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Evaluation of Dose Distribution Homogeneity and Accuracy for a Cs-137 Source Using Thermoluminescent Dosimeters ($CaSO_4$:Dy and LiF:Mg,Ti)

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ABSTRACT

Introduction: Cesium-137 (Cs-137) is a widely used source of ionizing radiation across various fields.Thermoluminescent dosimeters (TLDs), due to their sensitivity and reliability, are frequently employed to measure radiation dose in medical, industrial, and research applications. This study specifically aims to assess the homogeneity and accuracy of $CaSO_4$:Dy and LiF:Mg,Ti TLDs to support calibration and radiation safety practices.
Material and Methods: The experiment utilized the G-10-360-15CS Gamma Beam Irradiator as the radiation source. The $CaSO_4$:Dy and LiF:Mg,Ti TLDs were mounted on a 30 × 30 × 5 cm Polymethyl Methacrylate (PMMA) phantom. The testing procedure included TLD annealing, homogeneity testing, and dose accuracy assessment. The TLDs were calibrated using a Cs-137 reference source by comparing the actual delivered dose to the TLD readings. Testing was conducted at doses of (0.1 mSv and 0.5 mSv) and distances (100, 150, and 200 cm).
Results: The homogeneity test showed a uniform dose distribution (CV $\leq$ 15%) at distances of 150 cm and 200 cm. The accuracy test indicated a performance bias of –9.21% to –2.50% for TLD $CaSO_4$:Dy, with calibration factors ranging from 1.026 to 1.101, and a performance bias of 2.46% to –0.28% for TLD LiF:Mg,Ti, with calibration factors of 0.976 to 1.003. All values meet the required tolerance limits. Therefore, TLD $CaSO_4$:Dy and TLD LiF:Mg,Ti are suitable for radiation dose measurements.
Conclusion: Homogeneity and accuracy testing of TLD $CaSO_4$:Dy and LiF:Mg,Ti shows that dose distribution becomes more homogeneous as the distance increases. The best measurement accuracy is achieved at shorter distances.

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Introduction

Cesium-137 (Cs-137) is an ionizing radiation source widely used in various fields. It is a radioactive isotope that emits high-energy gamma radiation with an energy of approximately 662 keV and has a half-life of about 30.17 years [1]. Radiation protection is a structured effort based on three main principles: justification, optimization of protection, and dose limitation. These principles apply to all exposure situations, including planned, emergency, and existing situations, to minimize health risks associated with ionizing radiation for individuals and the environment. In practice, radiation protection includes strict monitoring of radiation sources across multiple sectors, including the use of individual monitoring devices such as personal dosimeters to ensure that the doses received by workers remain within recommended limits [2,3].

Dose analysis on organs can be performed using radiation dosimeters, such as ionization chambers or smaller devices including Thermoluminescent Dosimetry (TLD), Optically Stimulated Luminescence (OSL) dosimeters, and photodiode dosimeters [4]. TLDs use thermoluminescent crystals such as lithium fluoride doped with magnesium and titanium (LiF:Mg,Ti) and calcium sulfate doped with dysprosium ($CaSO_4$:Dy), which are highly sensitive to gamma, X-ray, and beta radiation. They work by storing radiation energy that is later released as light when heated, allowing accurate dose measurement. Although pocket dosimeters and film badges are also used in radiation monitoring, TLDs are increasingly preferred due to their high sensitivity and ability to retain dose information for extended periods [5,6].

The sensitivity of a TLD is strongly influenced by the material used. LiF:Mg,Ti has relatively high sensitivity because it possesses a high trap density and efficient electron and hole capture. $CaSO_4$:Dy shows moderate sensitivity due to its lower trap

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density and lower trapping efficiency compared with LiF-based TLDs, although it remains adequately sensitive [7,8]. This study aims to measure the homogeneity and accuracy of Cs-137 radiation dose distribution using TLD $CaSO_4$:Dy and TLD LiF:Mg,Ti with dose variations of 0.1 mSv and 0.5 mSv at distances of 100, 150, and 200 cm. The selected dose variations reflect general exposure levels and annual dose limits recommended by the International Commission on Radiological Protection (ICRP) [2]. The distance variation is intended to evaluate stability and dose distribution based on the distance principle described by the International Atomic Energy Agency (IAEA) [9].

