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Study of the uncertainty of measurements of gamma radiation from Cesium-137 and Cobalt-60 sources

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Abstract

Radiation dosimetry is a key element in medical, industrial, and scientific activities involving the use of ionizing radiation. Accurate measurements of radiation doses ensure the safety and effectiveness of radiological practices, which is critically important for protecting patients during medical procedures, adhering to industrial safety standards, and conducting scientific research. International studies are carried out to achieve this high measurement accuracy.

The National Scientific Centre "Institute of Metrology" (NSC "Institute of Metrology") actively participates in international projects aimed at improving the accuracy and consistency of radiation dosimetry. These projects unite National Metrology Institutes (NMIs) to standardize measurement and calibration methods, thereby enhancing the systems of ionizing radiation dosimetry.

The relevance of such projects is driven by the widespread use of ionizing radiation in medicine and industry. In medicine, particularly in radiotherapy, accurate dosimetry ensures effective treatment with minimal impact on healthy tissues. In industrial radiography, high-precision dosimetry guarantees compliance with safety standards, reducing the risk of excessive exposure to the radiation for workers.

Within the framework of this international project, involving the Physikalisch-Technische Bundesanstalt (PTB) and the Central Office of Measures (GUM), new calibration protocols for various types of radiation are being developed, traceability chains to ensure measurement accuracy are being established, and best practices are being shared among participants.

To achieve these objectives, preliminary comparisons were conducted among NMIs, with two Institutes acting as reference laboratories. This approach allowed the participants to compare their results with control data and make all necessary adjustments. Such collaboration has fostered knowledge exchange and stimulated the development of new dosimetry techniques, which, in the long term, will enhance the precision and reliability of measurements.

The NSC "Institute of Metrology" participated in the project as Ukraine's leading institution in the field of ionizing radiation. The results of this collaboration are presented in the paper, specifically focusing on comparisons of ionizing radiation using the ^{137}Cs and ^{60}Co sources. Additionally, within the framework of the project, the comparisons of X-ray beams with radiation qualities N-40, N-100, and N-200 were conducted.

Keywords: radiation safety; comparisons; dosimetry; ionizing radiation; X-ray beams.

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Materials and methods of the study

Reference chamber

The Seibersdorf HS01 ionization chamber was used as a reference chamber for detecting ionizing radiation (see Fig. 1) [1]. This spherical chamber has a nominal volume of 1 litre, and its external diameter is 140 mm. During the measurements, the participants applied the same voltage to the chamber.

The chamber was equipped with a BNC connector for current measurements and a Lemo connector for high-voltage (HV) connection. Appropriate connectors and adapters, including a TNC adapter shown in Fig. 2, were used for high-voltage supply. These technical solutions ensured reliable connections and stable system operation during calibration procedures.

Fig. 1. Seibersdorf HS01 reference chamber for H*(10) (Photo: Bildstelle PTB)

