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Experimental measurements and Monte Carlo calculations for ^{103}Pd dosimetry of the 12 mm COMS eye plaque

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Abstract Monte Carlo simulations and TLD dosimetry have been performed to determine the dose distributions along the central axis of the 12 mm COMS eye plaques loaded with IRA1- ^{103}Pd seeds. Several simulations and measurements have been employed to investigate the effect of Silastic insert and air in front of the eye on dosimetry results along the central axis of the plaque and at some critical ocular structures. Measurements were performed using TLD-GR200A circular chip dosimeters in a PMMA eye phantom. The central axis TLD chips locations were arranged in one central column of eye phantom, in 3 mm intervals. The off-axis TLD chips locations were arranged in three off-axis columns around the central axis column. Version 5 of the MCNP code was also used to evaluate the dose distribution around the plaque. The presence of the Silastic insert results in dose reduction of 14% at 5 mm; also about 7% dose reduction appears at the interface point, due to the air presence and lack of the scattering condition. The overall dosimetric parameters for the COMS eye plaque loaded with new palladium seeds are similar to a commercial widely used seed such as Theragenics200. As the dose calculations under TG-43 assumptions do not consider the effect of the plaque backing and Silastic insert for accurate dosimetry, it's suggested to apply the effect of the eye plaque materials and air on dosimetry results along the central axis of the plaque and at some critical ocular structures.

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Introduction

Eye plaques have been increasingly used in recent years in the radiation therapy of Choroidal melanoma since this method of therapy has the potentiality to preserve vision and save the eye globe [1–3]. Choroidal melanoma is the most common primary intraocular malignancy in adults, originating within the pigmented cells of the choroid [4,5]. In 1986, a 5 year randomized trial – the Collaborative Ocular Melanoma Study (COMS) – was launched to evaluate therapeutic interventions for this cancer [6]. Patients with a clinical diagnosis of medium-sized choroidal melanoma (between 2.5 and 10 mm in height and <16 mm basal diameter) are candidates for episcleral plaques if the patient is otherwise healthy and without metastatic disease [7].

Compared to charged particle radiation the collimating effect of the eye plaque creates better conformality than protons and essentially gives very low dose to the brain and orbit behind the plaque. In addition the tumor control rate for plaque therapy is very high with preservation of the eye and recovery of vision [9]. ^{125}I eye plaques are currently the most commonly used for treatment of intraocular tumors but after ^{103}Pd seeds became available in 1990's, some few centers use palladium-103. The short half-life (~ 17 days) and low energy photon emissions of ^{103}Pd (21 keV) present less radiation exposure hazard to personnel since it is more easily absorbed by the eye plaque in comparison with the ^{125}I sources [8]. In this work the experimental measurements and Monte Carlo calculations have been performed for a 12 mm COMS eye plaque loaded with IRA1- ^{103}Pd seeds to determine the dose distribution along the plaque central axis and at the points of interest, such as the center of lens, macula, optic disk, sclera and lacrima gland.

As the internal component of the seed is free to move inside the seed capsule, three geometric models of the seed, based on different locations of silver core inside the titanium capsule were simulated and dosimetric effect of this movement has been studied.

The palladium seeds are loaded into a Silastic seed-carrier insert, inside the gold backing. Due to the low energy of the photons from ^{103}Pd , the effect of Silastic insert on dose distribution is expected to be significant and was evaluated in this work. Also the effect of the air in front of eye has been investigated by the Monte Carlo and experimental dosimetry methods. All the Monte Carlo results have been compared with measurement values obtained in this study and compared with other similar published data, Zhang et al. [12], Thomson et al. [13], de la Zerda et al. [15] Melhus and Rivard [22], and Thomson and Rogers [23], to show that from a dosimetry point of view, COMS eye plaque loaded with IRA1- ^{103}Pd seeds are suitable for use in brachytherapy of eye melanoma.

Methods

Source description

The ^{103}Pd source used in this study is the model IRA1- ^{103}Pd seed which is designed and fabricated in Agricultural, Medical and Industrial Research School (AMIRS) [10,11].

Geometry and construction of the seed were taken from AMIRS institute.

