

Determination of Out-of-Field Doses and Related Risks from the Photon Beam Radiotherapy

AKM Moinul Haque Meaze^{1,2*}, M. Z. Hossain^{2,3}, Tangina Akter^{2,4}, M. S. Rahman⁵,
Tanjim Siddiqua⁵, Nourin Arobi^{5,6}, Santunu Porohit², and Sadeka Sultana Rubai²

¹Department of Physics, Faculty of Natural Science, Asian University for Women,
Chottogram 4000, Bangladesh, ²Department of Physics, University of Chittagong,
Chottagram 4331, Bangladesh; ORCID ID: 0000-0002-1526-2113, ³Department of Physics,
Bangladesh University of Engineering and Technology (BUET), Dhaka-100, Bangladesh,
⁴Department of Sciences, BGMEA University of Fashion and Technology, Dhaka-1230,
Bangladesh, ⁵Secondary Standard Dosimetry Laboratory, Bangladesh Atomic Energy
Commission, Savar, Dhaka-1349, Bangladesh, ⁶Department of Physics, Jahangirnagar
University, Dhaka-1342, Bangladesh

* Corresponding Author: [moinul.haque@auw.edu.bd], meaze@cu.ac.bd

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Abstract

This study investigates out-of-field radiation doses and associated risks in radiotherapy using experimental measurements and standard dosimetry techniques. Radiotherapy is a primary modality for cancer treatment, delivering therapeutic radiation doses to tumors while minimizing exposure to surrounding tissues. Although radiation outside the treatment field is small, it can still cause late radiogenic effects. This study investigates out-of-field doses and related risks using an Alderson Rando phantom and a ⁶⁰Co teletherapy beam. Absorbed doses in target organs and effective doses in peripheral organs were measured with thermoluminescence dosimeters (TLDs). Dosimetry was performed using an FC65G Farmer chamber, NE2575 ion chamber, and water phantom following IAEA TRS-398 protocols. TLDs were placed at different depths in target organs, including the left lung, right lung, stomach, and on the surface of peripheral organs. Irradiations were performed at 100 cGy and 200 cGy, and the TLD readings were obtained using a calibrated TLD reader. Measured organ doses were very close to or slightly lower than the expected values at most depths. The TLDs showed a linear dose response with an uncertainty of 1.54%. Depth dose correction factors for ⁶⁰Co beams were calculated to ensure accurate treatment and maximum dose delivery. The depth-dose correction factors obtained in this study for the lung, stomach, kidney, and spleen are 0.897±0.028, 0.775±0.023, 0.765±0.027, and 0.723±0.118, respectively. Age dependent secondary cancer risks were also estimated from the measured out-of-field doses. The findings provide useful data to support the optimization of treatment planning and to minimize the risk of secondary cancers in radiotherapy patients.

Keywords: Alderson Rando phantom, Thermoluminescence dosimeter (TLD), Out-of-field dose, Secondary cancer risk