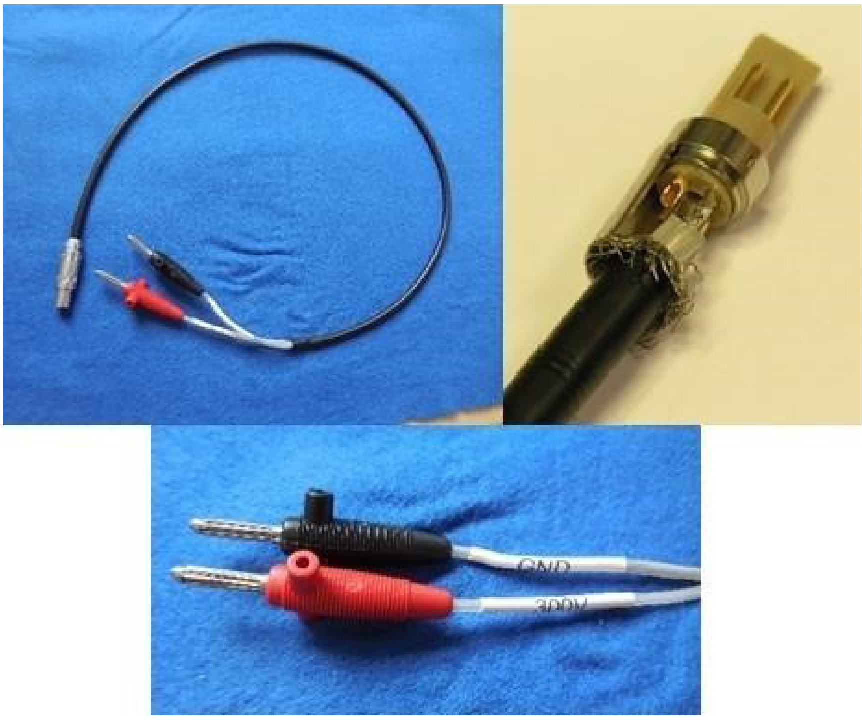

Fig. 2. High-voltage connection cable and connector details

Procedures performed prior to the comparisons

The Seibersdorf HS01 reference ionization chamber was used with the electrometers provided by the project participants. The participants followed these recommendations: “The measurement system shall remain in the measurement chamber to achieve thermal equilibrium, preferably for at least 12 hours. The transport container shall remain closed during this process, particularly in cold weather. The ionization chamber shall be used following the installation instructions provided with the transport container. The electrometer shall be switched on at least one hour before starting the measurements, and the chamber shall operate at the voltage agreed upon among the participants, applied to the collecting electrode (inner electrode). While pre-irradiation of the ionization chamber is not mandatory, it is recommended to perform it for at least 10 minutes. Before taking measurements, the chamber shall be prepared. The electrometer (UNIDOS) shall be zeroed, and at least 10 leakage current measurements shall be conducted to ensure that the leakage current does not exceed 0.1% of the expected signal”.

The results obtained within the project for narrow-spectrum X-ray beams, specifically N-40, N-100, and N-200, were presented in a previous study [2]. The calibration of dosimeters involved the precise measurement of the beam quality and energy spectrum. Dosimeters were irradiated with a predefined gamma radiation, ensuring that their readings were accurate. The radiation energy characteristics are as follows:

- ^{137}Cs is a radioactive isotope that emits gamma rays with an energy of approximately 662 keV. It is widely used in defectoscopy, medical practices for cancer treatment, and other fields involving gamma radiation. Calibration of dosimeters for gamma radiation involves exposing them to a ^{137}Cs source in reference setups. Dosimeter readings are corrected using calibration coefficients obtained from primary measurement standards, ensuring accurate gamma radiation dose measurements.
- ^{60}Co is a radioactive isotope that emits gamma rays with energies of approximately 1.17 MeV and 1.33 MeV. Its relatively high radiation energy makes it suitable for various applications, including radiotherapy and industrial radiography. In medical applications, ^{60}Co is used for cancer treatment, providing deep gamma radiation penetration necessary for effectively targeting tumours. In industrial applications, it is used for non-destructive testing of components and assemblies. Dosimeters are calibrated against a ^{60}Co source by exposing them to pre-defined gamma radiation doses. The measured readings are compared with reference values, ensuring precise reflection of the delivered radiation dose across different fields.

The calibration of dosimeters for various radiation qualities within the project aims to improve the accuracy of gamma radiation measurements, contributing to safer and more efficient radiation use across different areas.

Calibration coefficients and factors influencing their accuracy

Calibration coefficients play a critical role in accurately converting initial dosimeter readings into actual radiation doses. They are determined through specialized calibration procedures that account for the type of radiation, energy levels, and the dosimeter characteristics. The project objective was to obtain calibration coefficients to ensure high measurement accuracy across various application fields [3]. The steps in Determining Calibration Coefficients are:

- During the calibration, standardized radiation sources were used, including narrow-spectrum X-ray beams (N series) and gamma beams from ^{137}Cs (Cs series) and ^{60}Co (Co series). These sources generated controlled ionizing radiation fields necessary for the calibration, with measurements performed using reference dosimeters traceable to primary measurement standards. The procedure was carried out in controlled conditions to minimize the impact of temperature, humidity, pressure, and background radiation, ensuring the best conditions for determining the coefficients.
- Dosimeters were exposed to pre-defined radiation doses from the standardized sources, and their readings were compared to reference values. The recorded measurements were used to calculate the calibration coefficients through the comparison method (counting method).

