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Determination of correction factors and correction coefficients for calculations of the absorbed dose

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Abstract

The need to control the dose received by a patient during radiation therapy (RT) is dictated by the quality assurance requirements, which encompass a broad system of organizational and technical measures aimed at achieving consistency and precision in dosimetry measurements. The ultimate goal of using a quality assurance system in RT is to ensure high accuracy in delivering the dose to the tumour, reducing the irradiation volumes of normal, healthy tissues and organs near the target (tumour lesion). It has been established that to enhance the effectiveness of radiation treatment and to reduce the number of complications in subsequent periods, it is necessary to irradiate the local target in the patient's body with a dose error no greater than ±5%.

To control the calculation of the absorbed dose in water using thermoluminescent (TL) dosimeters, irradiated on a gamma therapeutic device for remote radiation therapy, it is necessary to study the influence of various factors (fading, non-linearity of indications, energy dependence, reproduction of the TL signal, presence of a holder) on the magnitude of the TL signal. We have studied and identified various corrective factors and their error values that may affect the calibration of the system (TLD-100 powder (Rexon), thermoluminescent reader PCL-3). In determining the corrective factors to account for the daily drift of the PCL-3 device, the TL signal obtained during the exposure was adjusted based on the control powder indicators. As a control powder, TLD-100 (Rexon) was used, irradiated with an absorbed dose of 2 Gy under standard conditions and aged four months to obtain a stable TL signal.

Keywords: radiation safety; radiation therapy; thermoluminescent dosimeters; thermoluminescent powder; clinical dosimetry.

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Materials and Methods

During this experimental study, **ionization and thermoluminescence dosimetry methods**, as well as statistical mathematics for data analysis, were used [1].

The ionization method was used to determine the radiation output of remote radiation therapy devices. The research was conducted using a UNIDOS universal dosimeter with an ionization waterproof reference chamber for measuring high-energy beams of photons, electrons, and protons, and a standard water phantom for measuring the absorbed dose in water at a depth of 5 cm [2].

The thermoluminescence method was used for measuring the absorbed dose. This method is based on the property of luminescent materials (crystalline substances based on lithium fluoride (LiF), which is a tissue-equivalent material) to accumulate energy under the influence of ionizing radiation and emit light when heated [3, 4].

Setting the Ionization Chamber to the "Zero" Reference Point and Calculating the Absorbed Dose in Water

To set the ionization chamber to the "zero" reference point, the following steps were taken:

- the ionization chamber was positioned along the water meniscus line (see Fig. 1*a*);
- the ionization chamber was positioned such that half of its working volume was above the water (see Fig. 1*b*);
- the ionization chamber was submerged in water to a depth equal to $0.55 \times R_{internal}$, where $R_{internal}$ is the value of the internal radius of the ionization chamber (see Fig. 1*c*).

The calculation of the absorbed dose in water is performed using the formula [5]:

$$D_w = p_u \cdot \left(s_{w,air}\right)_u \cdot N_D \cdot M, \quad (1)$$

$$N_D = \left(k_m \cdot k_{att}\right) \cdot \left(1 - g\right) \cdot N_k, \quad (2)$$