The seed contains a 3.5 mm silver core ($\rho = 10.5 \text{ g/cm}^3$), with a 0.5 mm layer of ^{103}Pd adsorbed on its surface. The seeds and silver wire are packed inside the 0.05 mm thick pure titanium capsule ($\rho = 4.54 \text{ g/cm}^3$) of 4.8 mm length and 0.8 mm external diameter. The end caps, which were laser welded on the wall of the capsule, have an average thickness of 0.6 mm. According to TG-43UI, the effective length is considered as the distance between proximal and distal aspects of the activity distribution which is 3.5 mm. The maximum possible displacement of the silver core from its nominal position is 0.1 mm along the seed axis and 0.2 mm in the radial direction (Fig. 1).

Eye plaque description

This study used a 12 mm COMS model eye plaque which is composed of two parts as follows:

- The plaque backing, which is made of gold with the composition of (by weight) 77% gold, 14% silver, 8% copper, and 1% palladium and a density of $15.8 \pm 0.06 \text{ g/cm}^3$ [13].
- The polymeric insert as a seed carrier. To obtain the effect of polymeric insert on dose distribution, two polymeric inserts have been tested in this study: a Silastic insert with the composition of (by weight) 6.3% hydrogen, 24.9% carbon, 28.9% oxygen, 39.9% silicon, and 0.005% platinum and a density of 1.12 g/cm^3 [13], and a PMMA insert with the composition of (by weight) H, 8%; C, 60%; O, 32% and density equal to 1.19 g/cm^3 .

Figure 1 Schematic cross-sectional view of the IRA1- ^{103}Pd brachytherapy seed in a) Ideal, b) Diagonal, and c) Vertical orientations.

The 12 mm COMS eye plaque (loaded with $\text{IrA1-}^{103}\text{Pd}$ seeds distributed in Silastic/PMMA insert) was applied to the eye phantom for experimental measurements (Fig. 2a).

The coordinates of 8 sources in a 12 mm COMS eye plaque were based on the original COMS design [14]. The longitudinal axes of the seeds are perpendicular to the eye phantom central plane.

Phantoms description

The eye phantom was designed with the same dimensions used by Thomson et al. [13]. We have performed thermoluminescent (TLD) dosimetry in a sphere PMMA eye phantom ($\rho = 1.19 \text{ g/cm}^3$) with 2.46 cm diameter manufactured in AMIRS. To determine the dose along the central axis of the eye phantom, the central axis TLD chips locations were arranged in one central column of the eye phantom, in 3 mm intervals, beginning from 2 mm from the external surface of the Silastic insert/PMMA insert. In order to measure the doses at the points of interest, which are not located along the central axis, the off-axis TLD chips locations were arranged in three off-axis columns around the central axis column (Fig. 2b). The eye plaque was applied to the eye phantom for experimental measurements. To consider the effects of the surrounding medium, all the components, as shown in Figs. 2c and 3, were

embedded in the $20 \times 20 \times 15 \text{ cm}^3$ PMMA slabs, large enough to provide full backscattering conditions during measurements. To investigate the effect of the air in front of the eye on dose distribution the PMMA slabs in front of the eye phantom have been replaced by air (Fig. 2d) and the central column of the eye phantom field by TLDs. To avoid interference and shielding effect from any TLD in each experimental run only one TLD chip has been located in each column and the other empty locations were filled by PMMA chips to fill the air cavities [3,15].

To evaluate the effect of the Silastic insert on dose distribution around the eye plaque, we repeated the above measurements by replacing the Silastic by PMMA insert. For each experimental study, the measurement was repeated three times.

Thermoluminescent dosimeters (TLD)

TLD-GR200A (LiF: Mg, Cu, P) (PTW, Freiburg, Germany) circular chips of 0.8 mm thickness and 4.5 mm diameter were used in this study [16]. The irradiated TLDs were read using a KFKI RMKI TLD reader (KFKI Research Institute of the Hungarian Academy of Sciences, Budapest, Hungary) and were annealed by heating at 240°C for 10 min followed by fast cooling.