Materials and Methods

System Stability Measurement and Standard Output Values Cs-137

The Cs-137 standard stability and output test used an A6 REF 92716 ion chamber detector with a capacity of 800 cc and a Farmer type dosimeter, the Max 4000 Plus. Through stability testing, the effects of environmental conditions such as temperature, humidity, and pressure on stability indicators, including those of the Cs-137 radiation source, can be identified [10]. The measured standard output of the Cs-137 source was converted into the air kerma rate and the personal dose equivalent at a depth of 10 mm, Hp(10), which were then used as reference data to determine the TLD irradiation time. An illustration of the stability test process and the standard Cs-137 output is shown in Figure 1.

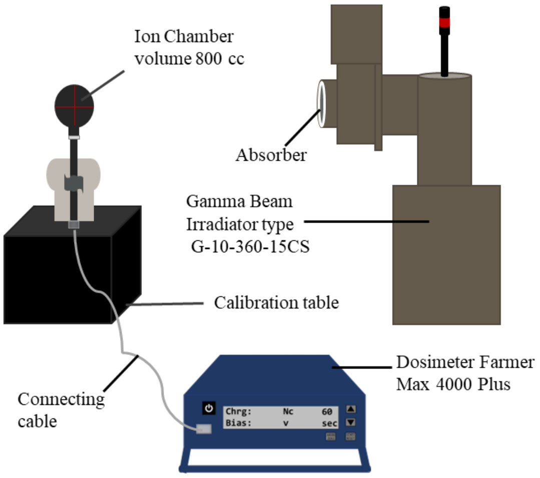


Figure 1. System Stability Measurement and Standard Output Values Cs-137

Dose Homogeneity and Accuracy

Before the irradiation process, the TLDs are annealed. Annealing is the process of heating a solid material and gradually cooling it to reduce internal strain and improve its crystal structure. This process lowers the material's free energy until it reaches a more stable condition [11,12]. The series of procedures are shown in Figure 2.

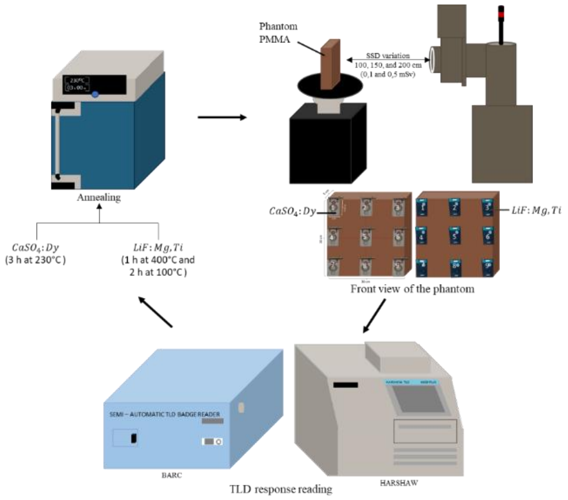


Figure 2. Homogeneity and Accuracy Test Procedure

In this study, the doses to be irradiated are 0.1 mSv and 0.5 mSv at distances of 100 cm, 150 cm, and 200 cm from the radiation source. For each dose, 9 TLDs were irradiated using the Cesium-137 source. The test medium was a PMMA (Polymethyl Methacrylate) phantom, an artificial material with an electron density similar to that of human tissue or organ [4]. The TLDs were placed at 9 points on the phantom surface, which measured 30 cm × 30 cm × 5 cm. Measurements were taken at the center and edges of the phantom, irradiated directly by the radioactive source without an absorber. TLD reading is performed using the Harsaw (6600 Plus) TLD reader for TLD LiF:Mg,Ti, and the Barc TLD reader (semi-automatic badge reader) for TLD $CaSO_4$:Dy.

Uniformity values are determined using Statistical Process Control (SPC). Each TLD response is plotted on a control chart using the upper and lower control limit formulas. The calculation is performed using Formula 1 [13].

$$\text{Coefficient of Variation (CV)} = \frac{\sigma_r}{\mu_r} \times 100 \qquad (1)$$

Determination of accuracy value, using performance or bias assessment, is carried out as follows: Performance bias (P_i) is calculated using Formula 2.

$$P_i = \frac{(H_m - H_T)}{H_T} \qquad (2)$$

Information:
H_T = True Dose (mSv)
H_m = Measured dose (mSv)
Pi = Performance bias

P_i indicates bias. A positive value means that the measured dose (HM) is greater than the actual dose (HT). Conversely, a negative PPP value means that the measured dose (HM) is smaller than the actual dose (HT) [14,15].

