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Evaluation of the combined standard uncertainty of the absorbed dose measured using thermoluminescent dosimetry

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Abstract

The paper discusses the calculation of the combined standard uncertainty of the absorbed dose measurements using the thermoluminescent dosimetry (TLD). This procedure serves as a key tool for independent dose verification in clinical practice, particularly within "dose-by-mail" audit programs. Ensuring proper metrological traceability and correct uncertainty determination are mandatory requirements for the accreditation of such dosimetry services. The calculation is performed in accordance with the GUM and IAEA international recommendations and involves determining the limits of the combined uncertainty.

The combined standard uncertainty of the absorbed dose is calculated as the combined influence of the uncertainties of individual factors in the calculation formula, specifically: the calibration coefficient of the TL system, correction factors for fading, the non-linearity of the "dose-TL signal" dependence, and the presence of the detector holder.

The most significant contribution to the combined uncertainty comes from the uncertainty of the calibration coefficient, which is associated with the accuracy of delivering the absorbed dose to water according to the ionization chamber readings. To minimize it, modern methods of statistical data processing, obtained experimentally, were applied. Experimental studies were conducted at various stages using a therapy unit and a water phantom, the state primary measurement standard of the absorbed dose, and a PMMA phantom in a horizontal beam geometry.

Under all irradiation conditions, the combined standard uncertainty of the absorbed dose did not exceed ±3%, which complies with the IAEA requirements for TLD audit centres. The proposed approach provides a reliable basis for metrological support of dosimetry in clinical practice and can be implemented in the work of dosimetry audit services.

Keywords: radiation therapy; TLD audit; uncertainty; absorbed dose; thermoluminescent dosimetry; ionizing radiation.

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Problem statement for uncertainty evaluation

External dosimetry audit using thermoluminescent dosimetry (TLD) is a key mechanism for independent verification of the accuracy of therapeutic dose delivery to patients in radiation therapy. In the context of Ukraine, where some medical institutions may lack modern dosimetric equipment or qualified personnel, such "dose-by-mail" audits are practically the only opportunity to independently verify the dose delivered to patients using radiation therapy units.

The effectiveness of this method is based on the use of tissue-equivalent detectors, specifically a LiF:Mg,Ti luminescent phosphor, which is distinguished by its high sensitivity, low fading, and stable reproducibility of results.

To achieve a combined standard uncertainty of no more than ±5% (with P=95%, k=2), it is necessary to reduce the influence of the uncertainty associated with each correction factor. In the previous part of our work [1], these key factors were studied in detail and determined, specifically the coefficients accounting for non-linearity, fading, the presence of a holder, and calibration conditions.

The continuation of this study and a mandatory requirement for metrological support of TLD audits is the detailed calculation of the combined standard uncertainty of all factors that influence and contribute uncertainty to the measurement process [1]. This evaluation is performed in accordance with international recommendations, specifically the IAEA Protocol No. 398 [2] and the "Guide to the expression of uncertainty in measurement" (GUM) [3].

The purpose of this paper is the processing of data and calculation of the combined standard uncertainty when evaluating the absorbed dose, the analysis of its individual components and determination of their contribution to the combined uncertainty at different stages of the system calibration.

The final combined standard uncertainty of the TLD audit method directly depends on the evaluation of the uncertainty of each individual factor used in the calculation: the calibration coefficient (*N*) and correction factors (f_{lin}, f_{fad}, f_{hol}) [1].

According to the international GUM recommendations, the combined standard uncertainty of a measured quantity shall be calculated as the combined influence of the uncertainty of all input factors [3].

This paper describes the use of general formulas for the dose calculation and its components, as well as provides a detailed analysis of the contribution of each parameter and correction factors to the combined standard uncertainty. This analysis is based on experimental data and methodologies tested during four stages (I–IV), which were described earlier (calibration in a water phantom and against the state primary measurement standard in a PMMA phantom) [1].

In the previous part of the study [1], the dosimetric properties of a TL system were studied in detail and key correction factors were determined. An important result was also the calculation of the uncertainty for each of these coefficients at different stages of the study.

These individual uncertainties are the input data for calculating the combined standard uncertainty of the TLD method, which is the subject of this paper.

Analysis of the obtained data shows that the application of an improved methodology for irradiating TL powder capsules during calibration significantly reduces the uncertainty.