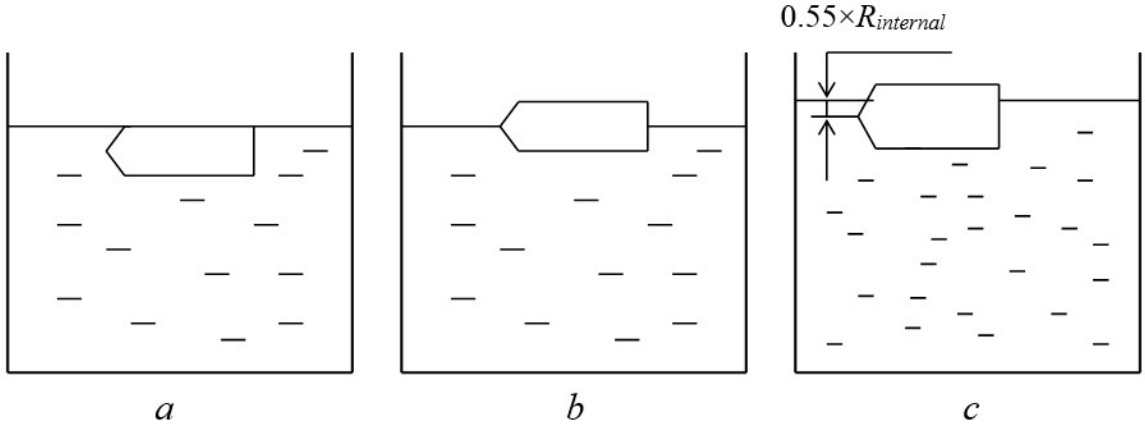

Fig. 1. Setting the Ionization Chamber at the "Zero" Reference Point

$$p_u = \frac{a \cdot s_{wall,air} \cdot \left(\overline{\mu_{en}} / \rho\right)_{w,wall} + (1-a) \cdot s_{w,air}}{s_{w,air}}, \quad (3)$$

$$a = 1 - e^{-11.88 \cdot \rho_{side.cham}}, \quad (4)$$

where:

D_w is the absorbed dose in water in 60 seconds, Gy;

p_u is a factor that accounts for the disturbance caused by the ionization chamber in the water medium;

$(s_{w,\,air})_u$ is a factor that accounts for the stopping power of air and water;

N_D is a calibration coefficient for the absorbed dose in air for ^{60}Co gamma radiation of the chamber, as documented in the calibration certificate;

M is a dosimeter reading;

$(k_m \cdot k_{att})$ is a corrective coefficient that accounts for the absorption and scattering in the chamber walls;

$(1-g)$ is an adjustment coefficient that accounts for losses due to bremsstrahlung (for ^{60}Co gamma radiation, $(1-g)$ equals 0.997);

N_k is a calibration coefficient in the air kerma for ^{60}Co gamma radiation;

$s_{wall,\,air}$ is a factor that accounts for the stopping power of the material of the chamber wall and air;

$\rho_{side.cham.}$ is the density of the material of the ionization chamber wall [g/cm²]. The value of $\rho_{side.cham.}$ is provided in the operational documentation for the chamber.

Values of the corrective factors $(k_m \cdot k_{att})$, $s_{wall,\,air}$, $s_{w,\,air}$, $(\overline{\mu_{en}} / \rho)_{w,wall}$ are listed in the technical documentation for this type of chamber, phantom type, and in reference materials on radiation quality.

The irradiation time of TL capsules in a water phantom is calculated using the formula [2]:

$$t = \frac{D \cdot 60}{D_w}, \quad (5)$$

where:

t is the irradiation time of TL capsules in a water phantom for a specified dose;

D is the specified dose that needs to be delivered during irradiation of TL capsules under standard conditions;

D_w is the absorbed dose in water over 60 seconds during irradiation under standard conditions.

Determination of the Calibration Coefficient for the TL System

The calibration coefficient of the system is determined as the reciprocal of the TL signal per unit dose.

The calibration coefficient for the TL system for the absorbed dose in water of 2 Gy was determined using the formula [5]:

$$N = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{D_i}{M_i - M_{background}}, \quad (6)$$

where:

N is the calibration coefficient of the TL system;

D_i is the magnitude of the absorbed dose in water of 2 Gy with which TL dosimeters were irradiated;

$M_{background}$ is the average value of the background signal from unirradiated TL dosimeters;

M_i is a value of the TL signal from the i-th dosimeter, irradiated with a dose of 2 Gy.

To determine the calibration coefficient of the TL system, 40 containers with TL powder, which had been irradiated with an absorbed dose of 2 Gy under standard conditions, were processed.

The determined value of the calibration coefficient for this batch of powder was:

$N = 3.52 \cdot 10^{-5} \pm 0.11 \cdot 10^{-5}$ at $p = 0.95$ with an error of 0.25%.

Determination of the Corrective Factor Accounting for the Presence of a Holder on the TL Signal Value

A corrective factor was determined that accounts for the presence of a holder for TL dosimeters, allowing compensation for the reduction in the TL signal due to partial attenuation of the gamma radiation beam by a standard plexiglass holder during irradiation of TL dosimeters. In the geometry of the vertical gamma radiation beam, instead of water, a part of the holder's tube, 5 cm in height, is positioned above a portion of the TL dosimeter. During the calibration of the TL system and conduction of TL audits, the

same irradiation conditions will be observed, and identical standard holders will be used. Therefore, the attenuation of the radiation beam in the TL Audit Centre and in the controlled medical institutions will be the same, and thus, it is possible to adopt $f_{hol} = 1$.

