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Experimental study of dosimetric properties of thermoluminescent powder TLD-100

K. Ozerskyi, A. Pystovyi, V. Skliarov

National Scientific Centre "Institute of Metrology", Myronosytska Str., 42, 61002, Kharkiv, Ukraine
ko525896@gmail.com

Abstract

The creation of a scientifically substantiated quality assurance system for dosimetry and the optimization of medical exposure of the population of Ukraine during diagnostic and therapeutic procedures (and the possibility of dosimetric control and monitoring of emergency situations) falls within the field of the application of ionizing radiation sources (IRs). Trends in modern medicine in most countries, including Ukraine, prove a continued increase in the share of medical exposure. The main requirements and recommendations for the use of IRs for medical purposes while ensuring the radiation safety requirements for patients are provided in the documents of such International Organizations as the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA), the World Health Organization (WHO) and the European Commission (EC).

One of the key factors to ensure the quality of radiation therapy is metrological and dosimetric support. To enhance the effectiveness of radiation treatment and reduce the number of complications in the future, it is necessary to irradiate the local target within the patient's body with a dose error of no more than 5%. Control of the radiation output of the therapeutic device, i.e., the calibration of the therapeutic beam used in the treatment process, is an essential element of radiation therapy.

Radiation protection programmes are based on checking the accuracy of the calibration of remote radiotherapy devices using thermoluminescent dosimeters (TLDs) – small plastic capsules filled with thermoluminescent powder that are sent by post to radiology centres for exposure to a specific dose in a water phantom.

Radiation therapy in Ukraine is primarily conducted using cobalt machines, X-ray therapy devices and linear accelerators.

The results of the study include the examination of the dependency of measurement results on various exposure parameters using the automatic reader PCL-3, the determination of dosimetric characteristics of the thermoluminescent powder TLD-100, and the development of a calibration method for thermoluminescent dosimeters under standard irradiation conditions on a remote gamma therapy device.

Therefore, the accuracy of beam calibration using TLD dosimeters has been studied, which will enable to timely detect errors in clinical dosimetry and reduce the number of cases of radiation-related complications for patients during their treatment.

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

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Materials and methods of the study

In the presented experimental study, both **ionization and thermoluminescent methods** of dosimetry were applied along with the method of mathematical statistics for processing of measurement results [1].

The ionization method was taken to determine the radiation output of remote radiation therapy devices. The study was conducted using a universal dosimeter UNIDOS with an ionization waterproof reference chamber for measuring high-energy beams of photons, electrons and protons (e.g., of TW300013 type), and a standard water phantom (e.g., manufactured by PTW) for measuring the absorbed dose in water at a depth of 5 cm [2].

The method of thermoluminescence was chosen to measure the absorbed dose. This method is based on the property of luminescent materials (a tissue-equivalent crystalline substance based on lithium fluoride, LiF) to accumulate energy when exposed to ionizing radiation and to emit light when heated [3,