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সারমর্ম: এ গবেষণায় পরীক্ষা-নির্ভর পরিমাপ এবং মানসম্মত ডোজিমেট্রি কৌশল ব্যবহার করে রেডিওথেরাপিতে চিকিৎসা ক্ষেত্রের বাইরের বিকিরণ ডোজ এবং এর সঙ্গে সংশ্লিষ্ট ঝুঁকি বিশ্লেষণ করা হয়েছে। রেডিওথেরাপি ক্যান্সার চিকিৎসার একটি প্রধান পদ্ধতি, যা টিউমারে চিকিৎসামূলক বিকিরণ ডোজ পৌঁছে দেয় এবং চারপাশের টিস্যুগুলিতে বিকিরণ কমানোর চেষ্টা করে। যদিও চিকিৎসা ক্ষেত্রের বাইরে বিকিরণ পরিমাণ কম, তবুও এটি দীর্ঘমেয়াদি বিকিরণজনিত ক্ষতিকর প্রভাব সৃষ্টি করতে পারে। এ গবেষণায় অন্ডারসন র্যান্ডো ফ্যান্টম এবং কোবাল্ট-৬০ টেলিথেরাপি বিম ব্যবহার করে চিকিৎসা ক্ষেত্রের বাইরের বিকিরণ ডোজ এবং এর সঙ্গে সম্পর্কিত ঝুঁকি অনুসন্ধান করা হয়েছে। লক্ষ্য অঙ্গসমূহে শোষিত বিকিরণ ডোজ এবং পার্শ্ববর্তী অঙ্গগুলোর কার্যকর ডোজ থার্মোলুমিনেসেন্স ডোজিমিটার (TLD) ব্যবহার করে পরিমাপ করা হয়েছে। IAEA TRS-398 নির্দেশিকা অনুসরণ করে FC65G ফার্মার চেম্বার, NE2575 আয়ন চেম্বার এবং ওয়াটার ফ্যান্টম ব্যবহার করে ডোজিমেট্রি সম্পন্ন করা হয়েছে। বাম ফুসফুস, ডান ফুসফুস ও পাকস্থলীসহ বিভিন্ন লক্ষ্য অঙ্গে ভিন্ন ভিন্ন গভীরতায় এবং পার্শ্ববর্তী অঙ্গগুলোর পৃষ্ঠে TLD স্থাপন করা হয়। ১০০ সেন্টিগ্রা এবং ২০০ সেন্টিগ্রা ডোজে বিকিরণ প্রদান করা হয় এবং মানানুযায়ী (ক্যালিব্রেটেড) TLD রিডার ব্যবহার করে পাঠ নেওয়া হয়। অধিকাংশ গভীরতায় পরিমাপকৃত অঙ্গের ডোজ প্রত্যাশিত মানের খুব কাছাকাছি বা সামান্য কম পাওয়া গেছে। TLD-গুলোর ডোজ প্রতিক্রিয়া রৈখিক ছিল এবং অনিশ্চয়তা ছিল ১.৫৪%। সঠিক চিকিৎসা নিশ্চিতকরণ এবং সর্বোচ্চ ডোজ সরবরাহের জন্য কোবাল্ট-৬০ বিমের জন্য গভীরতা-ডোজ সংশোধন গুণক নির্ণয় করা হয়েছে। এ গবেষণায় ফুসফুস, পাকস্থলী, কিডনি এবং প্লীহার জন্য প্রাপ্ত গভীরতা-ডোজ সংশোধন গুণক যথাক্রমে 0.899 ± 0.028 , 0.995 ± 0.023 , 0.965 ± 0.029 এবং 0.923 ± 0.118 । পরিমাপকৃত ক্ষেত্রের বাইরের ডোজের ভিত্তিতে বয়সভিত্তিক দৈনিক ক্যান্সারের ঝুঁকিও নিরূপণ করা হয়েছে। এ গবেষণার ফলাফল রেডিওথেরাপি রোগীদের চিকিৎসা পরিকল্পনা উন্নত করতে এবং দৈনিক দ্বিতীয় ক্যান্সারের ঝুঁকি কমাতে গুরুত্বপূর্ণ তথ্য প্রদান করে।

1. Introduction

This work aimed to investigate the out-of-field dose and associated secondary cancer risks and other long-term stochastic health effects due to unintended radiation exposure to nearby organs from high-energy photon beams generated by ^{60}Co machines. Precise estimation of such risks typically requires widespread observational lessons, which usually involve large-scale potential studies and long-term sequel.

In external beam radiotherapy, it is crucial to achieve a uniform dose distribution between the target tissues while minimizing the radiation exposure to the surrounding healthy tissues. This approach reduces the risk of secondary carcinomas in organs of out-of-field sites.

The treatment planning systems (TPS) often underestimate out-of-field dose, with the degree of underestimation increasing with the distance from the field edge [1]. In Intensity Modulated Radiation Therapy (IMRT), TPS underestimated the out-of-field dose by an average of 50% and was more noticeable at greater distances from the treatment field. In addition to that, the collimator scatter was also underestimated by the TPS near the treatment field [1].

The TiGRT TPS underestimates out-of-field doses, with discrepancies increasing toward the field edge. Toossi et al. [2] reported an average underestimation of approximately 39%, while in-field dose accuracy remained acceptable. The TiGRT TPS employs modified generic algorithms for 3D conformal radiotherapy (3D-CRT) and IMRT.

Sarli et al. [3] compared three different radiotherapy techniques for breast cancer and observed statistically similar dose values between the right and left breasts. However, significant differences in dose values were identified among the techniques. Mean peripheral doses were 7.16 ± 1.61 cGy for 3D-CRT, 27.75 ± 3.88 cGy for IMRT, and 12.20 ± 2.65 cGy for VMAT, demonstrating technique-dependent variations.

Monte Carlo (MC) modeling of out-of-field dose deposition was investigated by Clasié et al. [4], and agreement within 30% between simulations and measurements at distances of 10 - 20 cm from the field edge were reported. Neutron contributions to passive scattering dominated the total dose beyond the Bragg peak, accounting for 65–80% of the dose at distances greater than 10 cm.