The lowest uncertainty of the calibration coefficient was achieved at Stage IV when using a PMMA phantom against the state primary measurement standard of the absorbed dose and the absorbed dose rate of X-ray and gamma radiation (NSC "Institute of Metrology").

A reduction in the uncertainty associated with the non-linearity was determined with repeated use of the powder (from ±2% at Stage I to ±0.4% at Stage IV in the working dose range) [1].

The uncertainty associated with fading, under practical TLD audit conditions (readout 30 days after irradiation), stabilizes and can be evaluated at a level of ±0.7%. These experimentally determined values are the basis for the subsequent calculation of the combined standard uncertainty of the dose determination [1].

Evaluation of combined standard uncertainty of the absorbed dose measurements using thermoluminescent dosimetry

The combined standard uncertainty of any measurements shall be determined in accordance with the international guidelines on the uncertainty evaluation set out in the "Guide to the Expression of Uncertainty in Measurements" (GUM) [3].

According to these documents, there are two approaches to evaluate the measurement uncertainty:

• determination of the confidence limits of the combined standard uncertainty;

• determination of the limits of the expanded uncertainty of the measured quantity.

The combined standard uncertainty of any measured quantity [3] is calculated by the formula:

$$u_\Sigma = \sqrt{u_A^2 + u_B^2}, \qquad (1)$$

where u_A^2 is the Type A uncertainty; and u_B^2 is the Type B uncertainty.

When determining the absorbed dose (*D*) at a certain depth based on the TL signal (*M*) of thermoluminescent detectors in a water or PMMA phantom, the following formula is used [2]:

$$D_w = M \cdot N \cdot f_{lin} \cdot f_{en} \cdot f_{hol} \cdot f_{fad}, \qquad (2)$$

where D_w is the absorbed dose to water, Gy;

M is the TL signal value, corrected for any daily fluctuation of the TL reader using a correction factor accounting for the instrument sensitivity drift, rel. units;

N is the calibration coefficient of the TL system, Gy/rel.unit;

f_{lin} is the correction factor accounting for the non-linearity of the TL signal dependence on irradiation dose, dimensionless;

f_{en} is the correction factor accounting for the dependence of the TL signal on the energy of ionizing radiation, dimensionless;

f_{hol} is the correction factor accounting for the influence of the standard irradiation holder on the TL signal value, dimensionless;

f_{fad} is the fading correction factor, dimensionless.

It should be noted that the photon energy of radiation therapy units in medical facilities does not differ from the gamma energy of the reference source used for calibrating the TLD system, therefore f_{en} = 1, and the uncertainty of the energy correction factor is not evaluated.

The combined standard uncertainty (ε_Σ) of the measured dose consists of the errors when estimating each of the factors in the absorbed dose calculation formula (see Formula 2), which are determined experimentally or estimated from experimentally determined functions, and is calculated by the formula [3]:

$$u = \sqrt{u_{kal}^2 + u_{fad}^2 + u_{lin}^2 + u_{hol}^2}, \qquad (3)$$

where u_{kal} is the uncertainty when estimating the calibration coefficient of the TL system (*N*);

u_{fad} is the uncertainty when estimating the fading correction factor (f_{fad});

u_{lin} is the uncertainty when estimating the correction coefficient for the non-linearity of the "dose – TL signal" dependence (f_{lin});

u_{hol} is the uncertainty when estimating the correction factor for the presence of the TL detector holder (f_{hol}).

When estimating the calibration coefficient (N) of the TL system, the uncertainty is determined by the formula [2]:

$$u_{kal} = \sqrt{u_D^2 + u_r^2 + u_u^2}, \quad (4)$$

where u_D is the uncertainty of the accuracy of delivering the absorbed dose to water according to the ionization chamber readings;

u_r is the uncertainty in the accuracy of positioning the TL detector in the water or a PMMA phantom during its irradiation;

u_u is the uncertainty of the accuracy of measuring the TL signal on the PCL-3 reader for a given dose of 2 Gy.

When delivering the absorbed dose to water according to the ionization chamber readings, the uncertainty belongs to systematic uncertainties (Type B), as it does not depend on the result of repeated measurements but is associated with the consideration of all correction factors specified in the IAEA dosimetry protocol TRS 277 [4] and the data based on the verification results of the UNIDOS dosimeter.

The uncertainty in positioning the TL detector in the water phantom during its irradiation is also a systematic uncertainty (Type B) as it is related to the accuracy of placing the capsule with TL powder in the phantom using the holder. According to the data obtained from previous studies, this component is 0.2% [5].