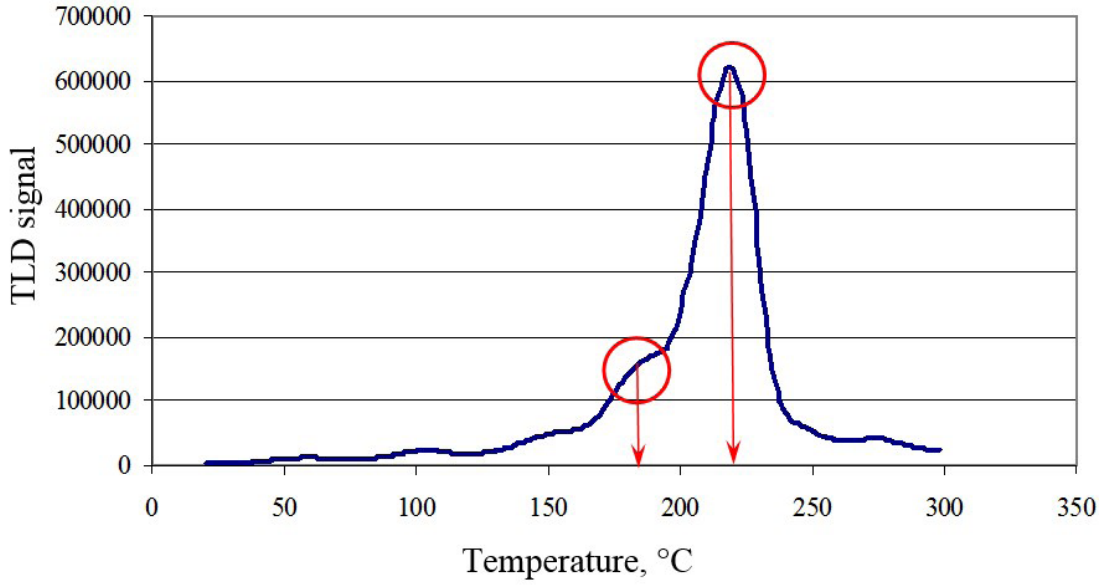


Fig. 1. Graph of the thermal radiation curve

4]. The total light amount emitted during the heating process is a measure of the absorbed dose.

The curve depicting the dependence of luminescence on the temperature of the luminescent material during continuous heating is called the thermoluminescence curve (TLC). A typical TLC is characterized by five peaks at specific temperatures. Each peak on the TLC corresponds to specific energy levels that are filled with electrons when the luminescent material is perturbed, and are released only when electrons overcome the energy barrier. In thermoluminescent dosimetry, peaks 1, 2, and 3 (low-temperature peaks) are eliminated from the measurement process, i.e. only peaks 4 and 5 are recorded in the temperature range of 180 to 220°C (Fig. 1).

The thermoluminescent (TL) powder based on LiF with impurities (Mg, Ti) of TLD-100 type manufactured in the USA was used. Since the dosimetric characteristics of the TL powder significantly depend on the grain size and its homogeneity, the powder with a grain size from 80 to 200 μm was used.

Dosimetric properties of the TL powder were studied using a PCL-3 thermoluminescent reader (manufactured by Fimel, France).

Technical features of the PCL-3 thermoluminescent reader when operating with TL materials are given in Table 1.

The dependence of the integral amount of light of the TL (thermoluminescence) signal on various parameter values with a wide range has been studied, and the optimal values of the parameters allowing for the most comprehensive and high-quality measurement of the TL signal on the thermoluminescence reader PCL-3 have been determined.

Dosimetric characteristics of thermoluminescent powder

The advantage of using a phosphor in the form of powder is that when heating the TL material in a steel container, it provides better thermal contact with the heater. Because the mass of the container is greater than the mass of the powder, heating occurs quickly and uniformly according to a constant law, which is repeated with each exposure [5, 6].

Preparation of TL powder for irradiation

The correct use of the TL powder is ensured by its degree of purification, homogeneity, granulometric composition and constancy of thermal treatment conditions after exposure. Regeneration of the used

Table 1

Technical features of the PCL-3 thermoluminescent reader

Measuring parameters	Measuring range
Preheating temperature	from 30 to 400 °C with a step of 1 °C
Heating temperature	from 30 to 600 °C with a step of 1 °C
Photomultiplier voltage	from 800 to 900 V
Heating time	from 3 to 3000 s with a step of 0.1 s
Illumination signal collection time	from 3 to 3000 s with a step of 0.1 s
Heating speed in linear lighting mode	from 0.1 to 5 °C/s with a step of 1 °C/s