Ruben et al. [5] showed that collimator and head scatter dominate out-of-field doses in IMRT, whereas patient scatter is the primary source in 3D-CRT.

Mazonakis et al. [6] examined peripheral organ doses and secondary cancer risk in photon radiotherapy, highlighting the limitations of water tanks and slab phantoms for organ-specific dosimetry. Direct measurements using anthropomorphic phantoms and TLDs were found to be more reliable.

Scarboro et al. [7] assessed the effect of stomach size and position relative to the field border using TLDs. Mean stomach doses ranged from 0.43 to 0.83 Gy for a delivered dose of 30 Gy, with no significant differences observed for symmetric expansion or lateral shifts up to 3 cm.

Howell et al. [8] demonstrated that inaccuracies in low-dose regions of dose–volume histograms (DVHs) can significantly affect mean organ dose estimates when discrepancies exceed 5%. They recommended combining TPS-calculated DVHs with measured data using volume-weighted techniques.

Osman Vefa Gul [9] investigated peripheral doses in electron beam radiotherapy and found that doses outside 6×6 cm² and 10×10 cm² applicator fields decreased

approximately linearly up to about 3.5 cm from the applicator edge for electron energies of 6–18 MeV. Beyond this region, dose reduction depended on applicator type and measurement depth.

Verdera et al. [10] reported that secondary neutron doses in boron neutron capture therapy (BNCT) can approach established equivalent dose limits under certain conditions and proposed reference limits of 5 mSv/Gy at 15 cm and 1 mSv/Gy(w) at 50 cm from the field edge.

Matuszak et al. [11] evaluated non-target and out-of-field doses in electron beam radiotherapy, emphasizing the need for comprehensive dosimetric assessment to reduce unintended exposure to healthy tissues.

Aghdam et al. [12] measured out-of-field doses in intraoperative electron radiotherapy using TLDs, reporting absorbed doses of 0.033–0.545 mGy/MU. Dose levels depended on applicator size, energy, and distance, and agreement with ion chamber measurements was within 1.82%, validating TLD-100 for intraoperative electron radiotherapy (IOERT) dosimetry.

Attalla et al. [13] assessed commercial TPS accuracy using GATE/GEANT4 MC simulations and established that PROWESS© TPS underestimated out-of-field doses by 34–65%, with underestimation increasing with field size, depth, and distance from the field edge.

Although out-of-field doses are substantially lower than in-field doses, they contribute to long-term radiation risks in non-target organs. Scatter and leakage radiation from linear accelerators can deliver measurable peripheral doses, highlighting the importance of accurate dosimetric assessment using anthropomorphic phantoms and advanced measurement techniques [14–16].

Although out-of-field doses have been extensively studied using various radiotherapy techniques, TPS, MC simulations, and experimental methods, uncertainties remain in estimating peripheral photon doses and related long-term stochastic risks. TPS often underestimate low-dose regions, and many experimental studies rely on simplified phantoms or specialized facilities. Data for ^{60}Co photon beam radiotherapy, still widely used clinically, are limited. Therefore, this work aimed to investigate out-of-field doses and associated secondary cancer risks and other long-term stochastic effects from high-energy photon beams generated by ^{60}Co machines for providing clinically relevant measurements to improve dose assessment, patient safety, and risk-informed treatment planning.

2. Experimental Details

The experiment was carried out at the Secondary Standard Dosimetry Laboratory (SSDL) of the Atomic Energy Research Establishment (AERE), Bangladesh.

The major instruments used in this work included a ^{60}Co teletherapy unit, TLD, TLD reader, Alderson Rando phantom, IAEA standard water phantom, gamma irradiator system, Farmer chamber (IBA FC65G), NE2575 cylindrical ion chamber, electrometer, barometer, and thermometer. Detailed specifications and characteristics are available in the following references: MTS-100 TLD [17], TLD reader [18], Alderson Rando phantom [19–21], NE2575 cylindrical ion chamber [21], IBA FC65G Farmer chamber [22], portable single-channel electrometer [23], standard thermometer and barometer (GTH 175/PT) [24, 25].



Figure 1: ^{60}Co teletherapy unit at SSDL, AREA

For radiotherapy, a pellet of radioactive ^{60}Co isotope is generally used as the radiation source. Since ^{60}Co does not exist in nature, it is produced by bombarding the stable isotope ^{59}Co with neutrons in a nuclear reactor. In a ^{60}Co teletherapy unit, the radiation source is usually at a distance of 80 or 100 cm from the isocenter, whereas in a linear accelerator (LINAC), the isocenter is about 100 cm from the focal spot [26]. The general form of ^{60}Co teletherapy unit is shown in Figure 1.