Statistical Analysis

The effects of TLD type, irradiation distance, radiation dose, and their interactions on the readings (mSv) and bias performance (%) were analyzed using a three-way analysis of variance (ANOVA). Statistical analysis was conducted using the Statistical Package for the Social Sciences (SPSS) Version 31. A P-value of less than 0.05 was considered statistically significant.

Results

Based on Tables 1 and 2, a higher administered dose results in a higher reading from the TLD reader. In addition, measurements taken at the nine positions show that the center position, or the fifth position, consistently produces the highest value for each distance and dose variation.

The reading data were calculated and compared, and the CV values are presented in Table 1. For a dose of 0.1 mSv using the $CaSO_4$:Dy TLD at distances of 100, 150, and 200 cm, the CV values are 49.67%, 8.44%, and 7.28%, respectively. For a dose of 0.5 mSv, the corresponding values are 34.97%, 11.53%, and 10.85%. For the LiF:Mg,Ti TLD at 0.1 mSv, the CV values at the same distances are 41.37%, 8.05%, and 7.67%, while at 0.5 mSv the values are 35.74%, 11.30%, and 10.46%. The tolerance limit for dose distribution homogeneity in this study follows ISO 12794, which specifies that %CV must be ≤ 15% [16]. As shown in Figures 3 and 4, the greater the distance from the Cs-137 source, the more homogeneous the received dose. Based on the ANOVA results in Table 3, distance (p = 0.000), dose (p = 0.000), and their interaction (p = 0.000) significantly affected the measured dose. TLD type and other interaction factors did not show significant effects.

Performance bias and calibration factors obtained by comparing the proper dose and the measured dose are presented in Table 2. In this study, the accuracy test was conducted at the center point of the radiation field because, at this position, the radiation arrives perpendicularly, allowing the dosimeter to receive an optimal dose distribution. Based on Table 2, the performance bias values range from –9.21% to –2.50% for TLD $CaSO_4$:Dy and from 2.46% to –0.28% for TLD LiF:Mg,Ti. These values remain within the acceptable tolerance level, as the allowable deviation according to ICRP is ±30% [2,17,18]. The calibration factor values range from 1.101 to 1.026 for TLD $CaSO_4$:Dy and from 0.976 to 1.003 for TLD LiF:Mg,Ti, all of which fall within the recommended tolerance range of 0.8 to 1.2 [19]. The ANOVA results for bias performance, shown in Table 4, indicate that TLD type (p = 0.000), dose (p = 0.001), the interaction between TLD type and distance (p = 0.004), and the interaction between distance and dose (p = 0.000) significantly affect bias performance. Distance and the remaining interaction factors do not show significant effects.

Table 1. Coefficient of variation (CV) of TLD responses for dose homogeneity evaluation using a Cs-137 source

Distance (cm)	True Dose (mSv)	CaSO4:Dy			LiF:Mg,Ti		
		Average (mSv)	Standard Deviation (mSv)	CV (%)	Average (mSv)	Standard Deviation (mSv)	CV (%)
100	0.1	0.047	0.023	49.67	0.054	0.023	41.37
	0.5	0.284	0.099	34.97	0.257	0.092	35.74
150	0.1	0.088	0.007	8.44	0.088	0.007	8.05
	0.5	0.416	0.048	11.53	0.438	0.049	11.30
200	0.1	0.088	0.006	7.28	0.093	0.007	7.67
	0.5	0.410	0.045	10.85	0.466	0.049	10.46

Note: Average values represent calibrated TLD dose reading

Table 2. Performance bias (*Pi*) and calibration factor of TLDs measured at the central position of the phantom

Distance (cm)	True Dose, H_T(mSv)	$CaSO_4$:Dy			LiF:Mg,Ti		
		Measured Dose, H_M(mSv)	Performance bias, *Pi* (%)	Calibration Factor (H_T/H_M)	Measured Dose, H_M(mSv)	Performance bias, *Pi* (%)	Calibration Factor (H_T/H_M)
100	0.1	0.098	-2.50	1.026	0.100	-0.28	1.003
	0.5	0.463	-7.37	1.080	0.496	-0.71	1.007
150	0.1	0.096	-3.64	1.038	0.100	0.34	0.997
	0.5	0.457	-8.61	1.094	0.505	1.00	0.990
200	0.1	0.095	-5.44	1.057	0.102	1.90	0.981
	0.5	0.454	-9.21	1.101	0.512	2.46	0.976