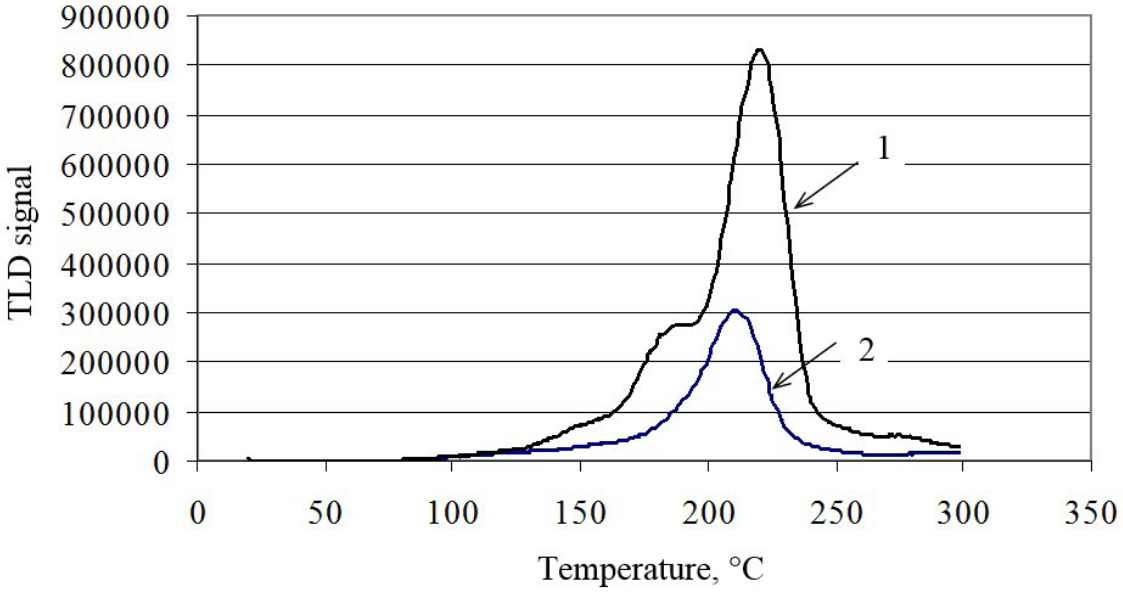


Fig. 2. Effect of heat treatment on dosimetric properties of TL powder: 1 – luminescence curve of the powder irradiated after heat treatment; 2 – luminescence curve of the powder irradiated without heat treatment

powder by heat treatment allows recovering its response and eliminating the residual dosimetric information having illuminated on the TLD device.

As a result of the study, the following modes of heat treatment of the TL powder were determined: temperature of 400 °C for 1 hour in a muffle furnace, cooling during 10 minutes in air on an aluminum plate, temperature of 100 °C for 2 hours in a drying cabinet with subsequent cooling. To remove sintered lumps of the TL material after heat treatment, it is necessary to sieve it. To stabilize the response, the TL powder was stored for at least 14 days. The effect of heat treatment on dosimetric properties of the TL powder is shown in Fig. 2.

As can be seen from Fig. 2, both powders demonstrate the thermoluminescence curve of the same shape [7], but the magnitude of the thermoluminescence signal in the powder after heat treatment is much larger, which indicates a complete recovery of its dosimetric properties.

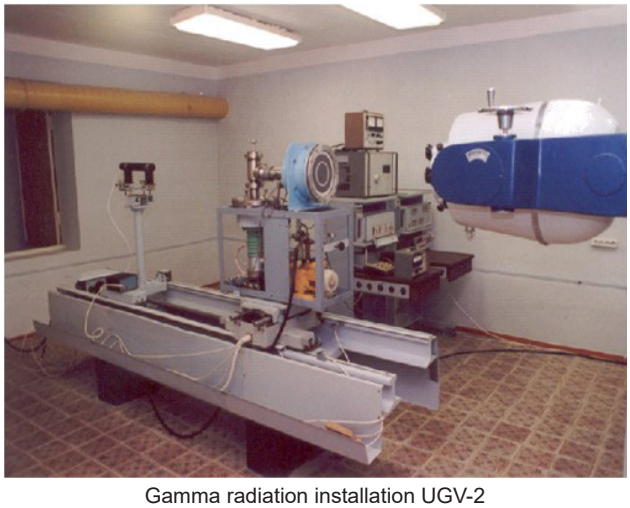
Irradiation of TL dosimeters

The International Atomic Energy Agency (IAEA) has provided recommendations on determining the absorbed dose in water using an ionization chamber.

According to the recommendations, the calibration of TL dosimeters is based on air kerma measurement standards. This procedure also considers a new trend of direct calibration of ionization chambers in a water phantom in units of the absorbed dose for therapeutic beams of cobalt-60 (^{60}Co) [8, 9].