Determination of the Correction Factor for the Energy Dependence of the TL Signal

A corrective factor for the energy dependence of the TL signal is introduced to compensate for the reduction in the TL signal per unit dose as the energy of ionizing radiation increases. It is planned to calibrate TL dosimeters at the energy level of ^{60}Co and to conduct TL audits only for gamma therapeutic devices with a ^{60}Co source. Therefore, it is possible to adopt $f_{en} = 1$. This implies that the calibration and audit processes assume a consistent energy environment, simplifying the correction for the energy dependence.

Determination of the Corrective Factor for Nonlinearity of the "Dose-Signal" Relationship

To account for changes in the TL signal magnitude per unit dose depending on the dose of irradiation, a corrective factor is calculated using the formula [2]:

$$f_{lin_i} = \frac{M_{D_0} / D_0}{M_{D_i} / D_i}, \qquad (7)$$

where:

M_{D_0} is the TL signal value obtained from a TL dosimeter irradiated in water with a dose D_0, which is used for monitoring during TL audits;

D_0 is the absorbed dose in water of 2 Gy, used for monitoring during TL audits;

M_{Di} is the TL signal value obtained from a TL dosimeter that has been irradiated with an absorbed dose in water D_i;

D_i is the specified absorbed dose, Gy.

TL dosimeters were irradiated with 12 different doses ranging from 0.5 to 4.0 Gy, with 5 capsules for each dose: 0.5, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.5, and 4.0 Gy to determine the corrective factor for nonlinearity. For each absorbed dose value, the value of $f_{lin\ i}$ was calculated, and the dependency of the corrective factor on the nonlinearity from the dose normalized to 2 Gy was obtained (see Fig. 2).

As seen in Fig. 2, for the system (TLD-100 Rexon – PCL-3), there is a dependency of $f_{lin\ i}$ on the dose of irradiation. When conducting an audit, it is necessary to consider the dose with which participants in the TL audit will irradiate TL dosimeters.

In cases where they irradiate with a dose different from 2 Gy, the corrective factor shall be accounted for. The values of $f_{lin\ i}$ are determined according to a linear function (see Fig. 2) for the dose calculation. This ensures that adjustments are made to accurately reflect a non-linear response of dosimeters at varying radiation doses, maintaining consistency and accuracy in dose measurements across different settings and conditions.

Determination of the Corrective Factor for Fading

Over time, between the irradiation of the TL dosimeter and its readout, the magnitude of the TL signal decreases, indicating a partial loss of the energy stored by the phosphor during irradiation. This phenomenon is known as fading.

During TL audits, it is necessary to correct the TL signal for fading because the time intervals between the irradiation of TL dosimeters at medical oncological centres and their readout at the TL Audit Centre may vary.

To determine the corrective factor, changes in the magnitude of the TL signal depending on the time interval between irradiation and readout were studied. The results of the experiment are shown in Fig. 3. This adjustment ensures that the measurements are accurate and reflect the actual dose absorbed by the dosimeters, compensating for any loss of the signal due to fading.

As seen in Fig. 3, within the first 10 days, the change in the TL signal exhibits a chaotic character and cannot be described by known functions. From 10 to 50 days, there is a noticeable trend (R = 0.82) of decreasing the TL signal magnitude, which can be