The uncertainty in measuring the TL signal for an absorbed dose of 2 Gy on a PCL-3 reader is determined as random (Type A), based on the results of repeated measurements of the TL signal from TL detectors irradiated with the given dose. It is determined as the standard Type A uncertainty for a TL detector and is calculated by the formula:

$$SD_m = \frac{SD}{\sqrt{n}}, \quad (5)$$

where SD is the standard deviation of the TL signal of the dosed powder mass; n is the number of measurements per capsule.

From the distribution of the standard deviation of the mean for many capsules, the uncertainty of the readings per capsule is evaluated as the mean value SD_m of this distribution.

The calculation of the uncertainty when estimating the correction factor for the non-linearity of the "dose – TL signal" dependence (f_{lin}) and the correction factor for fading (f_{fad}) is associated with the experimental determination of the dependence functions of these factors on dose ($f_{lin}=f(D)$) or time ($f_{fad} = f(\Delta t)$) and with the evaluation of the uncertainty of the regression coefficients calculated by the least squares method when approximating the experimental data with a linear function.

The fading function is described in terms of a complex non-linear dependence; therefore, to calculate the uncertainty when estimating the fading correction factor (f_{fad}), the uncertainty confidence corridor shall be accounted for each individual straight-line section, into which the fading curve can be divided according to time intervals.

During practical TLD audits, the time from irradiation of the TL powder capsule to readout typically exceeds 30 days; therefore, the uncertainty on the fading curve sections was evaluated for 30 to 50 days and beyond 50 days.

In the interval of 30–50 days after the irradiation, the uncertainty was evaluated as the standard uncertainty of the estimate of the regression coefficient of the function approximating the experimental fading values in this time interval. After 50 days, the fading is almost absent: f_{fad} approaches a constant value, so the uncertainty during this period is evaluated by standard statistical processing of the variation series of the TL signal measurements performed on different days after 50 days [1].

When reference TL detectors from the same powder batch are irradiated on the same day in medical facilities, fading correction is not applied ($f_{fad} = 1$) provided they are read out simultaneously [1].

The uncertainty of the correction coefficient accounting for the beam attenuation by the plexiglass holder material when irradiating the TL detector to water in a vertical beam geometry was experimentally evaluated at the IAEA/WHO TLD audit centre and was 0.3% [5].

Tables 1 and 2 provide comparative data on the calculations of the calibration coefficient uncertainty and the combined standard uncertainty of the absorbed dose when irradiating TL detectors on a therapy unit in a water phantom at Stages I and II and against the state primary measurement standard of the absorbed dose and the absorbed dose rate of X-ray and gamma radiation in a PMMA phantom in a horizontal beam geometry at Stages III and IV.

At Stage IV, the combined standard uncertainty of the absorbed dose based on the measured TL signal of the detectors irradiated against the state primary measurement standard of the absorbed dose and the absorbed dose rate of X-ray and gamma radiation in a horizontal beam geometry in a PMMA phantom was 2.43%, compared to the uncertainties obtained at Stages I–III (Table 2).

It should be noted that when the irradiation was performed in a horizontal beam geometry in a PMMA phantom, the capsule holder was not used; therefore, this component was not accounted for when calculating the combined uncertainty.

It was found that when irradiating TL detectors both against the reference horizontal gamma irradiation facility housed at the NSC "Institute of Metrology"

Table 1

Relative uncertainty of components associated with the determination of the calibration coefficient (*N*) of a TLD system

Uncertainty component	Stage I			Stage II			Stage III			Stage IV		
	Type A	Type B	Combined A & B	Type A	Type B	Combined A & B	Type A	Type B	Combined A & B	Type A	Type B	Combined A & B
Dose determination in the ionization chamber	0.50	2.00	2.06	0.50	2.00	2.06	0.50	2.00	2.06	0.50	2.00	2.06
TL signal measurement	0.45	—	0.45	0.45	—	0.45	0.34	—	0.34	0.39	—	0.39
TL detector positioning accuracy	—	—	—	—	—	—	—	0.20	0.20	—	0.20	0.20
Combined uncertainty of cal. coeff. ***N***	0.67	2.00	2.11	0.67	2.00	2.11	0.60	2.01	2.10	0.63	2.01	2.11

Table 2

Combined standard uncertainty associated with the determination of absorbed dose based on the measured TL signal