In addition, there are reports-recommendations of the IAEA regarding the determination of the absorbed dose for remote radiation therapy. These guidelines have two distinctive features: first, they imply using a single approach to determine the absorbed dose for therapeutic gamma rays, and second, they imply comparing not with national initial measurement standards of the air kerma exposure dose, as previously recommended, but with national measurement standards of the absorbed dose in water [10, 11].

X-ray installation URV-2P



Gamma radiation installation UGV-2

Fig. 3. National measurement standard DETU 12-05-02

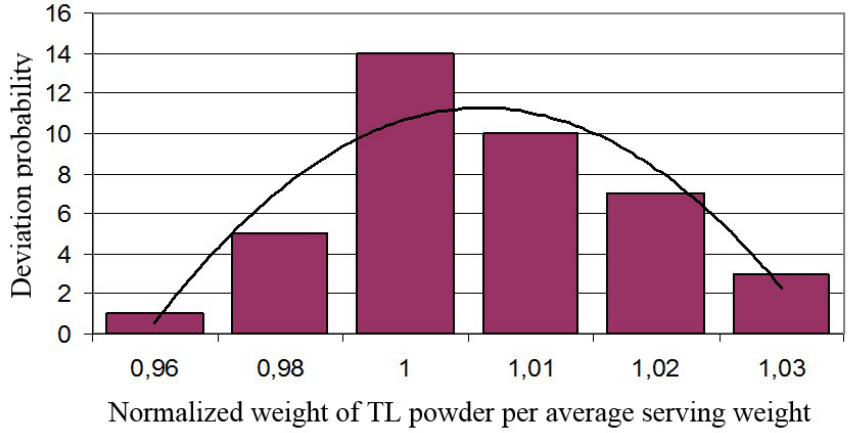


Fig. 4. Histogram of the distribution of the mass of a portion of powder when dosing on a **Teledyne** dispenser

In the recommendations, there is a proposal regarding the term "calibration" of the beam. This procedure is the initial stage in preparing the dosimetric examination of a therapeutic device that generates all types of radiation. In addition, the terms "reference point" and "reference depth" are used, referring to the point in a water phantom where measurements are performed with a dosimeter and to the depth of the phantom where this point is located (typically, measurements are performed at a depth of 5 cm below the water surface).

At the same time, not only the conditions for conducting such exposures (measurements), but also the procedure itself, are standardized. Therefore, when it comes to beam calibration, the term "standard dosimetry" is used. In the recommendations, the term "calibration" is used when they mean the transfer of the unit size of the absorbed dose from the measurement standard to the secondary one. The study was conducted at the X-ray and gamma installations of the state measurement standard of the unit of absorbed dose, power of the absorbed dose of X-ray and gamma radiation (DETU 12-05-02) (Fig. 3) [12].

These recommendations of the IAEA were used to develop the technology for irradiation of TL-dosimeters (a polyethylene capsule filled with TL-powder) and for calculation of the irradiation time of TL-capsules in a 40×40×40 cm water phantom with a dose of 2 Gy on a gamma therapy device. Irradiation conditions: the irradiation field is 10×10 cm, the "source-surface" distance of the water phantom is 750 mm, the capsule installation depth is 50 mm. This irradiation technology and the guidelines for calculating the irradiation time were tested during the calibration of the TL system on 70 TL capsules. The TL powder, which is in the TL dosimeter, was dosed into 4 containers for further studies using the Fimel Sapd dispenser.

Uncertainty of the result of measuring the dosage of a portion of TL powder

The PCL-3 automatic reader includes two dispensers, which are used to dispense a certain portion of the TL powder: Teledyne and Fimel Sapd dispensers.

10 series of 40 measurements were performed to determine the dosing error of the mass of the TL-powder portion released by the dispenser. The mass of each released portion was weighed on an analytical balance OHAUS with an accuracy of 0.1 mg.

As a result of the experiment, it was determined that the dispenser reproduces a portion of powder weighing $\overline{m} = (28.90 \pm 0.13)$ mg at $p = 0.95$. The expanded uncertainty of the dosage measurement result using the **Teledyne** dispenser was $U = 1.41\%$.

Fig. 4 shows the distribution of the normalized mass of a portion of the TLD-100 powder when dosing on a Teledyne device.

