex. The rate of decrease is quick for the higher z.

Conclusions

In this study, to investigate the various aspects of eye plaque dosimetry the COMS eye plaques loaded with model 6711-¹²⁵I seeds

Distance (mm)	Silastic	PMMA	Difference (%)
	(Gy mCi ⁻¹ h ⁻¹)		
-1	6.7	8.27	19
-0.5	5.16	6.17	16
0	4.15	4.97	16
0.5	3.62	4.09	12
1	2.99	3.43	13
1.5	2.64	2.99	12
2	2.2	2.46	11
2.5	1.87	2.16	13
3	1.68	1.89	11
4	1.29	1.41	9
5	1.01	1.09	8
6	0.82	0.93	12
7	0.63	0.71	12
8	0.47	0.52	10
9	0.41	0.48	16

Table 2: Calculated dose rate values on central axis of the eye plaque by considering Silastic and PMMA as the seed carriers.

Central depth axis (mm)	Dose rate per activity along the central axis (cGy·mCi ⁻¹ ·h ⁻¹)		
	mcnp5	mcnp4c	Difference (%)
-1	6.74	6.02	10.7
-0.5	5.14	4.67	9.15
0	4.14	3.85	6.82
0.5	3.63	3.26	10.3
1	2.98	2.65	11.1
1.5	2.63	2.47	6.19
2	2.19	2	8.74
2.5	1.92	1.69	12.4
3	1.73	1.55	10.3
4	1.28	1.17	9.05
(Apex)5	1	0.899	10.3
6	0.815	0.721	11.5
7	0.649	0.592	8.7
8	0.482	0.451	6.49
9	0.429	0.388	9.49

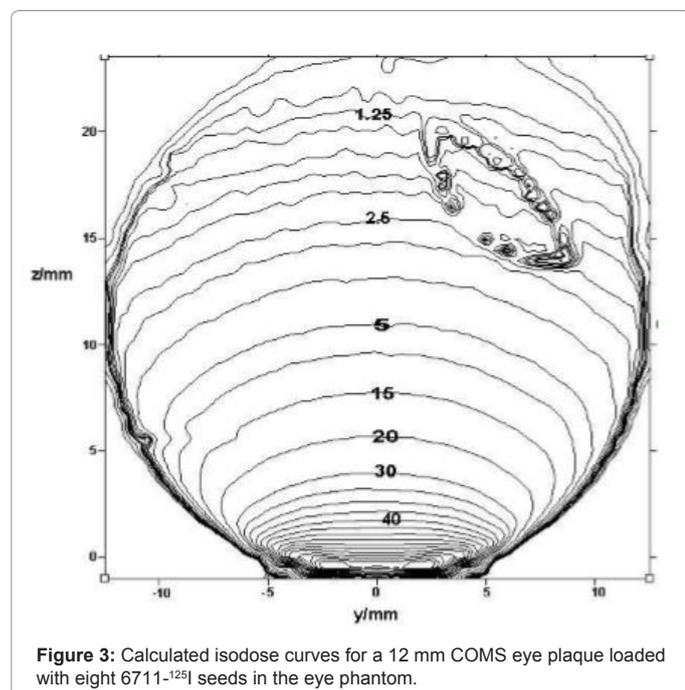
Table 3: Comparison of the Monte Carlo calculated dose rate per activity along the 12 mm eye plaque central axis using two versions of mcnp code in the water phantom.

Location	(a) Dose rate per activity (cGy·mCi ⁻¹ ·h ⁻¹)			(b) Absolute dose (Gy)
	MCNP5	MCNP4C	Difference (%)	MCNP5
	Center of lens	1.18E-01	1.11E-01	6.4
Macula	4.73E-01	4.32E-01	8.6	42
Optic disc	2.16E-01	2.03E-01	6.4	19
Center of eye	2.69E-01	2.48E-01	7.8	23.7
Sclera	5.04E+00	4.54E+00	10	442
Apex	9.68E-01	8.80E-01	9.1	85
Opposite side	5.89E-02	5.64E-02	4.3	5.2

Table 4: The Monte Carlo Calculated of a) dose rate per activity using MCNP4C and MCNP5 in the eye phantom and b) absolute dose at points of interest for a 12 mm diameter plaque.

Distance (mm)	Absolute dose (Gy)		
	Eye phantom	Water phantom	Water phantom [11]
-1	603	571	534.8
-0.5	442	436	435.7
0	362	351	358.2
0.5	303	308	301.1
1	258	253	255.6
1.5	220	223	218.2
2	190	185	207.2
2.5	163	163	162.7
3	142	146	141
4	109	109	108
5	85	85	85
6	67	69.1	67.2
7	54	55	53.8
8	43.3	40.9	44.2
9	35.7	36.4	36.4
source S ₀ (U/seed)	4.829	4.656	4.735

Table 5: The Monte Carlo calculated dose values using MCNP5 along the eye plaque central axis in water and eye phantoms.



was modeled. The dose on critical organs by employing eye and lens composition from ICRU 46 were obtained. These materials can considerably affect the source air-kerma strength and dose distribution as well. Due to the large attenuation of ^{125}I photons in Silastic, the PMMA material can be a suitable carrier instead of Silastic. Two different versions of MCNP code with different cross-section libraries were used to investigate on eye plaque dosimetry. A large discrepancy was observed between these two versions of MCNP code. User of this code must be aware; MCNP4C code underestimates the dose values for low energy brachytherapy sources.

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