Uncertainty component	Stage I			Stage II			Stage III			Stage IV		
	Type A	Type B	Combined A & B	Type A	Type B	Combined A & B	Type A	Type B	Combined A & B	Type A	Type B	Combined A & B
Calibration Coefficient	0.67	2.00	2.11	0.67	2.00	2.11	0.60	2.01	2.10	0.63	2.01	2.11
Correction coeff. for dose dependence non-linearity	0.94	—	0.94	1.30	—	1.30	1.02	—	1.02	0.90	—	0.90
Correction coeff. for fading	0.85	—	0.85	1.26	—	1.26	0.92	—	0.92	0.81	—	0.81
Correction coeff. for holder presence	0.30	—	0.30	0.30	—	0.30	—	—	—	—	—	—
Combined standard uncertainty of the dose determination	1.46	2.00	2.48	1.95	2.00	2.79	1.50	2.01	2.51	1.37	2.01	2.43

and against a remote gamma therapy device, the combined standard uncertainty of the absorbed dose assessment did not exceed ±3%, which meets the IAEA requirements for TLD audit centres.

Thus, under any irradiation conditions for TL detectors, the main contribution to the combined standard uncertainty of the absorbed dose assessment is made by the uncertainty when estimating the calibration coefficient, which is associated with the measurement of the absorbed dose in the ionization chamber. Therefore, the use of a gamma therapy unit to irradiate reference TL detectors is only possible provided it has been certified with a clinical dosimeter, the uncertainty of which does not exceed ±2.0%.

Conclusions and discussion of results

This study involved the determination and analysis of the contributions from individual correction coefficients and identification of ways to reduce the components of the combined standard uncertainty during TLD audits.

A combined standard uncertainty of less than 5% was achieved, which complies with the IAEA requirements for conducting TLD audits.

The obtained results should be used in organizing a TLD audit centre. It is also feasible to use a gamma therapy unit as a reference source, provided its beam is calibrated with a reference clinical dosimeter.

For the future TLD audit centre, it is crucial to participate annually in comparison programs for dose calculation results from controlled medical facilities with the IAEA and the NSC “Institute of Metrology”.

The priority for further enhancing the accuracy of the system is to improve reference dosimetry (reducing the uncertainty $u(N)$) as this component makes the largest contribution to the final result.

The results obtained also provide a solid basis for further studies.

Визначення сумарної невизначеності поглинутої дози, виміряної за допомогою методу TL-дозиметрії

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Анотація

У статті розглядається розрахунок сумарної невизначеності вимірювань поглинутої дози методом термолюмінесцентної дозиметрії (ТЛД). Ця процедура є ключовим інструментом для незалежної верифікації доз у клінічній практиці, особливо в рамках аудиторських програм "доза-поштою". Забезпечення належної метрологічної простежуваності та коректне знаходження невизначеності є обов'язковою вимогою для акредитації таких дозиметричних служб. Розрахунок виконується відповідно до міжнародних рекомендацій GUM та МАГАТЕ, полягає у визначенні меж сумарної невизначеності.

Сумарна невизначеність поглинутої дози розраховується як сукупний вплив невизначеностей окремих факторів розрахункової формули, зокрема: калібрувального коефіцієнта ТЛ-системи, поправочних коефіцієнтів на фединг, нелінійність залежності "доза-ТЛ-сигнал" та наявність тримача детекторів.

Найбільший внесок у сумарну невизначеність робить невизначеність калібрувального коефіцієнта, яка пов'язана з точністю відпущення поглинутої дози у воді за показаннями іонізаційної камери. Для її мінімізації було застосовано сучасні методи статистичної обробки даних, отримані експериментальним шляхом. Експериментальні дослідження проводилися на різних етапах із використанням терапевтичного апарата та водного фантома, державного первинного еталона одиниці поглинутої дози та фантома з ПММА в геометрії горизонтального пучка.

За будь-яких умов опромінення сумарна невизначеність поглинутої дози не перевищила ±3%, що відповідає вимогам МАГАТЕ до центрів проведення ТЛД-аудиту. Запропонований підхід забезпечує надійну основу для метрологічного забезпечення дозиметрії в клінічній практиці та може бути впроваджений у роботі дозиметрично-аудиторських служб.

Ключові слова: променева терапія; ТЛД-аудит; невизначеність; поглинута доза; термолюмінесцентна дозиметрія; іонізуюче випромінювання.

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