The **Fimel Sapd** dispenser is used for dispensing the irradiated TL powder into steel containers. 10 series of 23 measurements were performed to determine the expanded uncertainty of the result of measuring the dosage of the mass of a portion of the TL powder. The mass of each released portion was weighed on an analytical balance with an accuracy of 0.1 mg. As a result of the experiment, it was determined that the dispenser reproduces a portion of powder weighing $\overline{m} = (34.00 \pm 0.14)$ mg at $p = 0.95$. The expanded uncertainty of the dosage measurement result using the **Fimel Sapd** dispenser was $U = 0.97\%$.

Fig. 5 shows the distribution of the normalized mass of a portion of the TLD-100 powder when dosing on a **Fimel Sapd** device.

Regeneration of the used powder by heat treatment allows recovering its response and eliminating the residual dosimetric information after the illumination on the TLD device.

Measurement of the absorbed dose in water by thermoluminescence dosimetry method

To measure the absorbed dose in water using TL (thermoluminescent) dosimeters irradiated on a remote radiotherapy gamma device, it is necessary to consider the influence of various factors (fading, non-linearity of readings, energy dependence, TL signal reproducibility, the presence of holders) on the magnitude of the TL

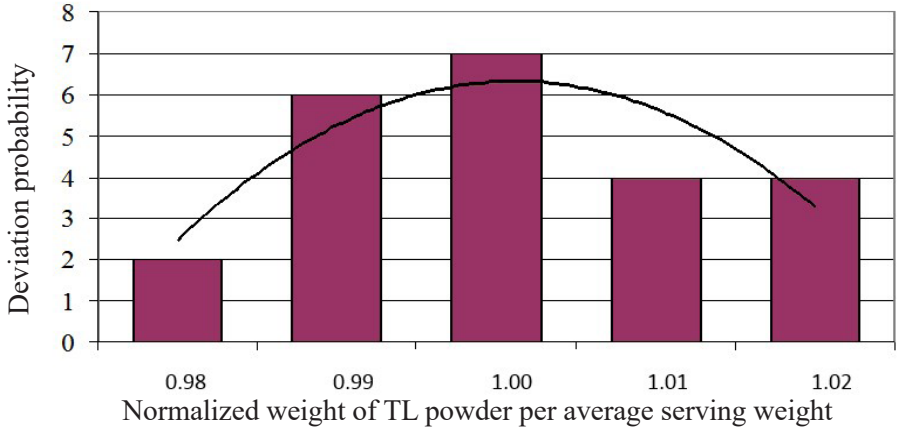


Fig. 5. Histogram of the distribution of the mass of a portion of powder when dosing on the **Fimel Sapd** dispenser

signal. Various correction factors and their associated uncertainties that affect the calibration of the system have been examined and determined during the study.

The absorbed dose in water is calculated according to the formula:

$$D_w = M \cdot N \cdot f_{lin} \cdot f_{en} \cdot f_{hol} \cdot f_{fad}, \quad (1)$$

where D_w is the absorbed dose in water, Gr;

M is the value of the TL signal, corrected for daily fluctuation of the TL reader using a correction factor that account for the response drift of the device;

N is the calibration coefficient of the TL system;

f_{lin} is the correction factor, which accounts for the nonlinearity of the dependence of the TL signal on the amount of irradiation dose;

f_{en} is the correction factor that accounts for the dependence of the TL signal on the energy of ionizing radiation;

f_{hol} is the correction factor that account for the effect of the presence of the holder on the value of the TL signal;

f_{fad} is the correction factor for fading.

Each of these correction factors is determined experimentally and introduces its uncertainty when determining the result of measuring the absorbed dose.

The expanded uncertainty of the dose measurement result obtained from TL (thermoluminescent) measurements consists of uncertainties from both the dose measurement using an ionization chamber and the TL dosimetry system.

During the study, the uncertainty of the result of the measurements of correction factors during multiple measurements was evaluated. According to [13], such uncertainties are associated with the concept of uncertainty of type A. Systematic errors (uncertainties of type B) were not determined experimentally, but were considered in accordance with the certificate of metrological verification of the ionization chamber No. TW30013-0461 and the UNIDOS clinical dosimeter.

