Comparison of the Measurement Uncertainty of Thermoluminescence Dosimeters (TLD-100 and GR-200) in Clinical Radiotherapy Energies

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ABSTRACT

Background: Accurate determination of individual radiation doses is critical in dosimetry, and international standards emphasize the importance of reporting measurement uncertainties. Neglecting measurement uncertainty undermines the reliability of reported dosimetric values, as emphasized by international standards.

Objective: This study aimed to evaluate the measurement of uncertainties in two Thermoluminescent Dosimeters (TLDs)-100 and GR-200, in the dose range of 30–150 cGy.

Material and Methods: In this experimental study, we evaluated the measurement of uncertainties in two thermoluminescent dosimeters, TLD-100 and GR-200, in the dose range of 30–150 cGy. The study investigated both random (Type A) and systematic (Type B) uncertainties. Random uncertainties include the non-uniformity of dosimeter sensitivity Element Correction Coefficient (ECC), variability in dosimeter response at zero dose, and repeatability. Systematic uncertainties include the dependence of dosimeter response on radiation energy, radiation angle, nonlinearity of dosimeter response, fading, ambient light effects, and reference calibration errors.

Results: The total uncertainty for TLD-100 was calculated as 10.99% at a 68% confidence level (21.99% at 95% confidence), while for GR-200, it was 13.63% at a 68% confidence level (27.26% at 95% confidence). These values are well below the 42% threshold recommended by the International Atomic Energy Agency (IAEA) for personal dosimetry services.

Conclusion: The GR-200 exhibits higher sensitivity for low-dose radiation detection; however, its greater uncertainty makes TLD-100 more suitable for clinical and personal dosimetry applications, where precision and reliability are paramount.

Keywords

Radiotherapy; Uncertainty; Thermoluminescent Dosimetry; TLD-100; GR-200

Introduction

Thermoluminescence dosimeters (TLDs) are widely recognized for their importance in medical dosimetry due to their small size, tissue-equivalent atomic number, and high sensitivity. These properties make TLDs particularly suitable for applications in radiotherapy, where accurate dose measurement is critical for effective treatment.

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Recent advancements in thermoluminescence dosimetry have focused on optimizing TLD materials to better mimic human tissue response, thereby improving their accuracy and reliability in clinical settings. Lithium fluoride-based TLDs, particularly TLD-100 (Mg, Ti-doped) and GR-200 (Mg, Cu, P-doped), are among the most commonly used dosimeters.

These materials are extensively employed in radiotherapy, where high-energy X-rays and gamma rays are used to target and destroy tumor masses, significantly contributing to cancer treatment [1, 2].

In radiotherapy, precise dose measurement is essential to ensure the safety and efficacy of treatment. However, the accuracy of dosimetry systems is inherently limited by various sources of uncertainty. Organizations, such as the International Commission on Radiological Protection (ICRP), the International Organization for Standardization (ISO), and the International Atomic Energy Agency (IAEA) have extensively studied these uncertainties and provided guidelines for their calculation and estimation. The IAEA, in particular, has published comprehensive reports on uncertainty analysis in radiation dosimetry, emphasizing the importance of quantifying uncertainty in clinical practice [3].

The overall uncertainty of a dosimetry system is determined by the combination of two types of uncertainty: random (Type A) and systematic (Type B). Type A of uncertainties arise from statistical variations with factors, such as the non-uniformity of dosimeter sensitivity to the same doses Element Correction Coefficient (ECC), variability in dosimeter response at zero dose, and repeatability. Type B uncertainties, on the other hand, are associated with systematic effects and include factors, such as dosimeter response dependence on radiation energy, radiation angle, nonlinearity of the dosimeter response to uniform radiation, fading effects, ambient radiation effects, and calibration uncertainties in reference laboratories (e.g., Secondary Standard Dosimetry Laboratories - SSDLs) maintaining traceability to national/international standards [4, 5].

Recent studies have further explored the sources of uncertainty in TLDs, particularly in the context of clinical radiotherapy. For example, studies by Jursinic [6] and Howell et al. [7] have highlighted the impact of energy dependence and angular response on TLD measurements, while Amit et al. [8] have investigated the effects of fading and environmental factors on TLD performance. These studies underscore the need for a comprehensive understanding of uncertainty sources to improve the accuracy of TLD-based dosimetry systems.

According to the IAEA's SAFETY GUIDE NO. RS-G-1.3, the maximum allowable measurement uncertainty for individual dosimetry at the 95% confidence level is 42% [3]. This guideline serves as a benchmark for evaluating the performance of dosimetry systems, including TLDs.