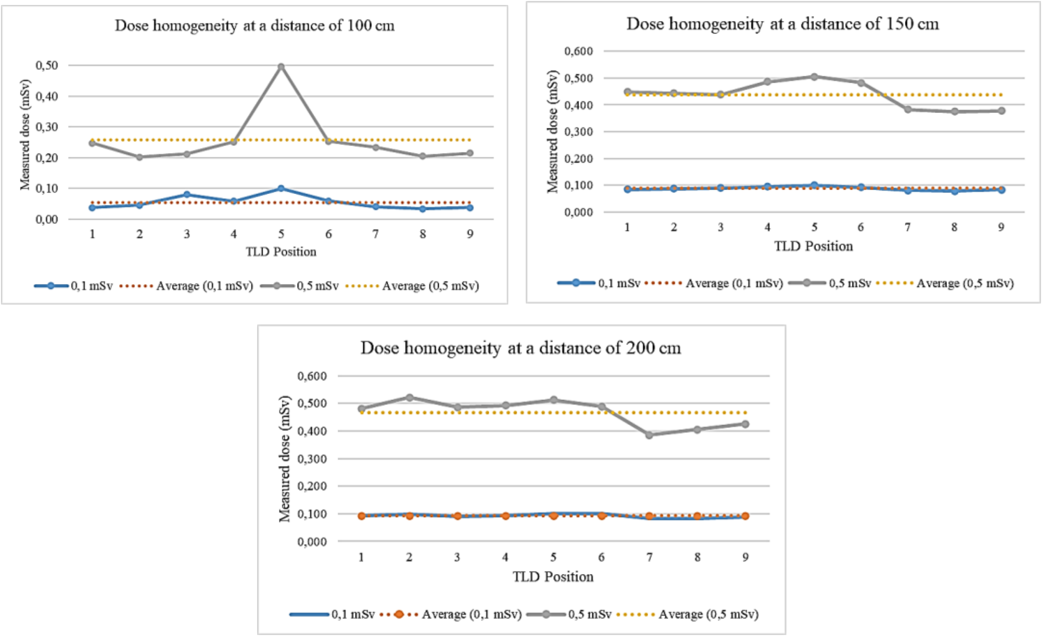


Figure 3. Dose Homogeneity TLD LiF:Mg,Ti at a distance of 100 cm, 150 cm and 200 cm from the Cs-137 source