There are several factors that may influence the accuracy of determining the calibration coefficients. It is essential to consider these factors during the calibration process [4, 5]:

- Energy Dependence. Calibration coefficients vary depending on the radiation energy. Inaccurate consideration of energy may lead to errors. A detailed analysis of energy dependence is provided in the work of Attix F.H., Introduction to Radiological Physics and Radiation Dosimetry, Wiley, 1986.
- Detector Types. Different detectors have varying sensitivities to radiation. The choice of a detector may affect the accuracy of results. The characteristics of different detector types are described in the book by Knoll G.F., Radiation Detection and Measurement, Wiley, 2010.
- Ambient Conditions. Temperature, humidity, pressure, and background radiation may affect the stability and accuracy of measurements. These aspects are discussed in more detail in the book by Podgorsak E.B., Radiation Physics for Medical Physicists, Springer, 2010.

Method for calculating the reference value and evaluating the international comparison results

The Comparison Reference Value (CRV) was calculated as the weighted average of the calibration coefficients (N_H) reported by primary standard laboratories. These laboratories provided traceability to their own primary measurement standards for air kerma (Ka) or ambient dose equivalent (H*(10)). The reference participants were designated as numbers 2 and 8 for all radiation qualities [3].

According to the equations provided in references [6, 7], the CRV was calculated as follows:

$$\mathrm{CRV} = \frac{\sum_{i=1}^{n} \frac{N_{H_i}}{u_i^2}}{\sum_{i=1}^{n} \frac{1}{u_i^2}}, \qquad (1)$$

where n is the number of laboratories with traceable calibration to their own primary measurement standard,

N_{Hi} is the i-th calibration coefficient,

u_i is the uncertainty of the i-th calibration coefficient.

The uncertainty of CRV, u(CRV), was calculated according to the equation [6, 7]:

$$u^2(\mathrm{CRV}) = (\sum_{i=1}^{n} \frac{1}{u_i^2})^{-1}. \qquad (2)$$

By calculating the deviation from the Comparison Reference Value (d_i) and the expanded measurement uncertainty of this deviation, the degrees of equivalence with the Comparison Reference Value were assessed. The deviation was calculated according to the formula $d_i = N_{H_i} - \mathrm{CRV}$. Individual calibration coefficients were compared against the CRV, which was derived using the calibration coefficients provided by the primary standard laboratories. Covariation was evaluated using the method described in [7]. If a laboratory contributed to the CRV, the equation $u(d_i)^2 = u_i^2 - u(\mathrm{CRV})^2$ was applied. In that comparison, the uncertainty due to the stable repeatability of the transfer chamber readings, evaluated as the standard deviation of at least four calibrations performed in VINS (U_{stab}), was added to the uncertainty.

In the case of primary standard laboratories, the uncertainty d_i is calculated according to equation [6]:

$$u(d_i)^2 = u_i^2 - u(\mathrm{CRV})^2 + u_{stab}^2. \qquad (3)$$

Any possible correlations were ignored in the case of laboratories with secondary measurement standards, and $u(d_i)$ was estimated according to equation [7]:

$$u(d_i)^2 = u_i^2 + u(\mathrm{CRV})^2 + u_{stab}^2. \qquad (4)$$

Relative deviation and the associated uncertainty were used to present the results, denoted as $D_i = 100 \cdot d_i / \mathrm{CRV}$ and $u(D_i) = 100 \cdot u(d_i) / \mathrm{CRV}$.

Laboratories used standard conversion coefficients, which did not introduce any correlation between results because each laboratory implemented its own gamma radiation measurement standards. These standards differ in their “true” conversion coefficient values. The differences between the true and recommended conversion coefficient values were distributed randomly. For monoenergetic radiation, the conversion coefficients were assumed to have no uncertainty [8].