TLDs were calibrated using the IAEA formalism in tissue-equivalent water for high doses and the air-kerma technique for low doses [27–28]. Calibration on the skin surface of the Alderson Rando phantom was necessary to assess the risk of second cancers by determining the out-of-field organs skin dose or effective dose. Twenty TLDs were exposed to doses ranging from 1 to 20 mSv using a ^{137}Cs source and read with a RE-2000 TLD Reader. Additionally, TLDs were calibrated in a water phantom with a ^{60}Co teletherapy beam to measure organ doses at various depths in the

Alderson Rando phantom. Reference dosimetry was performed with an IBA FC65-G Farmer chamber under standard conditions, and TLDs were covered with latex to ensure waterproofing. Calibration factors were calculated for each dose level.

In this study, organ dose and skin dose were assessed for the corresponding peripheral organs of the Alderson Rando phantom when targeting the left and right lungs, as well as the stomach. The phantom was divided into 36 horizontal slices, each 2.5 cm thick, with holes filled by bone, soft tissue, or lung-equivalent materials that could hold TLDs. For lung irradiation, slice #16 (mid slice of lung) was selected as the target, while slices #20 and #21 were chosen for the stomach. TLDs were placed at various depths within the target organs to measure dose distribution, and TLDs on the skin of corresponding organs measured out-of-field skin doses. The phantom was irradiated with a ^{60}Co teletherapy unit at 100 cGy and 200 cGy doses, using a 10×10 cm² field size.



Figure 2: Irradiation of the Alderson Rando phantom using a ^{60}Co teletherapy unit, placement of TLD chips on the surfaces of various organs of the phantom.

Figure 2 shows the setup for measuring radiation doses outside the treatment field. The Alderson Rando phantom was positioned under the ^{60}Co teletherapy unit, and TLD chips were placed on the surfaces of various organs. This arrangement simulates a patient during radiotherapy and allows accurate measurements of radiation received by organs that are not directly targeted, particularly those located far from the field edge.



Figure 3: Inner view of lung targeted slice of Alderson Rando phantom with TLDs.

TLDs were positioned on the lung region of the Alderson Rando phantom, as indicated in Figure 3, to simulate patient exposure and measure the absorbed dose during ^{60}Co teletherapy. This configuration allowed precise assessment of radiation received by the lungs, which are partially outside the primary treatment field. For organs such as the stomach, kidneys, and spleen, TLDs were placed on the corresponding regions of the phantom, as indicated in Figure 4, to capture organ-specific doses from scattered and leakage radiation.

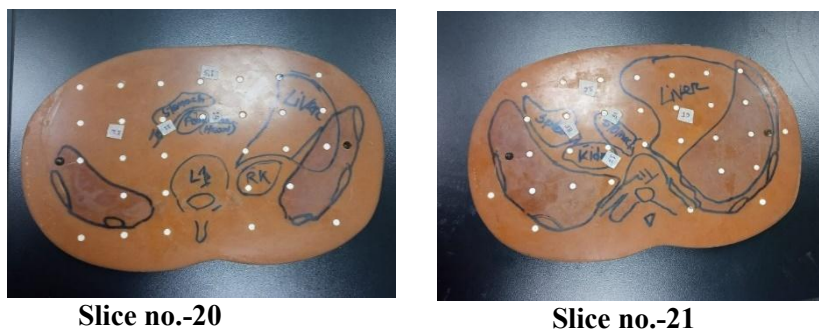


Figure 4: Inner view of stomach, kidney and spleen targeted slice of Alderson Rando phantom with TLDs.

The measured doses for all organs were then used to estimate the lifetime risk of radiation-induced cancer using the online RadRAT tool (Version 4.2.1) [29], which provide uncertainty intervals to indicate the likely range of the true risk (e.g., an estimated risk of 2.5% with a 95% uncertainty in the interval of 1.8% to 3.4%). This setup enabled comprehensive evaluation of out-of-field doses and facilitated organ-specific risk assessment under clinically relevant conditions.

3. Results and Discussion

This study investigates dose distribution in various target organs to ensure accurate radiotherapy delivery and assesses out-of-field doses to non-target organs to estimate the risk of secondary cancers in patients undergoing radiation therapy.