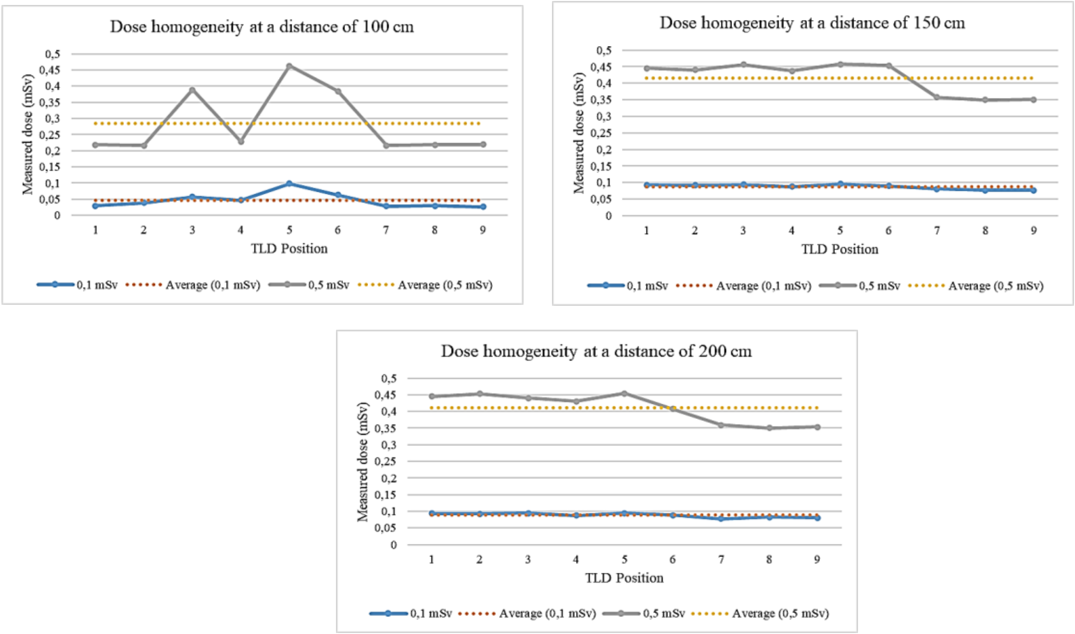


Figure 4. Dose Homogeneity TLD CaSO4:Dy at a distance of 100 cm, 150 cm and 200 cm from the Cs-137 source

Table 3. Three-way ANOVA results for the effect of TLD type, distance, and dose on measured dose (mSv)

Factor	F	p-value	Remark
TLD types	1.273	0.262	Not Significant
Distance (cm)	51.023	< 0.001	Significant
Dose (mSv)	1034.028	< 0.001	Significant
TLD type × Distance (cm)	1.469	0.235	Not Significant
TLD type × Dose (mSv)	0.444	0.507	Not Significant
Distance (cm) × Dose (mSv)	19.285	< 0.001	Significant
TLD type × Distance (cm) × Dose (mSv)	1.778	0.175	Not Significant
a. R Squared = 0.925 (Adjusted R Squared = 0.916)			

Table 4. Three-way ANOVA results for the effect of TLD type, distance, and dose on performance bias (Pi)

Factor	F	p-value	Remark
TLD type	154.558	< 0.001	Significant
Distance (cm)	0.032	0.968	Not Significant
Dose (mSv)	14.814	0.001	Significant
TLD type × Distance (cm)	6.944	0.004	Significant
TLD type × Dose (mSv)	18.650	< 0.001	Significant
Distance (cm) × Dose (mSv)	0.298	0.745	Not Significant
TLD type × Distance(cm) × Dose (mSv)	0.138	0.872	Not Significant

a. R Squared = 0.894 (Adjusted R Squared = 0.846)

Discussion

Based on the results, a higher administered dose produces higher readings from the TLD reader. Measurements taken at the nine positions show that the center position, or the fifth position, consistently has the highest value for each distance and dose variation. This occurs because the center point of the phantom is closest to the radiation source, receiving the beam perpendicularly at a 0° angle, whereas the edge points receive radiation at larger angles ($\theta > 0°$) [20,21]. These data form the basis for further analysis of dose homogeneity and accuracy. Variations in readings across the nine positions are used to evaluate homogeneity, while comparisons between the reference dose and the measured dose are used to assess accuracy.

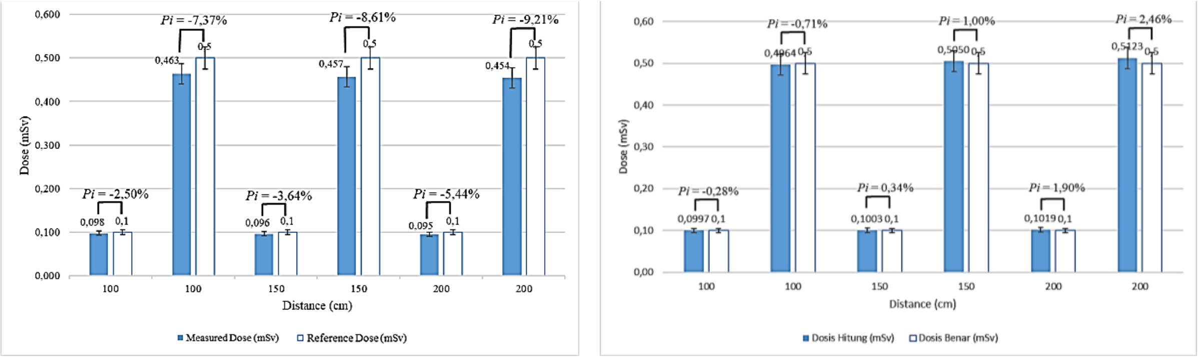
CV analysis showed that at a distance of 100 cm, the CV value exceeded the tolerance limit, indicating low homogeneity in dose distribution among the TLD positions. At distances of 150 cm and 200 cm, all CV values were within the tolerance limit, demonstrating homogeneous dose distribution at these distances. This pattern indicates that increasing the distance from the source improves dose uniformity. This occurs because photons from an external source spread out as they travel, causing a decrease in radiation intensity that follows the inverse square law [20,21]. The ANOVA results show that distance, dose, and their interaction significantly affect the measured dose ($p < 0.05$). This statistical evidence supports the observed trend and confirms that the effects of distance and dose on dose distribution are significant, strengthening the conclusions drawn from the CV values.