Traceability for air kerma was maintained through PTB or the IAEA. The uncertainty of the measurement standard, which contributed to the uncertainty of the calibration coefficient of the instrument, was minimal – in most cases, this contribution was less than 10%. This was calculated based on the uncertainty budgets provided by the participants.

During the comparisons, some laboratories were unable to achieve the recommended dose rate for certain radiation qualities. Results for such cases are shown in Tables 1–4 but were not corrected. Due to the high linearity of the ionization chamber response, it is expected that any deviations in dose rate will have a negligible impact on calibration coefficients, even outside the recommended range.

Results for gamma radiation from a ^{137}Cs source (mandatory for participants)

Table 1 presents the results obtained by the NSC “Institute of Metrology”, identified as participant number 13 in the summary results. Table 2 shows the intercomparison results for the radiation quality of a ^{137}Cs source. Uncertainties were determined according to the BIPM Guide to the Expression of Uncertainty in Measurement [9]. The uncertainties listed in the tables were expanded with a coverage factor of $k = 2$, providing a confidence level of approximately 95%. According to the criterion, the uncertainty reported by a participant was confirmed if the condition $|D_i| \le U(D_i)$ was satisfied. Fig. 3 provides a graphical representation of the results. If the uncertainty bar for a specific result crosses the zero value of D, it indicates confirmation of the reported uncertainty. This representation allows for a visual assessment of measurement accuracy and reliability

$$\mathrm{CRV} = (29.72 \pm 0.61)\ \mu\mathrm{Sv/nC}\ (k = 2),$$
$$U_{stab} = 0.29\ \mu\mathrm{Sv/nC}\ (k = 2).$$

The results of the comparison of gamma radiation from the radionuclide ^{137}Cs were consistent within the reported measurement uncertainty.

Results for gamma radiation from a ^{60}Co source

Table 3 contains the results obtained by the NSC “Institute of Metrology”. Table 4 provides the interlaboratory comparison results for the radiation quality of a ^{60}Co source. As in previous

Table 1

Results obtained by the NSC "Institute of Metrology"

Radiation quality:			S-Cs
Focus-detector-distance FDD:			200 cm
Field diameter:			60 cm
$K_{\mathrm{a,ref}}$:			12.864 mGy/h
$H^*(10)_{\mathrm{ref}}$:			15.437 mSv/h
N_H (comparison result):			29.594 µSv/nC
Reference $H^*(10)$ determination			
Uncertainties in this table are stated with k=1			
Source of uncertainty	$u_{i,A}$, %	$u_{i,B}$, %	$u_{i,C}$, %
Calibration coefficient of the national/reference measurement standard	0.01	0.42	0.42
Collected charge	0.01	0.06	0.06
Air density correction	–	0.05	0.05
Source to chamber distance	–	0.05	0.05
Conversion coefficient	–	2.00	2.00
Other sources of uncertainty	–	–	–
Combined uncertainty, $H^*(10)$			**2.05**
Transfer chamber measurements			
Source of uncertainty	$u_{i,A}$, %	$u_{i,B}$, %	$u_{i,C}$, %
Collected charge	0.01	0.06	0.06
Air density correction	–	0.05	0.05
Source to chamber distance	–	0.14	0.14
Other sources of uncertainty	–	–	–
Combined uncertainty, Q			**0.16**
Combined standard uncertainty, N_H	$u=\sqrt{\sum_i\left(u_{i,A}^2+u_{i,B}^2\right)}$		**2.05**

Table 2

Comparison results for ^{137}Cs radiation quality (all uncertainties reported with $k = 2$)