Figure 2 Schematic diagrams of a) ^{103}Pd seeds modeled in a 12 mm COMS eye plaque, b) COMS eye plaque loaded on the PMMA eye phantom. The TLD chips are arranged into channels along the columns, c) PMMA phantom contains eye phantom + COMS plaque to determine the dose rate and d) PMMA phantom contains eye phantom + COMS plaque to determine the effect of air in front of the eye.

Figure 3 Fabricated gold eye plaque, eye phantoms and PMMA slabs.

TLD measurement methodology followed by the following equation:

$$\frac{\dot{D}(r, \theta)}{S_K} = \frac{R_{\text{det}}(r, \theta) \cdot g(T)}{S_K \cdot \varepsilon_\lambda \cdot E(r, \theta)} \quad (1)$$

Where $R_{\text{det}}(r, \theta)$ is the TLD reading by considering the background doses and relative sensitivity of each detector derived from reading TLDs exposed to uniform doses, $g(T)$ is the decay correction and is equal to $1/(\text{effective exposure time})$, ε_λ is the measured response for calibrated beam and $E(r, \theta)$ is the relative TLD response at r in brachytherapy geometry [17].

TLD responses have been corrected for background by subtracting the average response of background TLDs from the responses of all other TLDs in each measurement. The sensitivity correction due to physical differences between the TLD chips for each TLD has been obtained by simultaneously irradiating the TLDs. Before every experiment, the entire batch of TLDs was exposed to a calibrated ^{60}Co standard beam (1250 keV) with a $10 \times 10 \text{ cm}^2$ field size, with a constant dose given each time. The variation of response of the TLDs to the same exposure was tracked by normalizing the individual TLD readings to the average value of the TLD readings [18].

Monte Carlo calculations

Dose distributions were simulated with the version 5 of the Monte Carlo (MC) radiation transport code by Los Alamos National Laboratory [19]. The MCPLIB04 photon cross-section library was applied using data from ENDF/B-VI [20]. Due to the low energy of the photons from ^{103}Pd (21 keV), it was assumed in the Monte Carlo calculations that all electrons generated by the photon collisions are absorbed locally; thus it was assumed that the dose is equal

to kerma at all points of interest [8]. The results from the MCNP5 calculations contain numerous flexible tallies: surface current and flux, volume flux, track length, point or ring detectors, particle heating, fission heating, pulse height tally. In this study cell-heating tally, F6, was employed to calculate absorbed dose. The characteristic X-ray production was suppressed with $\delta = 1 \text{ keV}$ (δ is the energy cut-off). The ^{103}Pd photon spectrum used in these simulations was obtained from TG-43U1 Table 13. Based on the photon energy spectrum recommended by TG-43U1, the uncertainty was set to 0.1% [21]. As the silver core is free to move within the titanium capsule, its location can vary with seed orientations. In our Monte Carlo calculations three geometric models of the seed were developed to investigate the effect of the seed orientation on dosimetric parameters. These models are as follows:

- 1 Ideal orientation, Fig. 1a.
- 2 Vertical orientation, Fig. 1b.
- 3 Diagonal orientation, Fig. 1c.

The simulations were performed with up to 2×10^9 histories for each orientation. With this number of histories, statistical uncertainty for the source along the longitudinal axis at $r \leq 5 \text{ cm}$ is lower than 1%, at 7 cm is 3.2% and at other angles it is between 0.03% and 0.09%. In air, with 1.4×10^8 histories, statistical uncertainty is less than 0.2%.

The plaque assumed a standard eye diameter of 2.46 cm. To obtain the dose rate around the eye plaque, eye ball and eye plaque are modeled in the center of $20 \times 20 \times 15 \text{ cm}^3$ phantom. The effect of Silastic insert on dose rate is provided by PMMA replacing by Silastic insert. To investigate the effect of the air on dose distribution more MCNP simulations have been done to model air in front of the eye.