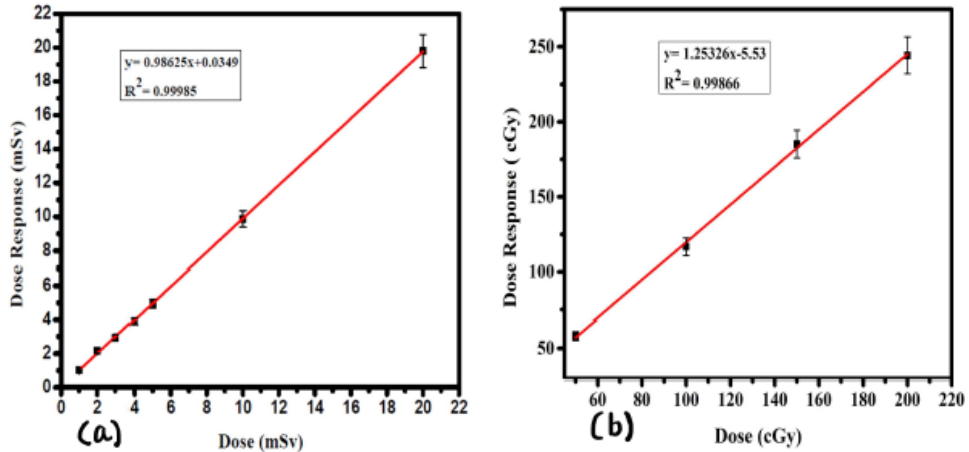


Figure 5: (a) Calibration curve of TLD-100 exposed in air using a ^{137}Cs source, and (b) in water using a ^{60}Co teletherapy beam.

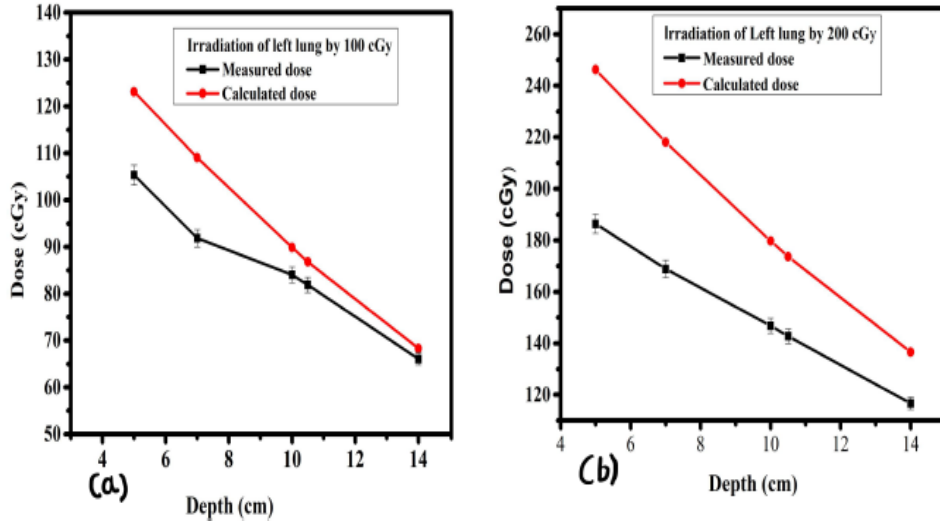


Figure 6: Comparison of TLD-measured and calculated absorbed doses as a function of depth in the left lung for ^{60}Co irradiation at (a) 100 cGy and (b) 200 cGy.

The TLD-100 calibration curve in air, shown in Figure 5(a), for doses ranging from 1 to 20 mSv demonstrates near-perfect linearity with a relative standard uncertainty of 1.04%. Figure 5(b) shows the TLD dose-response in water for doses between 50 and 200 cGy, with a relative standard uncertainty of 1.54%, well within the recommended 3%–5% range for clinical TLD systems [30]. These results are consistent with the multi-institutional study by Amols et al. [30], which reported comparable linearity and reproducibility in TLD measurements across different clinical settings, confirming the reliability of TLD-100 for both low- and high-dose measurements in radiotherapy dosimetry.

The measured doses were compared with the computed central axis depth dose values for a 10×10 cm² field. A good agreement between experimental measurements and reference dosimetric calculations [31] was observed. This confirms the accuracy of TLD-based dosimetry for capturing in-field and out-of-field dose distributions, providing a reliable basis for organ-specific risk assessments.