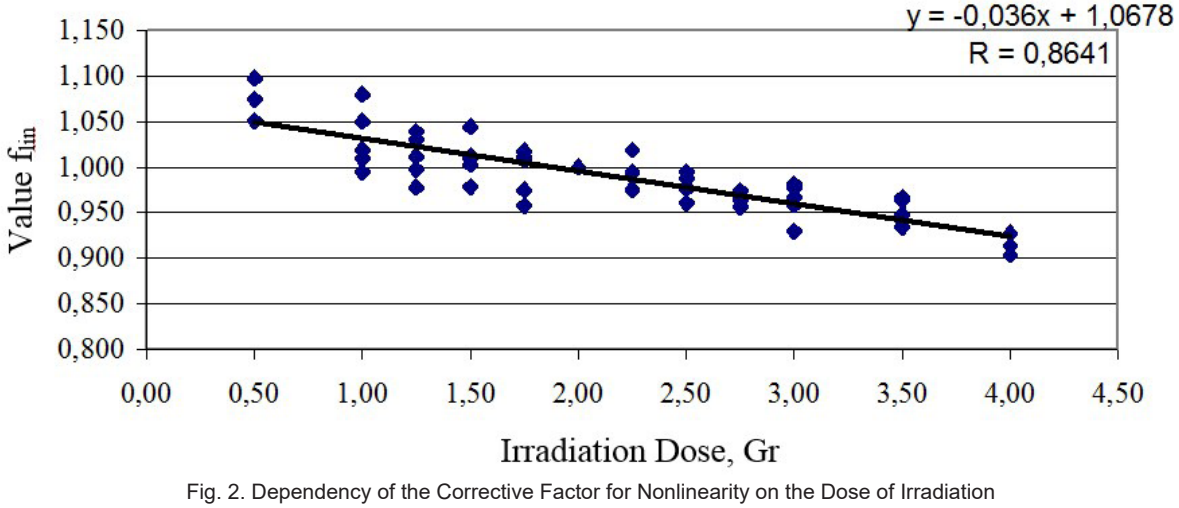

Fig. 2. Dependency of the Corrective Factor for Nonlinearity on the Dose of Irradiation

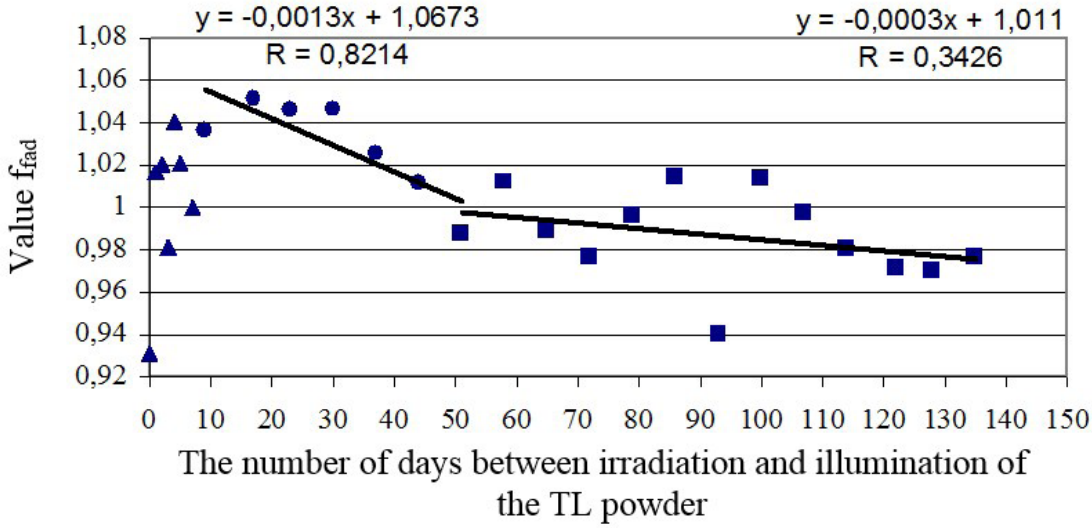

Fig. 3. Dependency of the Normalized TL Signal on the Time Interval Between Irradiation and Readout

described by a linear dependency. When calculating the dose during the period from 10 to 50 days, a fading correction factor (f_{fad}) is determined according to the linear function in Fig. 2. Starting from 50 days, the trend of the decrease significantly reduces, and the magnitude of the TL signal stabilizes, which is confirmed by the regression equation found using the least squares method. The correlation coefficient R = =0.34, and the regression coefficient approaches to the value of one. Thus, the fading correction factor shall be considered for the period of 10–50 days after the irradiation. The fading correction factor equals one after 50 days since the irradiation.

Determination of a Total Error in Measurements of Absorbed Dose in Water by Thermoluminescent Dosimetry

A total error in determining the dose from TL measurements is composed of errors from both the ionization chamber and the TL system.

In the calculation of absorbed dose (D) in water based on the TL signal readings (M), it is necessary to use the calibration and corrective factors (N, f_{hol}, f_{lin}, f_{en}, f_{fad}), which are determined experimentally and thus introduce their own error into the absorbed dose calculation.

The absorbed dose in water is calculated using the formula [5]:

$$D_w = M \cdot N \cdot f_{lin} \cdot f_{en} \cdot f_{hol} \cdot f_{fad}, \quad (8)$$

where:

D_w is the absorbed dose in water, Gy;

M is the magnitude of the TL signal, adjusted for daily fluctuation of the TL reader using a corrective factor that accounts for the device sensitivity drift;

N is the calibration coefficient of the TL system;

f_{lin} is a corrective factor that accounts for the nonlinearity of the TL signal dependency on the irradiation dose;

f_{en} is a corrective factor that accounts for the dependency of the TL signal on the energy of ionizing radiation;

f_{hol} is a corrective factor that accounts for the influence of the holder on the TL signal value;

f_{fad} is a corrective factor for fading.