The total dose is calculated by the following equation [13,22]:

$$\dot{d}(x, y, z) = {}_{sp}\dot{d}(x, y, z) \left[{}_{source}S_K \left(\frac{sk}{A} \right)^{-1} K \right] \cdot n \quad (2)$$

Where $\dot{d}(x, y, z)$ is the dose rate at (x, y, z) position, ${}_{sp}\dot{d}(x, y, z)$ is the dose rate per starting particle (MCNP output), ${}_{source}S_K$ is the product of the air-kerma rate and the square of the distance d to the point of specification from the centre of the source in its transverse plane, sk is the air-kerma strength per history estimated using Monte Carlo methods, A is the activity (mCi), K is the photons emitted per unit activity (photons mCi^{-1}), and n is the number of sources which are loaded in the eye plaque [21,22].

Central axis depth dose was calculated using the MCNP F6 tally for 0.05 mm radius and 0.01 mm thick cylindrical detectors from outer sclera (-1 mm) to 11 mm inside the eye in 0.5 mm steps. The doses were also calculated at the points of interest in the eye: center of eye, macula, optic disk, proximal sclera, tumor apex, lacrima gland and retina opposite to the apex. In this study the position of the points followed Thomson et al. [23]. The plaque is positioned between the posterior pole and equator and the Rayleigh scattering, Compton scattering, photoelectric absorption and fluorescent emission of characteristic K and L -shell X-rays are all modeled. For variance reduction technique,

Table 1 2-D anisotropy functions for the IRA1-¹⁰³Pd seed calculated by Monte Carlo method for the: a) Ideal orientation, b) Vertical orientation, and c) Diagonal orientation.a) 2-D anisotropy function, $F(r, \theta)$ in ideal seed orientation

r (cm)	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
0.25	0.026	0.076	0.568	0.819	0.93	0.964	0.982	0.985	0.996	1.000
0.50	0.104	0.167	0.456	0.673	0.815	0.912	0.981	0.991	0.996	1.000
0.75	0.149	0.210	0.506	0.675	0.811	0.901	0.966	0.996	0.996	1.000
1.00	0.172	0.251	0.494	0.679	0.805	0.892	0.957	1.011	1.014	1.000
2.00	0.237	0.323	0.537	0.697	0.812	0.891	0.948	0.993	1.032	1.000
5.00	0.313	0.407	0.581	0.719	0.816	0.892	0.944	0.985	1.015	1.000
7.00	0.362	0.455	0.602	0.736	0.823	0.889	0.945	0.981	1.008	1.000

b) 2-D anisotropy function, $F(r, \theta)$ in vertical seed orientation

r (cm)	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°
0.25	0.027	0.078	0.574	0.844	0.943	0.983	1.003	0.995	0.982	1.000	0.977	0.951	0.922	0.944	0.858	0.793	0.487	0.255	0.023
0.50	0.107	0.170	0.473	0.692	0.826	0.931	1.002	0.973	0.972	1.000	0.971	0.951	0.925	0.885	0.736	0.648	0.415	0.256	0.096
0.75	0.153	0.211	0.516	0.692	0.823	0.920	0.986	0.976	0.979	1.000	0.973	0.940	0.927	0.862	0.732	0.639	0.445	0.287	0.130
1.00	0.176	0.254	0.499	0.693	0.838	0.902	0.968	1.000	0.993	1.000	0.979	0.956	0.899	0.838	0.747	0.611	0.449	0.296	0.144
2.00	0.241	0.332	0.543	0.710	0.835	0.907	0.960	0.982	1.012	1.000	0.982	0.989	0.883	0.867	0.756	0.636	0.461	0.338	0.215
5.00	0.320	0.416	0.600	0.735	0.834	0.903	0.955	0.995	0.992	1.000	0.975	0.955	0.910	0.836	0.734	0.684	0.516	0.405	0.294
7.00	0.371	0.464	0.612	0.755	0.840	0.903	0.965	1.005	0.992	1.000	0.972	0.960	0.886	0.860	0.763	0.697	0.550	0.439	0.327