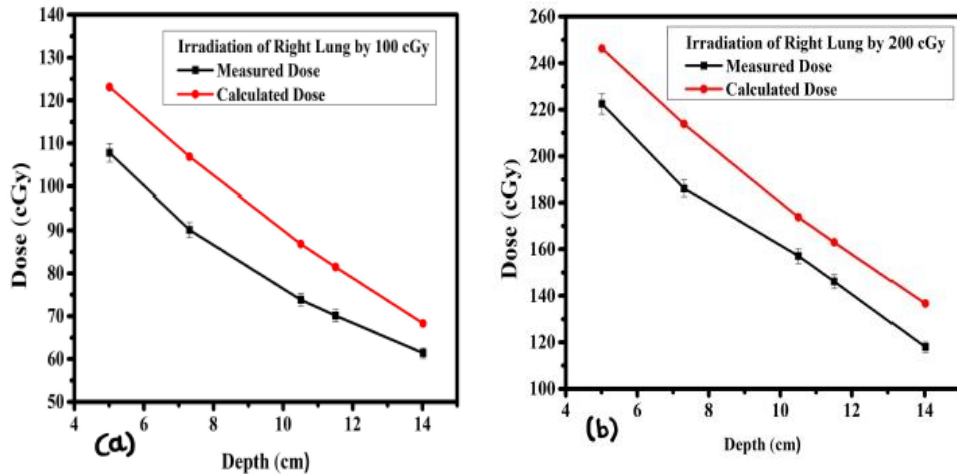


Figure 7: Comparison of TLD-measured and calculated absorbed doses as a function of depth in the right lung for ⁶⁰Co irradiation at (a) 100 cGy and (b) 200 cGy.

Figures 6–8 show the variations of absorbed dose with depth when the lungs and stomach are irradiated with doses of 100 cGy and 200 cGy. In all cases, the measured doses are lower than the calculated doses, which can be attributed to photon scattering in the water-equivalent tissues of the human body. Nevertheless, the ratio of measured to calculated doses remains close to unity, indicating reasonable agreement between experimental and calculated values as observed in other studies [32–35].

The measured TLD dose, as a function of depth, decreases with increasing depth and is always lower than the calculated standard dose. The ratio of measured absorbed dose to the standard dose lies within the ranges (0.747–0.934) and (0.85–0.93) for the left and right lungs respectively. Since the measured dose is lower than the calculated dose, the depth-dose correction factor for ^{60}Co teletherapy beams is 0.877 ± 0.0543 for the left lung and 0.916 ± 0.0364 for the right lung. This results in a mean correction factor of 0.897 ± 0.0275 for lung treatments using ^{60}Co teletherapy.

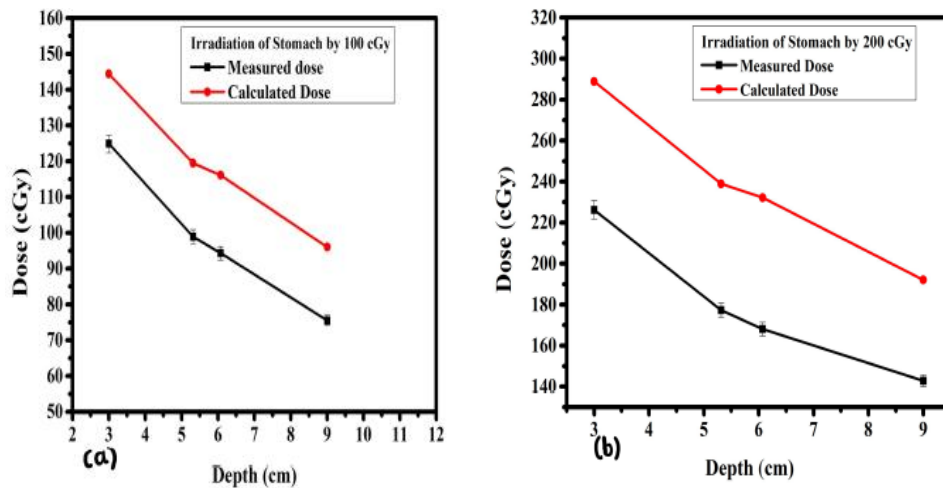


Figure 8: Comparison of TLD-measured and calculated absorbed doses as a function of depth in the stomach for ^{60}Co irradiation at (a) 100 cGy and (b) 200 cGy.

Figure 8 presents the TLD readings obtained when positioned in other slices of the Alderson Rando phantom, including adjacent organs such as the kidney and spleen, to study the stomach dose distribution. The absorbed doses in the stomach, kidney, and spleen decreased with increasing depth. The ratio of measured absorbed dose to the standard dose ranged from 0.67 to 0.88, and the corresponding depth-dose correction factors were 0.775 ± 0.023 for the stomach, 0.765 ± 0.027 for the kidney, and 0.723 ± 0.118 for the spleen.