Participant	N_H, µSv/nC			$H^*(10)$, mSv/h	h_k, Sv/Gy	D_i, %	$U(D_i)$, %
1	29.46	±	1.26	0.63	1.20	-0.87	4.81
2 (control participant)	29.99	±	0.85	5.95	1.210	0.91	2.22
3	29.04	±	1.54	5.27	1.200	-2.29	5.66
4	29.53	±	1.29	7.40	1.20	-0.64	4.90
5	29.24	±	1.22	6.44	1.20	-1.62	3.69
6	30.08	±	1.09	6.17	/	1.21	4.31
7	30.03	±	1.28	6.18	1.21	1.04	4.87
8 (control participant)	29.64	±	1.25	6.01	1.210	-0.27	3.80
9	29.64	±	1.24	0.80	1.20	-0.27	4.75
10	29.46	±	1.25	5.57	1.21	-0.87	4.78
11	29.84	±	1.34	6.01	1.21	0.40	5.05
12	29.51	±	1.33	4.49	1.21	-0.71	5.02
13	29.59	±	1.22	15.44*	1.20	-0.44	4.69

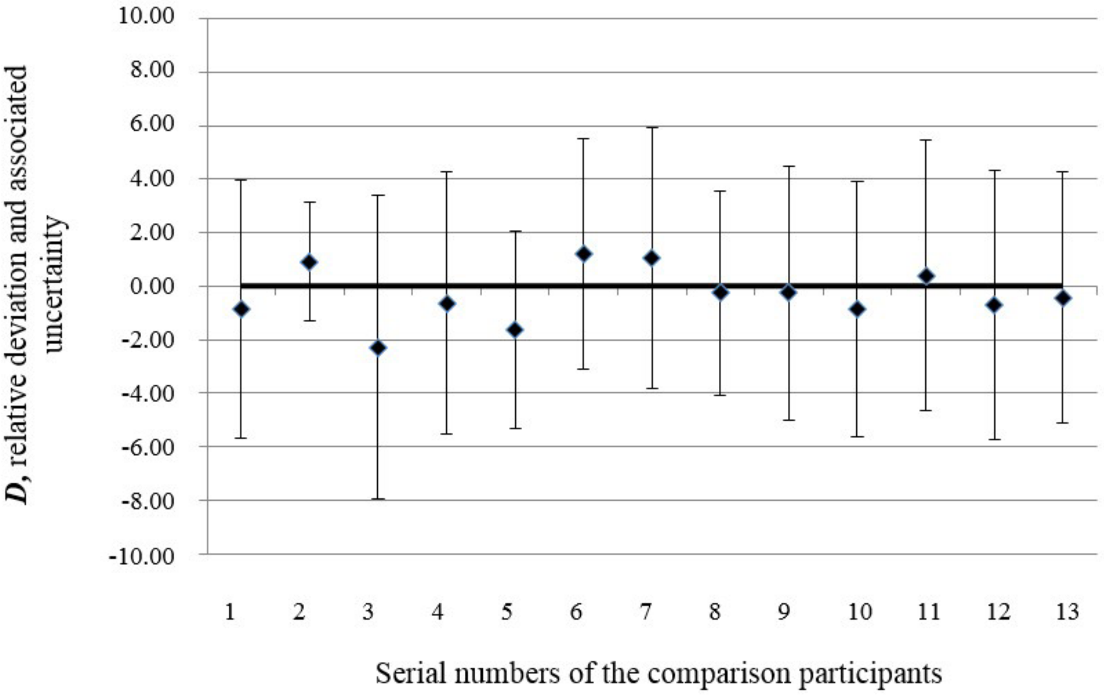

Fig. 3. Relative degrees of equivalence for ^{137}Cs radiation quality

tables, the uncertainties listed were expanded with a coverage factor of $k = 2$, ensuring a confidence level of approximately 95%. The uncertainty reported by a participant was confirmed if the condition $|D_i| \leq U(D_i)$ was satisfied. Not all participating laboratories were able to take part in this stage due to the lack of necessary material and technical resources.