Geometric parameters such as distance and radiation angle influence the received radiation dose [22–24]. Shorter distances produce sharper radiation gradients, increasing variability between detector readings, whereas longer distances result in flatter dose profiles. Previous studies have also shown that the physical characteristics of TLD materials affect batch homogeneity. In a comparison between TLD-100 and MTS-N, MTS-N demonstrated better batch homogeneity (10.84%) than TLD-100 (13.65%). TLD-100 has an effective atomic number of 8.2 and a density of 2.64 g cm^{-3}, while MTS-N has an effective atomic number of 8.2 and a density of 2.50 g cm^{-3} [18]. These findings suggest that the physical characteristics of the material influence energy absorption and the uniformity of the thermoluminescence response.

The fundamental differences between $CaSO_4$:Dy and LiF:Mg,Ti TLDs also affect their homogeneity, accuracy, and calibration factors. $CaSO_4$:Dy has a higher effective atomic number (Z_{eff}) of approximately 15.1 and a density of 2.52 g cm^{-3} [25]. A higher Z_{eff} increases the probability of photoelectric interaction, making this material more sensitive to radiation dose. However, this high sensitivity can also lead to greater variation in readings between TLDs, resulting in reduced homogeneity and increased performance bias. In contrast, LiF:Mg,Ti has a Z_{eff} closer to that of biological tissue (≈7.4), making it more stable and capable of producing consistent measurement results across a wide range of irradiation distances [26]. $CaSO_4$:Dy excels in detecting low doses, whereas LiF:Mg,Ti is superior in dose homogeneity and accuracy, as reflected in its calibration factor being closer to 1 in this study.

Determining the calibration factor and assessing the effect of radiation dose on measurement accuracy are essential to ensure that the TLD provides results that accurately reflect the received radiation dose. Based on the calculated performance bias and calibration factors, all distance and dose variations fell within the tolerance limits. As shown in Table 2, the best accuracy was achieved at a distance of 100 cm for the $CaSO_4$:Dy TLD and at a distance of 150 cm for the LiF:Mg,Ti TLD, where the calibration factor is closest to 1.

From a performance bias perspective, accuracy decreases as distance increases, accompanied by a rise in bias. Figure 5 shows the effect of distance variations on the measured dose in the TLD, clearly illustrating that accuracy declines with increasing distance from the source. Distance significantly affects radiation distribution, as dose measurements taken at shorter distances are more stable and exhibit smaller bias values [9]. The greater the measurement distance, the lower the radiation intensity received, and vice versa [27]. The ANOVA results show that TLD type, dose, and the interactions between TLD type and distance, as well as distance and dose, significantly influence bias performance ($p < 0.05$).



(a) (b)

Figure 5. Relationship of Distance Variation to Measured Dose (a) $CaSO_4$:Dy (b) LiF:Mg,Ti

These findings confirm that the observed variation in measurement accuracy is statistically meaningful, demonstrating that both the physical characteristics of the TLD and the experimental conditions have a substantial impact on measurement performance.

The results of this study are consistent with previous findings showing that $CaSO_4$:Dy has a thermoluminescence response approximately 5.6 times higher than that of LiF:Mg,Ti (TLD-100) under low-dose X-ray exposure [6]. This helps explain why $CaSO_4$:Dy tends to exhibit larger bias values in this study, despite still maintaining calibration factors within the acceptable range. Therefore, although $CaSO_4$:Dy offers higher sensitivity, LiF:Mg,Ti provides a more stable and accurate response across a wider range of distances.