The underestimation of absorbed dose varies with depth, as indicated by the depth-dependent dose distributions in Figures 6–8. This variation is partly attributed to differences in TLD sensitivity, since individual TLDs may respond differently to photon irradiation, leading to inhomogeneities in the measured dose patterns across depths. The results presented in Figures 6, 7 and 8 further show that lung tissue absorbs more radiation than the stomach. This behavior is mainly due to the lower density of lung tissue ($\approx 0.3 \text{ g/cm}^3$) arising from its air-filled structure, which alters photon scattering and attenuation compared with denser abdominal tissues.

Table 1: Skin doses received by out-of-field organs with the left lung as the target organ.

Slice No. of phantom	Organs	Skin dose, E (cGy)	
		For 100 cGy irradiation	For 200 cGy irradiation
4	Left Eye	2.1000 ± 0.0004	2.3000 ± 0.0005
4	Right eye	1.7100 ± 0.0003	2.0400 ± 0.0004
10,11	Thyroid	14.1600 ± 0.0028	20.6200 ± 0.0041
16	Right Lung	44.5200 ± 0.0088	62.0300 ± 0.0123
20	Stomach	65.6200 ± 0.0130	96.6000 ± 0.0191
20	Liver	15.4800 ± 0.0010	20.5300 ± 0.0041
20,21	Spleen, Left Kidney	5.4200 ± 0.0005	7.9500 ± 0.0016
22,23	Pancreas	2.4700 ± 0.0005	3.2800 ± 0.0006
28	Colon	24.6300 ± 0.005	33.1200 ± 0.0065
32	Urinary Bladder	6.9400 ± 0.0014	6.7800 ± 0.0013

Table 2: Excess future risk of second cancer from scattered out-of-field doses for the left lung as the target organ, by cancer site (per 100,000), with a 90% uncertainty range.

Cancer site ↓	Age of patient →	For 100 cGy irradiation			For 200 cGy irradiation		
		30 years	50 years	70 years	30 years	50 years	70 years
Stomach		3.360	2.940	1.380	5.530	4.350	2.040
Colon		3.430	2.940	1.310	4.610	3.950	1.760
Liver		0.602	0.496	0.242	0.798	0.658	0.321
Pancreas		0.058	0.049	0.020	0.078	0.066	0.027
Lung		5.350	4.960	2.630	7.460	6.910	3.670
Bladder		0.694	0.643	0.329	0.678	0.628	0.321
Kidney		0.175	0.134	0.043	0.257	0.196	0.063
Thyroid		0.223	0.030	0.002	0.325	0.043	0.003
Others (Eye)		0.396	0.282	0.107	0.452	0.321	0.122
Total future risk		14.600	12.500	6.060	20.000	17.100	8.330

Table 3: Skin doses received by out-of-field organs with the right lung as the target organ.

Slice No. of phantom	Organs	Skin dose, E (cGy)	
		100 cGy	200 cGy
4	Left Eye	1.4800 ± 0.0030	1.5300 ± 0.0003
4	Right eye	1.1400 ± 0.0002	1.9600 ± 0.0004
10,11	Thyroid	10.8700 ± 0.0021	18.9600 ± 0.0037
16	Left Lung	31.6000 ± 0.0062	48.9400 ± 0.0097
20	Stomach	34.5000 ± 0.0068	59.2100 ± 0.0117
20	Liver	19.2800 ± 0.0038	34.6400 ± 0.0068
20,21	Spleen, Left Kidney	2.3700 ± 0.0003	3.2500 ± 0.00064
22,23	Pancreas	2.7500 ± 0.0005	4.5800 ± 0.00091
28	Colon	17.5900 ± 0.0035	25.4600 ± 0.0050
32	Urinary Bladder	4.2700 ± 0.00084	5.1300 ± 0.0010

Table 4: Excess future risk of second cancer due to scattered out-of-field doses for the right lung as the target organ, by cancer site (chances per 100,000), with a 90% uncertainty range.