c) 2-D anisotropy function, $F(r, \theta)$ in diagonal seed orientation

r (cm)	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°
0.25	0.027	0.077	0.574	0.845	0.962	0.987	1.008	1.003	0.972	1.000	0.989	0.951	0.974	0.957	0.945	0.811	0.540	0.283	0.026
0.50	0.106	0.169	0.469	0.699	0.834	0.922	1.004	0.978	0.982	1.000	0.979	0.951	0.977	0.898	0.818	0.673	0.457	0.281	0.105
0.75	0.151	0.213	0.517	0.689	0.826	0.929	0.977	0.972	0.969	1.000	0.984	0.946	0.957	0.898	0.800	0.671	0.497	0.318	0.139
1.00	0.176	0.256	0.504	0.700	0.830	0.913	0.977	1.000	0.990	1.000	0.989	0.963	0.937	0.894	0.781	0.666	0.493	0.331	0.168
2.00	0.241	0.330	0.553	0.717	0.829	0.901	0.964	0.972	1.019	1.000	0.982	0.986	0.934	0.888	0.776	0.664	0.530	0.383	0.236
5.00	0.321	0.415	0.594	0.740	0.826	0.907	0.965	1.010	0.995	1.000	0.977	0.964	0.939	0.886	0.818	0.710	0.587	0.446	0.305
7.00	0.371	0.463	0.610	0.751	0.832	0.899	0.955	0.992	0.982	1.000	0.979	0.960	0.925	0.883	0.790	0.712	0.585	0.474	0.363

Table 2 Central axis dose distributions in 12 mm COMS eye plaques loaded with three $\text{IrA1-}^{103}\text{Pd}$ seeds in PMMA phantom, compared with the data by Mehus and Rivard's study [22].

Central axis depth (mm)	12 mm COMS eye plaque				
	Loaded with $\text{IrA1-}^{103}\text{Pd}$ seeds				Loaded with ^{103}Pd model 200 seeds
	With Silastic insert		Without Silastic insert		With Silastic insert
	MCNP5	TLD	MCNP5	TLD	Ref. [22]
–1	577.91	573.15	670.18	621.49	479.9
–0.5	468.56	476.73	542.04	511.73	423.8
0	370.62	424.33	424.47	407.03	366.5
0.5	309.43	—	353.84	—	313.1
1	299.62	291.26	342.06	328.71	268
1.5	251.95	—	288.97	—	230.2
2	197.54	197.42	226.93	209.46	199.1
2.5	176.64	—	202.03	—	171
3	144.88	144.56	166.35	154.07	147.1
4	116.42	119.62	133.67	127.13	111
5 (Apex)	85.00	85.00	85.00	85.00	85
6	60.08	54.93	68.36	58.21	65.8
7	46.46	43.02	52.81	45.53	51.8
8	28.93	26.73	32.92	28.23	41.3
9	23.29	21.66	26.43	23.10	32.7
10	19.11	18.27	21.57	19.37	26.1

the electron and photon transport energy cut-off in all calculations [13] was chosen at 1 and 5 keV, respectively.

In general 3.7×10^{10} photon histories were simulated and the statistical uncertainties of 0.6% and 1% were obtained at 5 mm (tumor apex) and 11 mm depth of central axis, respectively. Statistical uncertainties exceeded 2.6% at the opposite side of the eye which has the largest uncertainty among the interest points.

Results and discussions

To demonstrate the accuracy of our Monte Carlo calculations, the MCNP simulation method in this work was benchmarked with the Theragenics model 200 palladium source. Therefore the value of Δ of the model 200

brachytherapy seed was calculated in this study and compared with the previously published data for the seed [21,24].

The comparison between these two data sets, $0.685 \pm 0.021 \text{ cGy h}^{-1} \text{ U}^{-1}$ and $0.686 \text{ cGy h}^{-1} \text{ U}^{-1}$, is about 0.1%, which demonstrates the accuracy of our simulation method.

Based on the MCNP5 calculations, for the three seed orientations, the values of Δ in three orientations, ranged from 0.668 ± 0.02 to $0.673 \pm 0.02 \text{ cGyU}^{-1} \text{ h}^{-1}$, with the seed geometry uncertainty of 0.52% for this seed. According to TG43-U1, a standard geometry uncertainty of 3% for all Monte Carlo studies seems reasonable. Since the influence of variable orientation does not have a significant effect on dosimetric results, the ideal data set can be used for all

Table 3 Doses in gray at points of interest for 12 mm COMS eye plaque loaded with $\text{IrA1-}^{103}\text{Pd}$ seeds in PMMA phantom, with and without Silastic insert compared with the data by Thomson et al. [23] (eye plaque is positioned on equator nasal).