Each of these corrective factors is determined experimentally, and thus introduces its own error in determining the absorbed dose. The determination of the total dose error based on the results of TL measurements consists of both the error of dose determination using the ionization chamber and the TLD system.

Random errors in determining the corrective factors were calculated based on multiple measurements. According to [5], this type of error is associated with type A uncertainty. Systematic errors (type B uncertainties) in the study were not experimentally determined but corresponded to the information about the metrological verification (ionization chamber, UNIDOS clinical dosimeter).

The error in the calibration coefficient of the TL system is related to the accuracy of the absorbed dose delivery in water as measured by the ionization chamber, hence depending on the calculation of all the corrective factors of the chamber listed in [6].

The error in the dose delivery estimation is also related to the accuracy of placing the capsule in the water phantom during irradiation.

The error in reproducing the measurement results of the TL signal is assessed based on multiple measurements of the TL signal from samples irradiated with the same dose. The standard deviation of the average TL capsule signal is calculated using the formula [5]:

$$SD_m = SD / \sqrt{n}, \quad (9)$$

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

The error of readings per capsule is estimated from the distribution of the standard deviation of the average TL signal for a large number of capsules.

The error in determining the corrective factor for the nonlinearity of the dose-signal dependency f_{lin} is related to the experimental error in estimating the coefficients of the regression equation, which are determined by experimental data using the least squares method in a linear approximation.

The error in determining the corrective factor for fading f_{fad} in the interval from 10 to 50 days after irradiation is determined by the standard error of the regression coefficient of the function approximating the experimental fading values. For the period beyond 50 days when the fading significantly decreases, the error was determined through statistical processing of the variational series of the TL signal measurements on different days after the specified time.

If the irradiation of standard TL dosimeters from one batch at the TL Audit Centre and in medical institutions was conducted simultaneously with simultaneous readout, no adjustment for fading is made.

The error in determining the corrective factor for energy f_{en} is determined when the energy of photon radiation of devices in medical institutions differs from the energy of ^{60}Co gamma radiation.

According to the requirements [7] for determining the measurement error, the total standard error of the TL system is determined by the formula [7]:

$$\varepsilon = \sqrt{\varepsilon_{fad}^2 + \varepsilon_{lin}^2 + \varepsilon_{kal}^2 + \varepsilon_{hol}^2}, \quad (10)$$

where:

ε_{fad} is an error in determining the fading;

ε_{lin} is an error in determining the nonlinearity of the TL signal dependency on the dose of irradiation;

ε_{kal} is an error in determining the calibration coefficient;

ε_{hol} is an error in determining the influence of the presence of a holder on the TL signal value.

Tables 1 and 2 provide data on the calculated errors of the measured absorbed dose in water using the TL method.

This table and the formula above outline how various uncertainties combine to give a total measurement error in the TL system. The process ensures that all possible sources of error are accounted for, leading to a more accurate and reliable dosimetry system for clinical and research purposes.

Metrological Laboratories (Centres for Metrology and Standardization) ensure the irradiation of standard TL dosimeters at TL Audit Centres with precisely calculated absorbed doses of ^{60}Co energy and, if necessary, with high-energy photon beams.

The accuracy of dose measurements using the TL system at the TL Audit Centre is verified by a “blind” comparison of doses released by the primary

Table 1

Relative Error of Individual Components Associated with the Determination of the Calibration Coefficient (N) of the TL System

Component	Type A Error, %	Type B Error, %	Total A and B Error, %
Dose Determination via Ionization Chamber	0.5	2.0	2.06
TL Signal Measurement	0.45	-	0.45
Total Error of Calibration Coefficient N	0.67	2.0	2.11

Table 2

Total Error Associated with the Determination of the Absorbed Dose in Water by a Measured TL Signal from a ^{60}Co Beam

Component	Type A Error, %	Type B Error, %	Total A and B Error, %
Calibration Coefficient (from Table 1)	0.67	2.0	2.11
Correction for Nonlinearity of Dose	1.30	-	1.30
Correction for Fading	1.26	-	1.25
Correction for Presence of Dosimeter Holder	0.30	-	0.30
Total Error in Dose Determination	1.95	2.0	2.79

or secondary standard metrological laboratory at the TL Audit Centre.