Fig. 4 presents a graphical representation of the results. If the uncertainty bar for a specific result

Table 3

Results obtained by NSC "Institute of Metrology"

Radiation quality:			S-Co
Focus-detector-distance FDD:			80 cm
Field diameter:			24 cm
$K_{\mathrm{a,ref}}$:			0.594 mGy/h
$H^*(10)_{\mathrm{ref}}$:			0.689 mSv/h
N_H (comparison result):			29.008 µSv/nC
Reference $H^*(10)$ determination			
Uncertainties in this table are stated with k=1			
Source of uncertainty	$u_{i,A}$	$u_{i,B}$	$u_{i,C}$
Calibration coefficient of the national/reference measurement standard	0.06%	0.40%	0.40%
Collected charge	0.06%	0.13%	0.14%
Air density correction	–	0.05%	0.05%
Source to chamber distance	–	0.13%	0.13%
Conversion coefficient	–	2.00%	2.00%
Other sources of uncertainty	–	–	–
Combined uncertainty, $H^*(10)$			**2.05%**
Transfer chamber measurements			
Source of uncertainty	$u_{i,A}$	$u_{i,B}$	$u_{i,C}$
Collected charge	0.03%	0.13%	0.13%
Air density correction	–	0.05%	0.05%
Source to chamber distance	–	0.35%	0.35%
Other sources of uncertainty	–	–	–
Combined uncertainty, Q			0.38%
Combined standard uncertainty, N_H	$u=\sqrt{\sum_i \left(u_{i,A}^2+u_{i,B}^2\right)}$		**2.08%**

Table 4

Comparison results for ^{60}Co radiation quality (all uncertainties reported with $k=2$)

Participant	N_H, µSv/nC			$H^*(10)$, mSv/h	h_k, Sv/Gy	D_i, %	$U(D_i)$, %
1	28.26	±	1.20	2.03	1.16	-1.00	4.74
2 (control participant)	28.62	±	0.82	5.95	1.160	0.26	1.87
3	28.53	±	1.51	9.27	1.160	-0.05	5.72
4		±					
5	28.24	±	1.63	376.00*	1.16	-1.07	5.28
6		±					
7	28.36	±	1.21	6.05	1.16	-0.65	4.77
8 (control participant)	28.55	±	1.19	6.10	1.160	0.02	3.55
9		±					
10		±					
11	28.69	±	1.27	5.73	1.16	0.51	4.96
12		±					
13	29.01	±	1.21	0.69	1.16	1.63	4.77

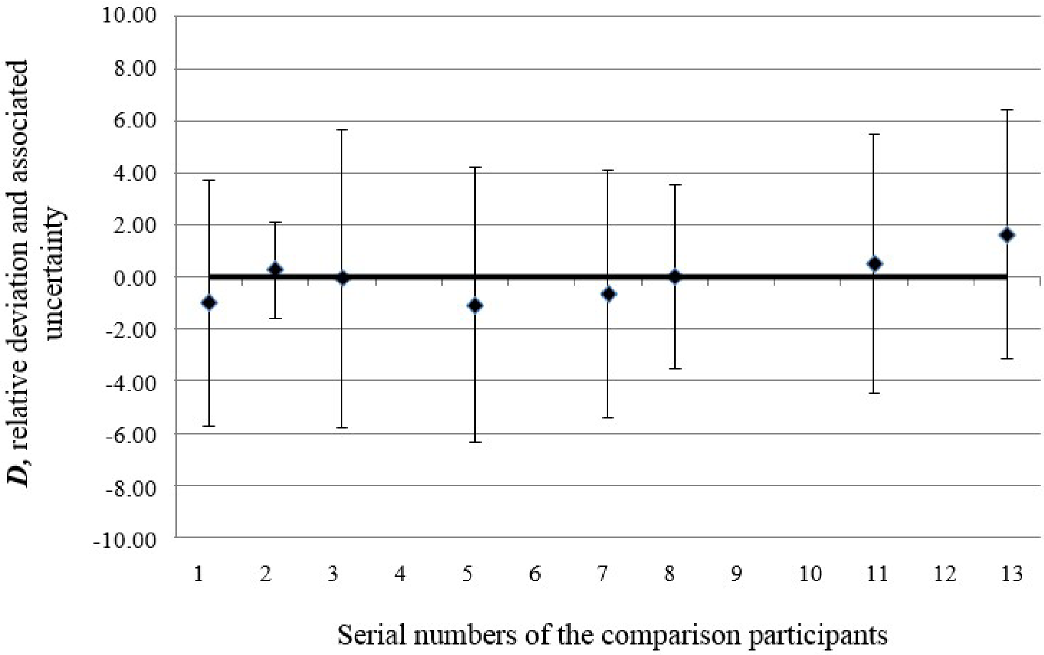

Fig. 4. Relative degrees of equivalence for ^{60}Co radiation quality

crosses the zero value of D, it indicates confirmation of the reported uncertainty, demonstrating consistency with the declared measurement accuracy