Points of interest	12 mm COMS eye plaque with $\text{IrA1-}^{103}\text{Pd}$ seeds				16 mm COMS with Theragenics 200 seeds
	With Silastic insert		Without Silastic insert		With Silastic insert
	MCNP5	TLD	MCNP5	TLD	Ref. [23]
Center of eye	4.93	5.18	5.56	5.13	18.3
Macula	8.57	—	9.81	—	8.09
Optic disk	4.20	—	4.82	—	14.1
Center of lens	11.02	11.56	12.43	11.55	12.5
Sclera	298.32	307.64	347.21	313.93	211
Apex	85.00	85.00	85.00	85.00	68.7
Lacrimal gland	1.50	—	1.68	—	3.03
Opposite side	1.75	1.41	1.96	1.39	2.94

possible capsule orientations. The air-kerma strength per seed, $_{\text{source}}Sk$, to obtain a prescription dose of 85 Gy at the tumor apex for a 168 h, was calculated 5.658 U/seed.

The anisotropy function, $F(r, \theta)$, of the IRA1- ^{103}Pd seed was calculated using MCNP5 at radial distances of $r = 0.25, 0.5, 0.75, 1, 2, 5$ and 7 cm relative to the seed center, and with a polar angle, θ ranging from 0° to 90° for ideal orientation and 0° – 180° for vertical and diagonal orientations in 10° increment with respect to the seed long axis. The results are shown in Table 1. The effect of the internal core configuration changes the value of anisotropy function as much as 5%. As shown in Table 1 the related uncertainty increases as photon energy decreases.

Based on the Monte Carlo calculations and TLD measurements, dose values at the central axis of the eye plaque and at points of interest have been determined and tabulated in Table 2 and Table 3, respectively. As the new seed model for this study does not appear to be widely used in brachytherapy, to study the effect of changing the seed model, we compare the calculated results with the published data for COMS eye plaque loaded with Theragenics200 seeds (Table 2) [22]. The difference between these two data sets derives from the use of two different palladium seed models (IRA1- ^{103}Pd and Theragenics 200). Using two different phantom materials in our study the dose distributions have been calculated and measured in PMMA phantom, while Melhus et al. [22] calculations were done in water phantom.

To investigate the effect of the Silastic insert on dose distribution along the plaque central axis, all the Monte Carlo simulations and experimental measurements were repeated by removing the Silastic insert (Table 2). For comparison all the measured data were renormalized to deliver the same apex dose of 85 Gy for the measured columns of the tables.

The TLD measured and calculated dose distribution along the central axis of the plaque is compared in Fig. 4. The differences between these two data sets are ranging from 5% (at 5 mm) to 15% (at 11 mm) and are large by depending on the distance. Errors of the measurements may be due to an inadequate energy response or to the

Figure 4 Comparison of the measured and the Monte Carlo dose of the 12 mm COMS eye plaque loaded with IRA1- ^{103}Pd seeds in PMMA phantom, along the central axis of the eye plaque. The solid line represents the polynomial fitted curve on simulation data.

finite dimensions of the TLDs used in this study. In our MCNP simulations as from TG-43U1 recommendation, all seeds were assumed to be positioned in ideal orientation. However in the experimental study the position of the silver core varied for seed orientation and this produces a disagreement between the two data sets.

The comparison shows that the attenuation of PMMA carrier is significantly less than that of the Silastic carrier. The calculated and measured values of the doses at points of interest (with and without Silastic insert) are tabulated in Table 3 and compared with Thomson et al. study [23]. Doses at the interest points from COMS plaque loaded with IRA1- ^{103}Pd seeds are lower the doses from COMS plaque loaded with Theragenics200 seeds with the exception of sclera.