In this study, we identified, measured, and calculated uncertainties in a personal dosimetry system using TLDs. Specifically, we compared the uncertainties of TLD-100 and GR-200 in clinical radiotherapy energies. By addressing the sources of uncertainty and providing a detailed comparison of these two widely used dosimeters, this study aimed to contribute to the ongoing efforts to improve the accuracy and reliability of dosimetry in radiotherapy.

Material and Methods

Material

In this experimental study, LiF: Mg, Ti (TLD-100) with dimensions of approximately 3×3×1 mm^3 and LiF: Mg, Cu, P (GR-200) with dimensions of approximately 5 mm in diameter and 1 mm in thickness were used.

The TLD-100 and GR-200 dosimeters were irradiated using a linear accelerator (Linac, Versa-HD) at Arak Khansari Hospital. The irradiation was performed at clinical radiother-

apy energies of 6, 10, and 18 MV. The dose range for irradiation was set between 0.5 Gy and 5 Gy, covering typical therapeutic doses in radiotherapy. Each TLD was exposed to three different dose levels (1, 2, and 4 Gy) to evaluate the dose-response relationship and measurement uncertainty.

The uncertainty calculations were performed using a Slab Phantom (PTW, Germany) with a Source-to-Axis Distance (SAD) of 100 (see Figures 1 and 2). Before irradiation, the TLD-100 and GR-200 chips were annealed using a calibrated electric furnace according to the manufacturer's protocols. For TLD-100, the annealing process involved heating the chips at 400 °C for 1 hour, followed by rapid cooling to room temperature. For GR-200, the chips were annealed at 240 °C for 10 minutes, followed by rapid cooling. This process ensures the elimination of any residual signal from previous irradiations and prepares the dosimeters for accurate dose measurement.

After annealing, the TLD-100 and GR-200

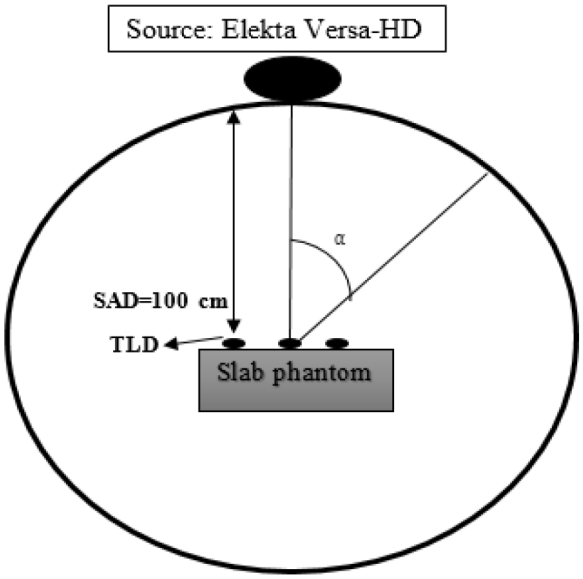

Figure 1: Schematic of the Thermoluminescent Dosimeter (TLD) 100 & GR200 uncertainty measurement set up: Elekta Vrsa-HD Linac, 6, 10, and 18 MV energies at different gantry angles (0, 20, 40, and 60), Source-to-Axis Distance (SAD)=100 cm.