Several limitations should be acknowledged in this study. The phantom used (PMMA 30 × 30 × 5 cm) and the nine-point fixed measurement configuration may not fully represent the complex scattering conditions encountered in real clinical or environmental settings. The dose variations (0.1 mSv and 0.5 mSv) and distances (100 cm to 200 cm) also reflect a limited exposure range, so extrapolation to higher doses should be approached with caution. The findings confirm that both $CaSO_4$:Dy and LiF:Mg,Ti TLDs are suitable for low-dose gamma radiation dosimetry. LiF:Mg,Ti demonstrates better uniformity, higher accuracy, and a calibration factor close to unity, whereas $CaSO_4$:Dy provides higher sensitivity to low doses, although with greater variation. These results support selecting TLD materials based on the intended application: LiF:Mg,Ti for routine or precision dosimetry, and $CaSO_4$:Dy for environmental or low-intensity monitoring where high sensitivity is required.

Conclusion

The test results showed that the $CaSO_4$:Dy and LiF:Mg,Ti TLDs met the homogeneity criteria at distances of 150 cm and 200 cm, in accordance with the tolerance limits specified in ISO 12794. The measurement bias values ranged from –9.21% to –2.50% for the $CaSO_4$:Dy TLD and from 2.46% to –0.28% for the LiF:Mg,Ti TLD, all of which fall within the ICRP standard of ±30%. Increasing the distance between the dosimeter and the radiation source improved the uniformity of the dose distribution but reduced measurement accuracy. The ANOVA results indicated that distance, dose, TLD type, and several interactions among these factors significantly affected the measured dose and bias performance ($p < 0.05$). These findings confirm that the observed variations in measurements were indeed influenced by the tested factors.

The selection of TLD materials must align with their intended application. LiF:Mg,Ti is suitable for routine or precise dosimetry, whereas $CaSO_4$:Dy is better suited for environmental or low-dose monitoring where high sensitivity is required. However, this study has limitations, including the restricted dose variations (0.1 mSv and 0.5 mSv), the limited distance range (100 cm to 200 cm), and the fixed measurement-point configuration, which may not fully reflect real-world conditions. Despite these constraints, the findings can help optimize dosimeter placement and spacing during calibration or radiation protection activities. Further research is recommended to explore a wider range of distances and dosimeter types, as well as to examine the effects of irradiation angles, to better understand how geometric factors and energy dependence influence dose homogeneity and accuracy.

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References

1. Brady SL, Toncheva G, Dewhirst MW, Yoshizumi TT. Characterization of a 137-Cs irradiator from a new perspective with modern dosimetric tools. Heal Phys. 2013;97(3):195–205.
2. International Commission on Radiological Protection. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Oxford (UK); 2007.
3. Asadian S, Zarghani H. Evaluation of knowledge, attitude, and performance of radiographers towards

radiation protection in Southern Khorasan Province, Iran. Iran J Med Phys. 2018;15:222–5.