$$\mathrm{CRV} = (28.55 \pm 0.62)\ \mu\mathrm{Sv/nC}\ (k = 2),$$
$$U_{stab} = 0.028\ \mu\mathrm{Sv/nC}\ (k = 2).$$

Conclusions

The international comparison revealed shortcomings in the work of individual participants and confirmed the effectiveness of such collaborations. A detailed analysis of the protocols of all NMIs involved in the project and subsequent adjustments to calibration procedures will contribute to improving the accuracy and reliability of measurements. The comprehensive approach to calibration, measurements, and statistical analysis has ensured significant progress. Dosimetric measurements will remain a key tool for monitoring and minimizing risks associated with the use of ionizing radiation.

The NSC “Institute of Metrology” obtained the results demonstrating that ionizing radiation measurements are at an appropriate level, with a minor systematic error identified. The source of this error will be further investigated. During the implementation of the project, measurement practices were harmonized, and standardized protocols were developed, ensuring global consistency.

Дослідження невизначеності вимірювань гамма-випромінювання з джерелами цезій-137 та кобальт-60

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Анотація

Дозиметрія випромінювання є ключовим елементом у медичній, промисловій та науковій діяльності, пов’язаній із використанням іонізуючого випромінювання. Точність вимірювання доз випромінювання забезпечує безпеку та ефективність радіологічних практик, що є критично важливим для захисту пацієнтів у медичних процедурах, дотримання промислових стандартів безпеки та проведення наукових досліджень. Для досягнення високої точності вимірювань проводяться міжнародні дослідження.

ННЦ “Інститут метрології” бере активну участь у міжнародних проєктах, спрямованих на підвищення точності й узгодженості дозиметрії випромінювання. Ці проєкти об’єднують національні метрологічні інститути (NMI) для стандартизації методів вимірювання та калібрування, що сприяє вдосконаленню систем дозиметрії іонізуючого випромінювання.

Актуальність таких проєктів зумовлена широким використанням іонізуючого випромінювання в медицині та промисловості. У медицині, зокрема в радіотерапії, точність дозиметрії забезпечує ефективне лікування з мінімальним впливом на здорові тканини. У промисловій радіографії високоточна дозиметрія гарантує дотримання стандартів безпеки, знижуючи ризик надмірного опромінення працівників.

У рамках міжнародного проєкту за участю PTB (Фізико-технічного федерального інституту) та GUM (Головного управління мір) розробляються нові протоколи калібрування для різних видів випромінювання, створюються нові ланцюги простежуваності для забезпечення точності вимірювань, а також відбувається обмін практиками між учасниками.

Для досягнення мети проводилися попередні звірення між NMI, де два інститути були опорними (зразковими). Такий підхід дозволив учасникам звірити свої результати з контрольними даними та внести необхідні корективи. Колаборація сприяла обміну знаннями й стимулювала розробку нових технік дозиметрії, що в довгостроковій перспективі забезпечить поліпшення точності й надійності вимірювань.

ННЦ “Інститут метрології” брав участь у проєкті як провідна організація з галузі іонізуючих випромінювань в Україні. У статті наведено результати співпраці, а саме звірень іонізуючого випромінювання з джерелами ^{137}Cs і ^{60}Co. Також у рамках проєкту було виконане звірення рентгенівських пучків із якостями випромінювання: N-40, N-100, N-200.

Ключові слова: радіаційна безпека; звірення; дозиметрія; іонізуюче випромінювання; рентгенівські пучки.

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