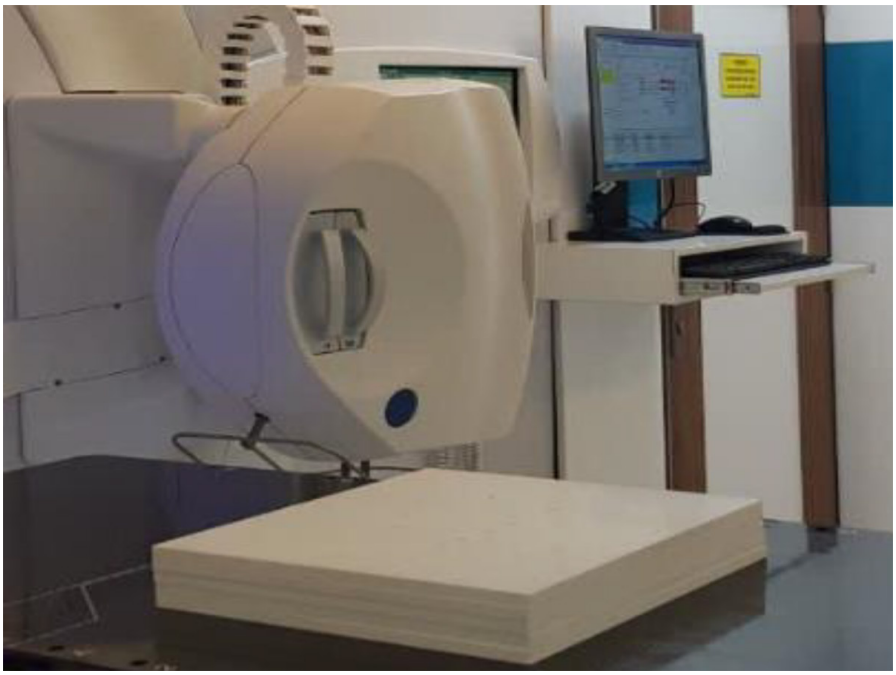

Figure 2: The necessary slab (PTW (Physikalisch-Technische Werkstätten), Germany) thickness (2 cm for 6 MV & 3 cm for 10, 18 MV) for build-up conditions was placed on the Thermoluminescent Dosimeters (TLDs), depending on the energy level

chips are placed in polyethylene plates in a matrix and prepared for irradiation to measure the background dose received by the dosimeters during each irradiation session at Khansari Arak Hospital. Four annealed dosimeters are irradiated as control dosimeters along with the irradiated dosimeters. These dosimeters are read under the same conditions as the irradiated ones, and the readings are then subtracted from the responses of the irradiated dosimeters.

Methods

The uncertainty in thermoluminescence dosimetry was calculated according to the guidelines provided by the International Atomic Energy Agency [3]. The overall uncertainty (Uc) was determined by combining Type A (random) and Type B (systematic) uncertainties, as shown in equation 1.

$$U_c = \sqrt[2]{U_A^2 + U_B^2} \quad (1)$$

Where U_A and U_B represent type A and B uncertainties, respectively. Type A uncertainty includes factors that decrease as the number of measurements increases. The factors contributing to type A uncertainty can be assumed to follow a normal statistical distribution (equation 2).

$$U_A = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n(n-1)}} \quad (2)$$

Where x_i represents an individual measurement value, n is the number of measurements (samples), and $\bar{x}$ is the mean of the x_i values. The type of B uncertainty, in thermoluminescence dosimetry, does not decrease with repeated measurements and is calculated with a rectangular probability distribution in the dosimetry process using equation 3.

$$U_{Bi} = \frac{a_i}{\sqrt{3}} = \frac{(a_{max} - a_{min})}{2\sqrt{3}} \quad (3)$$

Where "α_i" represents the half-width of the measurement interval (i.e., half the difference between the maximum and minimum measurement values). The factor $\frac{1}{\sqrt{3}}$ is used under the assumption of a rectangular probability distribution for Type B uncertainty.

The Type B uncertainty is determined by using equation 4.

$$U_B = \sqrt{\sum_i U_{Bi}^2} \quad (4)$$

Hence, the overall uncertainty is calculated using equation 5.

$$U_C = \sqrt[2]{U_A^2 + \frac{1}{3}\sum_i a_i^2} \quad (5)$$

The Type A uncertainty in equation (5) was calculated with a confidence level of 68% and will be combined with the Type B uncertainty, also at a confidence level of 68%. Finally, the result of the relationship will be multiplied by the coverage factor k=2 to obtain the total uncertainty with a confidence level of 95% according to Equation 6. In a normal distribution, one standard deviation (σ) covers 68% probability, whereas two standard deviations cover 95% probability [9-11].

$$U = K \times U_c \quad (6)$$

This method is consistent with previous studies on TLD uncertainty analysis [5,8,9]. This study assessed parameters contributing to measurement uncertainty using TLD dosimeters and the reader system in personal dosimetry for medical centers.

Type A

Uncertainty of non-uniformity of sensitivity of dosimeters

The sensitivity of dosimeters can vary due to differences in manufacturing quality, leading to variations in TLD (thermoluminescent dosimeter) responses. To assess this, a group of dosimeters is exposed to 50 cGy of 6 MV X-ray radiation under uniform conditions. The uncertainty in dosimeter sensitivity is determined by first calculating the standard deviation of the ECC, and then finding the average. The correction factor is calculated using equation 7.

$$ECC_{ii} = \frac{TL_{ave}}{TL_{ij}} \quad (7)$$

Where TL_{ave} is the average of all readings,

and TL_{ii} is the individual reading. The standard deviation of ECC compared to its average value is considered the uncertainty of the non-uniformity of the sensitivity of the dosimeters.