This table and associated practices illustrate how metrological standards are applied to ensure the precision and reliability of TL dosimetry, crucial for maintaining quality and safety in radiation therapy and related medical practices.

Conclusions

1. Calibration Technology Developed: A calibration methodology for TL dosimeters under standard irradiation conditions using a gamma therapeutic device has been developed. This ensures consistent and accurate performance under all standard conditions in clinical settings.

2. Measurement Reproduction Studied: The reproduction of the TL signal measurement of thermoluminescent powder TLD-100 (Rexon) using the automatic reader PCL-3 has been studied. The error was found to be $\varepsilon = 0.45\%$ ($p = 0.95$), demonstrating high reliability and precision of the TL signal readout from dosimeters.

3. Calibration Coefficient and Corrective Factors Determined: TO calibrate the TL system, a calibration coefficient and corrective factors were determined. These factors account for the nonlinearity of the TL signal dependency on the irradiation dose, and the fading of the TL powder over periods from 10 to 50 days and from 51 to 135 days. This step ensures that the TL system can accurately reflect changes in dosimetric properties over time and varying radiation conditions.

4. Total Error Determined: a total error in determining the absorbed dose using the TL system (thermoluminescent powder TLD-100 (Rexon) and automatic reader PCL-3) was determined, meeting the requirements of the International Atomic Energy Agency (IAEA) for TL audit centres. The error was found to be $\varepsilon = 2.79\%$ ($p = 0.95$), validating the system's compliance with international standards and its suitability for precise dosimetry assessments.

These conclusions underscore the effectiveness of the developed methodologies and the reliability of the TL dosimetry system in clinical and research settings.

They also highlight the continuous need for stringent quality control and calibration to maintain the accuracy required for radiation therapy and safety assessments.

Визначення коригувальних факторів та поправкових коефіцієнтів для розрахунків поглинутої дози

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Анотація

Необхідність контролю дози, що отримує пацієнт при променевій терапії (ПТ), диктується вимогами до гарантії якості, яка охоплює велику систему організаційних та технічних заходів, спрямованих на досягнення єдності й точності дозиметричних вимірювань. Кінцева мета використання системи гарантії якості у ПТ – забезпечення високої точності відпускання дози на пухлину, зменшення об'ємів опромінення нормальних, здорових тканин та органів, що знаходяться біля мішені (пухлинного ураження). Встановлено, що для підвищення ефективності променевого лікування та зниження кількості ускладнень у наступному періоді необхідно опромінювати локальну мішень у тілі пацієнта з похибкою дози не більше ±5%. Якщо ця вимога не виконується, то при відпусканні поглинутої дози нижче заданого значення ефективність променевої терапії різко знижується та призводить до виникнення рецидиву захворювання, тоді як при перевищенні заданої дози – високий ризик виникнення променевих ускладнень.

В основі цього аудиту лежить перевірка точності калібрування струменів апаратів дистанційної променевої терапії за допомогою термолюмінесцентних (ТЛ) детекторів – невеличких пластикових капсул, наповнених термолюмінесцентним порошком, які надсилають поштою до радіологічних центрів для опромінення певною дозою у водному фантомі.

Для контролю розрахунку поглинутої дози у воді за допомогою ТЛ-дозиметрів, опромінених на гамма-терапевтичному апараті дистанційної променевої терапії, необхідно вивчити вплив різних чинників (фейдінгу, нелінійності показів, енергетичної залежності, відтворення ТЛ-сигналу, наявності тримача) на величину ТЛ-сигналу. Нами були вивчені та визначені різні коригувальні чинники й значення їхніх похибок, які впливають

на калібрування системи (порошок TLD-100 (Rexon), термолюмінесцентний зчитувач PCL-3). При визначенні коригувальних чинників для врахування денного дрейфу приладу PCL-3 значення ТЛ-сигналу, отриманого при висвічуванні, корегувалося за показниками контрольного порошку. Як контрольний порошок використовувався TLD-100 (Rexon), опромінений поглинутою дозою у воді 2 Гр за стандартних умов, витриманий чотири місяці для отримання стабільного ТЛ-сигналу.

Ключові слова: радіаційна безпека; променева терапія; термолюмінесцентні дозиметри; термолюмінесцентний порошок; клінічна дозиметрія.

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