Cancer site ↓	Age of patient →	For 100 cGy irradiation			For 200 cGy irradiation		
		30 years	50 years	70 years	30 years	50 years	70 years
Stomach		1.900	1.540	0.725	3.270	2.650	1.250
Colon		2.450	2.100	0.934	3.540	3.040	1.350
Liver		0.749	0.617	0.301	1.350	1.110	0.541
Pancreas		0.065	0.055	0.023	0.108	0.092	0.038
Lung		3.790	3.520	1.860	5.880	5.450	2.890
Bladder		0.427	0.396	0.202	0.513	0.475	0.243
Kidney		0.077	0.059	0.019	0.105	0.080	0.026
Thyroid		0.171	0.023	0.001	0.299	0.034	0.002
Others (Eye)		0.278	0.198	0.075	0.356	0.253	0.096
Total future risk		9.910	8.500	4.150	15.400	13.200	6.430

Tables 1–4 present skin doses and estimated second cancer risks for out-of-field organs during lung irradiation at 100 cGy and 200 cGy with a ^{60}Co beam. Organs near the lungs such as the liver, colon, stomach, and thyroid, receive higher doses and show greater lifetime cancer risk, particularly, in younger patients and at higher

dose levels, consistent with previous studies [35–38]. Stochastic effects also increase with dose as observed in Tables 2 and 4.

Table 5: Skin doses received by out-of-field organs with the stomach as the target organ.

Slice No. of phantom	Organs	Skin dose, E (cGy)	
		100 cGy	200 cGy
4	Left Eye	0.8000 ± 0.0002	0.9200 ± 0.0018
4	Right Eye	0.7200 ± 0.00014	1.0100 ± 0.0002
10,11	Thyroid	5.9500 ± 0.0012	9.7200 ± 0.0019
16	Right lung	33.1500 ± 0.0066	53.1300 ± 0.0105
16	Left lung	40.6900 ± 0.008	64.2900 ± 0.0127
20	Liver	34.2900 ± 0.0068	96.3500 ± 0.019
23	Right kidney	6.4000 ± 0.0013	13.5700 ± 0.0027
23	Left kidney	11.2300 ± 0.0022	14.7700 ± 0.0029
28	Colon	31.3800 ± 0.0062	51.4600 ± 0.0102
32	Urinary Bladder	4.9300 ± 0.0097	7.3200 ± 0.0014

Table 6: Excess future risk of second cancer due to scattered out-of-field doses for the stomach as the target organ, by cancer site (chances per 100,000), with a 90% uncertainty range.

Cancer site ↓	Age of patient →	For 100 cGy irradiation			For 200 cGy irradiation		
		30 years	50 years	70 years	30 years	50 years	70 years
Colon		4.370	3.740	1.670	7.170	6.150	2.740
Liver		1.330	1.100	0.536	3.770	3.110	1.520
Lung		4.330	4.110	2.180	7.060	6.540	3.470
Bladder		0.493	0.457	0.234	0.732	0.678	0.347
Kidney		0.285	0.217	0.070	0.458	0.350	0.112
Thyroid		0.094	0.013	0.0008	0.153	0.022	0.001
Others (Eye)		0.158	0.113	0.043	0.201	0.143	0.054
Total future risk		11.200	9.750	4.730	19.500	17.000	8.230

Tables 5–6 show similar results for stomach irradiation, where nearby organs, including the lung, liver, kidney, and colon, receive higher doses and face a greater risk of late effects, while more distant organs, such as the eye and thyroid, are less affected. The lifetime risk of second cancer remains strongly dependent on patient age and the prescribed dose.

The results of this study show that out-of-field organ doses measured using TLDs are consistently lower than the calculated values, primarily due to photon scattering and tissue heterogeneity. The depth-dependent dose variations and the organ-specific correction factors obtained for the lungs, stomach, kidney, and spleen highlight the need for appropriate adjustments when estimating peripheral doses in ^{60}Co teletherapy. The estimation of excess future risks of second cancer based on measured out-of-field doses confirms that higher absorbed doses generally correspond to higher risk levels. Overall, these findings provide a more reliable basis for assessing out-of-field radiation exposure and support improved radiotherapy dose evaluation and treatment planning.

4. Conclusion

This study confirms that precise dosimetric measurements are essential for safe and effective external beam radiotherapy. Calculations based on experimental data substantiate the cumulative biological impact of small out-of-field doses in patients receiving photon beam radiotherapy. Estimated values of age-dependent excess future risk of second cancer consistently show that doses far from the field edge for different target organs, though small compared to target doses, could lead to a measurable increase in secondary malignancies, especially in younger patients. Moreover, it is observed that the depth-dose correction factors are vital for more effective treatment. The findings of the present work provide experimental validation for achieving precise out-of-field dose predictions using Monte Carlo simulations and advanced TPS correction algorithms to minimize out-of-field exposure and ensure the safety and well-being of patients undergoing radiation therapy.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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