The uncertainty of the measurement result of the calibration coefficient of the TLD system is related to the value of the absorbed dose in water according to the readings of the ionization chamber, that is, it depends on the calculation of all correction factors of the chamber [14].

The uncertainty of the released dose measurement result is also related to the accuracy of the placement of the capsule in the water phantom during irradiation.

The uncertainty of the TLD measurement result is determined by results of multiple measurements of the TL signal on samples irradiated with the same dose. As regards errors, the standard deviation of the mean signal of the TL capsule is calculated by the formula:

$$SD_m = \frac{SD}{\sqrt{n}}, \quad (2)$$

where SD is the standard deviation of the TL signal of the dosed mass of the powder;

n is the number of measurements per capsule.

The uncertainty of the measurement result for one capsule is evaluated from the distribution of the standard deviation of the mean value of the TL signal for many capsules.

The uncertainty of the measurement result of correction factor for the nonlinearity of dependence on the irradiation dose f_{lin} is related to experimental uncertainty of the measurement result of the coefficients in the regression equation, which are determined from experimental data by the least squares method with linear approximation.

The uncertainty of the measurement result of a correction factor for fading f_{fad} in the interval from 10 to 50 days after irradiation is evaluated by the standard uncertainty of the measurement result of the regression coefficient of a function that approximates experimental values of fading. For a period of more than 50 days, when fading is significantly reduced, the uncertainty of the measurement result was evaluated using statistical processing of the variation series of the TL signal measurements on different days after the above-mentioned time. When the irradiation of standard TL dosimeters of one batch was completed at the same time with simultaneous illumination, the correction for fading was not conducted.

Table 2

Uncertainty of the result of measurements of individual components, which are related to the determination of the calibration coefficient of the TLD system

Component	Type A	Type B	Combined uncertainty
Dose determination based on ionisation chamber readings	0.5	2.0	2.06
Measurement of the TL signal	0.45	–	0.45
The combined uncertainty of the measurement result of the calibration coefficient *N*	0.67	2.0	2.11

Table 3

Total error associated with the determination of the absorbed dose in water from the measured TL signal of the ^{60}Co beam

Component	Type A	Type B	Combined uncertainty
Calibration factor *N* (from Table 1)	0.67	2.0	2.11
Correction for non-linearity of dose dependence	1.30	–	1.30
Fading correction	1.26	–	1.26
Correction for the presence of a dosimeter holder	0.30	–	0.30
Combined uncertainty of the result of measurements of the absorbed dose in water	1.95	2.0	2.79

The uncertainty of the measurement result of a correction factor for energy f_{en} is evaluated when the energy of photon radiation of radiation therapy devices in medical institutions differs from the energy of gamma radiation of ^{60}Co.

According to the requirements [15] for evaluating the uncertainty of the measurement result, the combined standard uncertainty of the TLD system is evaluated according to formula [16]:

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

where u_{fad} is the uncertainty of the result of fading measurements;

u_{lin} is the uncertainty of the result of measurements of nonlinear dependence of the TL signal on the amount of radiation dose;

u_{kal} is the uncertainty of the measurement result of the calibration coefficient;

u_{hol} is the uncertainty of the result of measurements of the effect of the presence of the TL dosimeter holder on the value of the TL signal.

Tables 2 and 3 provide data on the evaluated uncertainty of the result of measuring the absorbed dose in water using the TL method.

Medical laboratories provide irradiation of standard TL dosimeters with calculated absorbed dose energy of ^{60}Co and, if necessary, with high-energy photons beams. Checking the accuracy of dose measurements using the TLD system is performed by "blind" comparison of doses provided to the metrology laboratory and scientific metrology centres.

Conclusions

1. The optimal conditions of heat treatment with a given granulometric composition of the thermoluminescent powder TLD-100 were determined for the study of its dosimetric characteristics.

2. As a result of the study, the reproduction of the TL signal of the TLD-100 thermoluminescent powder on the PCL-3 automatic reader and the average weights of the portion of the TLD-100 thermoluminescent powder released by the dispensers were determined:

– **Teledyne** dispenser: $\overline{m} = (28.90 \pm 0.13)$ mg at p = 0.95;

– **Fimel Sapd** dispenser with a nozzle № 3: $\overline{m} = (34.00 \pm 0.14)$ mg at p = 0.95.