4. Akpochafor MO, Adeneye SO, Kehinde O, Omojola AD, Oluwafemi A, Nusirat A, et al. Development of Computed Tomography Head and Body Phantom for Organ Dosimetry. Iran J Med Phys. 2019;16(1):8–14.
5. Kartikasari D, Zulys A, Hiswara E, Nuraeni N. Synthesis of Thermoluminescence Dosimeter (TLD) Using Calcium Sulfate (CaSO4) With Variations of Dysprosium (Dy) and Thulium (Tm) Dopants. AIP Conf Proc [Internet]. 2018;2023(020084):1–5. Available from: https://doi.org/10.1063/1.5064081.
6. Fernández SDS, García-Salcedo R, Sánchez-Guzmán D, Ramírez-Rodríguez G, Gaona E, León-Alfaro MA de, et al. Thermoluminescent Dosimeters for Low Dose X-ray Measurements. Appl Radiat Isot [Internet]. 2016;107:340–5. Available from: http://dx.doi.org/10.1016/j.apradiso. 2015.11.021
7. Efenji GI, Iskandar SM, Yusof NN, Rabba JA, Mustapha OI, Fadhirul IM, et al. Structural Properties of Thermoluminescence Dosimeter Materials, Preparation, Application, and Adaptability: A Systematic Review. J Appl Sci Environ Manag. 2024;28(4):1129–50.
8. Stanković Petrović JS, Knežević ŽI, Kržanović NL, Majer MC, Živanović MZ, Ciraj-Bjelac OF. Review of the thermoluminescent dosimetry method for the environmental dose monitoring. Nucl Technol Radiat Prot. 2021;36(2):150–62.
9. IAEA. Calibration of Radiation Protection Monitoring Instruments (Safety Report Series No. 16). 2000.
10. Asiah NM. Cek Stabilitas Dan Pengukuran Laju Kerma Udara. J Sains Fis. 2023;3(2):26–37.
11. Laarhoven PJM van, Aarts EHL. Simulated Annealing: Theory and Applications. Bulletin of the London Mathematical Society. Dordrecht: D. Reidel Publishing Company. 1987; 187.
12. Arief S, Fitri M. Machinability Analysis of SUH 35 Material Subjected to Annealing Process on Engine Valve Making Surface Grinding. J Tek Mesin. 2025;14(1):66–73.
13. Oktaviani A, Setiawati E, Hidayanto E, Nuraeni N. Determination of Uniformity Value Response and Calibration Factors TLD Chips Using GAMMA Sources. Int J Sci Res Sci Technol. 2023;9(11):296–300.
14. Romanyukha A, Hoy A. Comparison of the performance of thermoluminescence and direct ion storage dosimeters in accreditation proficiency testing. Radiat Meas. 2020;135(106371).
15. American National Standards Institut. American National Standard for Dosimetry __ Personnel Dosimetry Performance __ Criteria for Testing. McLean (VA); 2009.
16. Vanhavere F, Carinou E, Gualdrini G, Clairand I, Merce MS, Ginjaume M, et al. ORAMED: Optimization of Radiation Protection of Medical Staff. EURADOS Re. 7TH EURADOS Report 2012-02. Braunschweig: EURADOS. 2012; 194.
17. Widhianasari Y, Satoto B, Darmini. Kualitas Performa TLD Reader. Bojonegoro: Madza Media. 2022.
18. Alanazi SF, Alarifi H, Alshehri A, Almurayshid M. Response Evaluation of Two Commercial Thermoluminescence Dosimeters (TLDs) Against Different Parameters. BJR Open [Internet]. 2023;5(20220035). Available from: https://doi.org/10.1259/bjro.20220035
19. Kardianto, Kristanti KH, Tiswati KA, Dwihapsari Y. Analisis Nilai Ketidakpastian dan Faktor Kalibrasi pada Alat Ukur Radiasi di Balai Pengamanan Fasilitas Kesehatan Surabaya. J Fis dan Apl. 2019;15(2):56–61.
20. IAEA. Radiation Oncology Physics: A Handbook for Teachers and Students (E. B. Podgorsak, Ed.). Vienna: International Atomic Energy Agency. 2005.
21. Bartkoski DA, Bar-David A, Kleckner M, Mirkovic D, Tailor R, Moradi-Kurdestany J, et al. Analysis of a novel X-ray lens for converging beam radiotherapy. Sci Rep [Internet]. 2021;11(19180). Available from: https://doi.org/10.1038/s41598-021-98888-8
22. Grygier A, Skubacz K, Chałupnik S. The correction factors for UD802 dosimeters irradiated with different radiation energies and at different incidence angles. J Radiol Prot. 2021;41(3):526–38.
23. Diyona F, Milvita D, Herlinda S, Sandy KYP. Analisis Pengaruh Sudut Penyinaran terhadap Dosis Permukaan Fantom Berkas Radiasi Gamma Co-60 pada Pesawat Radioterapi. J Fis Unand. 2016;5(2):131–5.
24. Pashazadeh A, Baghani HR, Robatjazi M, Kadavil P. The effect of geometrical parameters of skin brachytherapy patch source on depth dose distribution using Monte Carlo simulation. Appl Radiat Isot. 2024;204(111117).
25. Pradhan AS, Adtani MM, Varadharajan G, Bakshi AK, Srivastava K, Bihari RR. Hand Book On The Use of TLD Badge Based On CaSO4:Dy Teflon TLD Discs for Individual Monitoring. Mumbai: Bhabha Atomic Reseach Center. 2002.
26. Liuzzi R, Savino F, Avino VD, Pugliese M. Evaluation of LiF : Mg, Ti (TLD-100) for Intraoperative Electron Radiation Therapy Quality Assurance. PLoS One. 2015;10(10).
27. Purwantiningsih. Analisis Sebaran Dosis Paparan Radiasi Pesawat C-ARM Terhadap Jarak Pada Ruang Operasi. J Sainstek. 2017;9(2):183–9.