Uncertainty due to zero dose

To assess this, 50 readings are taken without any dosimeter inside the TLD reader. Subsequently, 50 unirradiated and unannealed dosimeters are read one after the other. The uncertainty is calculated using Equation 2 by comparing the readings with and without dosimeters. Even though the TL values at zero dose are minimal, the variability of the detector readings at zero dose significantly increases the standard deviation. While the mean zero dose value is low, the standard deviation remains high.

Uncertainty due to reproducibility

A specific number of dosimeters are exposed to the same conditions and a dose of 50 cGy (using an X-ray source with an energy of 6 MV). The uncertainty is calculated using Equation 2 at a confidence level of 68% [9-11].

Type B

Energy dependence

Most personal dosimeters and TLDs are energy-dependent, which is a major source of uncertainty. In this study, three groups of five dosimeters are placed in dedicated matrix boxes and exposed to X-rays of different energies (6 MV, 10 MV, 18 MV). Each group of dosimeters is subjected to a dose of 50, and the ratio of TL_{ave} (average thermoluminescence) to the dose delivered at each energy, as well as the ratio of the width of the TL_{ave} half value to the dose delivered at each energy, is calculated. Finally, the ratio of the width of the TL_{ave} half value to the dose, divided by their average, at three different energies provides the uncertainty of the dosimeter response depending on the radiation energy. This uncertainty is obtained with a confidence level of 68%.

Directional dependence

The dosimeter's sensitivity to beam direction introduces significant uncertainty because of angular dependence. In a study, four groups of dosimeters were exposed to 50 cGy from a 6 MV X-ray source at angles of 0°, 20°, 40°, and 60°, as recommended in the literature [3]. The ratio of TLave to the dose at each angle is calculated. The uncertainty, due to angular dependence, is determined by the ratio of the half-width of these values to their average dose, with a 68% confidence level.

Non-linearity of the response

The response of TLDs is not linear and is influenced by both the type of TLD and the electronic properties of the reader system. To calibrate the reader, dosimeters with an ECC close to one are utilized. These dosimeters are divided into four groups of five: three groups are exposed to different radiation doses, while one group serves as control dosimeters and is not exposed to radiation. After reading the dosimeters and adjusting for ambient radiation using the control dosimeters, the ratio of average Thermoluminescent (TL) values to the dose for each exposed group is calculated. The uncertainty arising from non-linearity is determined by the ratio of the range of the TL values to the average dose.

Uncertainty of light effect

Twenty GR-200 chips and TLD-100 were prepared and heated for irradiation. After the irradiation, the chips were split into two groups of ten. One group was kept in darkness, while the other was exposed to a 30-watt moonlight lamp for one week. After one week, both groups were assessed under the same conditions. The ratio of the half-width of TL_{ave} values between the two groups to the average value represents the uncertainty due to the light effect on the dosimeter response.

Uncertainty of fading

The fading of TL materials is caused by surface traps in TLDs. In an experiment, twenty chips were irradiated with 50 cGy from a 6 MV X-ray source and then heated. These chips were then split into two groups of ten each. One group was read 24 hours after

irradiation, while the second group was stored in darkness for 25 days before being read under the same conditions as the first group. The ratio of the half-width of TL_{ave} values between the two groups to the average value indicates the uncertainty caused by the fading effect on the dosimeter response.

Reference calibration uncertainty

The uncertainty of the X-ray output from this Linac is 2% at the 95% confidence level or 1% at the 68% confidence level [11-14].

Results

Each source of random and systematic uncertainty from the previous paragraphs was separated and analyzed. The total uncertainty at the 68% confidence level was then calculated using Equations 5, and 8 was applied for the final computation.

$$U_c = \sqrt{u_{Ecc}^2 + u_{zero}^2 + u_{rep}^2 + u_{fad}^2 + u_{lin}^2 + u_{light}^2 + u_{SSDL}^2 + u_{Energy}^2 + u_{Dir}^2} \quad (8)$$

Tables 1 and 2 display the calculated uncertainties for different dose ranges along with their corresponding calibration coefficients

Table 1: Calculated uncertainties for GR-200 chips (30-150 cGy) with Reader Calibration Factor (RCF)=0.105.