3. When studying the modes of the PCL-3 automatic reader, the operating values of the parameters were determined:

– for linear mode, the heating rate is 0.2 °C/s;

– for normal mode, the voltage of the photoelectronic converter is 850 V;

– preheating temperature is 170 °C;

– the main heating temperature is 300 °C;

– the integration time is 25 s.

4. The technology for calibrating TL dosimeters under standard conditions of irradiation on gamma therapy devices has been developed.

5. The reproduction of the measurement of the TL signal of the TLD-100 thermoluminescent powder on the PCL-3 automatic reader was considered. The expanded uncertainty of the measurement result is U = 0.45%.

6. To calibrate the TLD system, the following has been defined: the calibration coefficient and correction factors that account for the nonlinearity of the dependence of the TL signal on the irradiation dose and the fading of the TL powder in the periods from 10 to 50 days and from 51 to 135 days.

7. The uncertainty of the result of the absorbed dose measurements using the TLD system (thermoluminescent powder TLD-100 and PCL-3 automatic reader) was evaluated, which meets the requirements of the IAEA for the TL audit centres. The uncertainty of the measurement result is U = =2.79%.

8. The results of the study were used and implemented in radiation medicine institutions.

Експериментальне дослідження дозиметричних властивостей термолюмінесцентного порошку TLD-100

К.Л. Озерський, А.С. Пустовий, В.В. Скляров

Національний науковий центр "Інститут метрології", вул. Мироносицька, 42, 61002, Харків, Україна
ko525896@gmail.com

Анотація

Створення науково обґрунтованої системи забезпечення якості дозиметрії та оптимізація медичного опромінення населення України при проведенні діагностичних і терапевтичних досліджень (та можливості проведення дозиметричного контролю й моніторингу позачергових ситуацій) належить до царини застосування джерел іонізуючого випромінення (ДІВ). Тенденції сучасної медицини в більшості країн, у тому числі й в Україні, свідчать про подальше зростання частки медичного опромінення. Основні вимоги та рекомендації щодо використання ДІВ із медичною ціллю з дотриманням вимог радіаційної безпеки пацієнтів, що подані в документах таких міжнародних організацій, як Міжнародна комісія з радіаційного захисту (МКРЗ), Міжнародне агентство з дії атомної енергії (МАГАТЕ), Всесвітня організація охорони здоров`я (ВООЗ), Європейська комісія (ЄК).

Одним із головних факторів гарантії якості променевої терапії є метрологічне та дозиметричне забезпечення. Для підвищення ефективності променевого лікування та зниження кількості ускладнень у наступному періоді потрібно опромінювати локальну мішень у тілі пацієнта з похибкою дози не більше 5%. Контроль радіаційного виходу терапевтичного апарата, тобто калібрування терапевтичного струменя, що використовується в лікувальному процесі, є потрібним елементом променевої терапії.

В основі програм протирадіаційного захисту пацієнтів лежить перевірка точності калібрування струменів апаратів дистанційної променевої терапії за допомогою термолюмінесцентних дозиметрів (ТЛД) – невеличких пластикових капсул, наповнених термолюмінесцентним порошком, що надсилаються поштою до радіологічних центрів для опромінення певною дозою у водному фантомі.

Променева терапія в Україні здійснюється головним чином на кобальтових, рентгенотерапевтичних апаратах та лінійних прискорювачах.

Результати роботи – це вивчення залежності результатів вимірювання від різних параметрів висвічування на автоматичному зчитувачі PCL-3, визначення дозиметричних характеристик термолюмінесцентного порошку TLD-100, розроблення технології калібрування термолюмінесцентних дозиметрів за стандартними умовами опромінення на дистанційному гамма-терапевтичному апараті.

Таким чином, досліджено точність калібрування струменів з використанням ТЛ-дозиметрів, що дозволить своєчасно виявляти помилки клінічної дозиметрії та знизити кількість випадків радіаційних ускладнень у пацієнтів при лікуванні.

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

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