The central axis doses for the IRA1- ^{103}Pd seeds in Silastic insert with gold plaque backing are shown in Fig. 5 relative to the doses for the same condition without Silastic insert. As Silastic ($Z_{\text{eff}} \sim 10.7$) is a more attenuating medium than PMMA ($Z_{\text{eff}} \sim 7$), the dose reduction for the gold + Silastic combination relative to gold + PMMA is about 14% at 1 cm and 15% at 0.5 cm (Apex) [6,25]. An acceptable agreement is observed between the calculated dose reduction and measured average values. Thomson et al. [13] reported a 17% dose reduction for Theragenics model 200 ^{103}Pd seed at distance of 1 cm in COMS plaque due to presence of Silastic insert. Chiu-Tsao et al. [3] obtained a 10% dose reduction at 1 cm for Silastic insert only, in a 20 mm COMS eye plaque for ^{125}I and 16% for ^{103}Pd (without gold backing) relative to water along the central axis.

By replacing PMMA slabs with air in front of the eye, the effect of air on dose distribution has been evaluated. As shown in Fig. 6, the presence of air in front of the eye results in backscatter absorption and decreases the dose of $\sim 7\%$ near the air interface due to the lack of the scattering condition. As the distance increases the reduction decreases and reaches 1% at larger distances. TLD dosimetry to investigate the effect of the air shows a dose reduction of about 11% at the air interface. The difference between measured and calculated data at the air interface is attributed to experimental error.

Figure 5 Ratio of the doses along the plaque's central axis for 12 mm COMS plaque loaded with IRA1- ^{103}Pd seeds with Silastic insert relative to the doses without Silastic insert in the PMMA phantom.

Figure 6 Ratio of the doses with air in front of the eye relative to the doses with no air in PMMA phantom.

Table 4 Uncertainty determination in experimental measurements of dose rate with the coverage factor $k = 2$.

TLD uncertainties

Component	Type A (%)	Type B (%)
Repetitive measurements	4.4	
TLD dose calibration		2
Energy dependence of LiF		5.5
Source to TLD positioning		1.1
Correction of PMMA to liquid water conversion factor		3
Combination in quadrature	4.4	6.7
Total combined standard uncertainty (u_c)	8	
Expanded uncertainty ($U = ku_c$), $k = 2$	16	

Type A uncertainty of repetitive TLD measurements of dose rate was determined to be 4.4% (calculated from five separate measurements for each condition). Type B uncertainties of TLD dose calibration, correction of energy dependence of LiF, seed to TLD positioning and correction of PMMA to liquid water conversion factor were obtained to be 2%, 5.5%, 1.1% and 3%, respectively. The combination in quadrature of these uncertainties is 4.4% and 6.7% for type A and B, respectively. The total combined uncertainty was 8% (Table 4).

Conclusion

The dose distributions from the IRA1- ^{103}Pd brachytherapy seeds in the 12 mm COMS eye plaque in the eye phantom have been obtained by theoretical calculations and experimental measurements. As the internal core of the seed is free to move inside the Ti capsule the dosimetric parameters of the seed have been calculated in three orientations of the seed. Since the impact of variable positioning of internal core does not have significant effect on dose rate, the ideal data set can be used for all possible capsule orientations.

Determinations of the dose values have been simulated using version 5 of MCNP code while the measurement were done using TLD-GR200A thermoluminescent dosimeters (TLDs). The agreement between the measured and Monte Carlo values indicated the proper selection of design, dimensions, and composition material of both the source and the phantom in the Monte Carlo simulations. We have also investigated the effect of the Silastic insert and air in front of the eye on dose distribution along the central axis of the plaque and at critical points of eye at off-axis. The dose reduction due to the presence of the Silastic was about 14% at 1 cm and 15% at 0.5 cm. Due to the large attenuation of ^{103}Pd in Silastic, the PMMA material can be a suitable carrier instead of the Silastic insert. Presence of air in front of the eye reduces the dose by 7% at the interface point. As the dose calculations done under TG-43 assumptions do not consider the effect of the plaque backing and Silastic insert, for accurate dosimetry, it's recommended to take into account the effect of the eye plaque materials and air on dose calculations.

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