Type	Source of uncertainty	Number Of TLDs	Values (%)	U_c% (Confidence Level 68%)	U_c% (Confidence Level 95%)
A	ECC	28	0.456	13.63	27.26
	Zero dose	50	4.89		
	Repeatability	20	0.728		
B	Energy	15	3.290		
	Direction	16	3.571		
	Fading	20	1.198		
	Light	20	0.845		
	Calibration errors	-	1		
	Linearity	20	11.595		

TLDs: Thermoluminescent Dosimeters, ECC: Electron Compensation Coefficient

Table 2: Calculated values of uncertainties for Thermo Luminescent Dosimeter (TLD)-100 chips in the range (30-150 cGy) with calibration factor Reader Calibration Factor (RCF=2.2793)

Type	Source of uncertainty	Number Of TLDs	Values (%)	U_c% (Confidence Level 68%)	U_c% (Confidence Level 95%)
A	ECC	40	1.81	10.99	21.99
	Zero Dose	50	5.63		
	Repeatability	20	0.052		
B	Energy	15	5.75		
	Direction	16	3.57		
	Fading	20	1.47		
	Light	20	0.77		
	Calibration Errors	_	1		
	Linearity	20	6.01		

TLDs: Thermoluminescent Dosimeters, ECC: Electron Compensation Coefficient

related to GR-200 and TLD-100.

Discussion

The results of this study provide a comprehensive comparison of the measurement uncertainties associated with TLD-100 and GR-200 dosimeters in clinical radiotherapy settings. The total uncertainty values of 10.99% for TLD-100 and 13.63% for GR-200 (at a 68% confidence level) are significantly lower than the 42% threshold recommended by the International Atomic Energy Agency (IAEA) for personal dosimetry services [3]. This indicates that both dosimeters are suitable for clinical applications, with TLD-100, demonstrating slightly better performance in terms of uncertainty.

The superior performance of TLD-100 in terms of uncertainty can be attributed to its well-documented stability and lower sensitivity to environmental factors, such as fading and light exposure. According to McKeever [4], TLD-100 exhibits a more linear dose-response relationship and less energy dependence compared to other TLD materials, making it a reliable choice for clinical dosimetry. In contrast, GR-200, while offering higher sensitivity for low-dose radiation detection, shows greater susceptibility to environmental influences, leading to higher overall uncertainty. This finding is consistent with the work of Amit et al. [8], who reported that GR-200's sensitivity to fading, and light effects can significantly impact its performance in clinical settings.

The energy dependence of both dosimeters was also evaluated in this study. TLD-100 demonstrated lower energy dependence compared to GR-200, which aligns with previous studies by Horowitz [5]. This characteristic makes TLD-100 more suitable for applications involving a wide range of photon energies, such as radiotherapy. On the other hand, GR-200's higher energy dependence may limit its use in clinical settings where precise dose measurement across different energy levels is critical.

Another important factor contributing to the uncertainty of TLD measurements is the non-uniformity of dosimeter sensitivity. Our results show that TLD-100 has a lower non-uniformity uncertainty (1.81%) compared to GR-200 (0.456%). This finding is consistent with the work of Olko [1], who highlighted the importance of calibration and batch uniformity in reducing measurement uncertainty in TLDs.

Despite its higher uncertainty, GR-200's superior sensitivity for low-dose radiation detection makes it a promising candidate for applications requiring high sensitivity, such as environmental monitoring or low-dose research. However, for clinical dosimetry, where precision and reliability are paramount, TLD-100 remains the more appropriate choice.

Conclusion

This study evaluated the measurement of uncertainties in TLD-100 and GR-200 dosimeters in clinical radiotherapy settings. The results demonstrate that TLD-100 has a lower overall uncertainty (10.99%) compared to GR-200 (13.63%), making it more suitable for clinical dosimetry applications. While GR-200 exhibits higher sensitivity for low-dose radiation detection, its increased uncertainty limits its reliability in clinical settings. These findings highlight the importance of selecting the appropriate dosimeter based on the specific requirements of the application, with TLD-100 being the preferred choice for high-precision dosimetry.

Future studies could focus on further optimizing the performance of GR-200 by addressing its sensitivity to environmental factors and nonlinear response. Additionally, the development of new TLD materials with improved sensitivity and lower uncertainty could be explored to enhance the accuracy of clinical dosimetry.

Authors' Contribution

F. Seif and MR. Bayatiani conceived the

idea and designed the study. Introduction of the paper was written by F. Seif and B. Sadeghi. The method implementation was carried out by R. Purimani and H. Kiani. Results and Analysis was carried out by B. Sadeghi and MR. Bayatiani. The research work was proofread and supervised by F.Seif and R.Purimani. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The Ethics Committee of the Research Council of Arak University of Medical Sciences approved the protocol of the study (Ethic cod: IR.ARAKMU.REC.1403.182).

Informed Consent

In this study, data collection was performed using TLD dosimeters, and no intervention involving human or animal subjects was conducted. Therefore, informed consent was not applicable.

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Conflict of Interest

None

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