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Study of uncertainty budget components in X-ray and gamma radiation dosimetry

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Abstract

Dosimetry of X-ray and gamma radiation is widely used in medicine. The accuracy of measurements and their reproducibility directly affect the efficiency and safety of using radiation in radiotherapy and clinical diagnostics. Problems caused by the instability of radiation sources, environmental parameters, and the complexity of calibrating dosimetry chambers remain unresolved.

In view of a growing need to standardize dosimetry measurements of X-ray and gamma radiation, international and national laboratories are conducting interlaboratory comparisons. This process allows for the evaluation of a laboratory's capabilities and the development of practical approaches to improve the unification of standards and minimize the measurement uncertainty.

The results of international comparisons were analysed. The components of the uncertainty budget when measuring the operational quantities of X-ray and gamma radiation were compared. Recommendations for reducing uncertainties and improving the measurement accuracy are proposed. Finally, the uncertainty budget of the NSC "Institute of Metrology" was compared with those of other laboratories participating in the comparison.

Keywords: comparisons; uncertainty; X-ray and ɣ-dosimetry; ionizing radiation.

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Introductionr

Problems that the dosimetry of X-ray and gamma radiation face are:

- inaccuracies in the calibration of dosimetry systems that can lead to errors in dose measurements, which is critical in radiotherapy;
- the complexity of accounting for factors such as energy dependence, the stability of the radiation source, and environmental parameters that tends to increase measurement uncertainties.

One of the key objectives of dosimetry is to achieve reproducible and reliable measurements, especially in high-energy X-ray or gamma radiation modes. Uncertainties in dosimetry can be caused by both hardware and methodological factors: instability of the source, incorrect instrument calibration, and the influence of external factors. This may lead to significant distortions in measurement results, for example:

- underexposure or overexposure of a patient's tumour during radiotherapy;
- substantial errors in determining the dose received by the personnel working with ionizing radiation.

Modern challenges in dosimetry include the need to consider the impact of innovative technologies, such as the use of automated measurement systems for data analysis. These systems allow for improved measurement accuracy and faster processing of results, but their implementation requires careful evaluation and standardization. Interlaboratory comparisons serve as an important tool for sharing expertise and allow for:

- comparing the measurement results of various laboratories, since they use their own procedures and different equipment, which may lead to potential discrepancies. These comparisons help identify inconsistencies and develop recommendations;
- validating the methods;
- analysing the obtained results and formulating recommendations to enhance the applicable standards.

Interlaboratory comparisons also aid in updating standards, such as ISO 4037 on Radiological Protection – X and gamma reference radiation for calibrating dosimeters and dose rate meters and for determining their response as a function of photon energy [1, 2].

One of the most important goals of interlaboratory comparisons is to ensure the uniformity of measurements.

Participation in these comparisons plays a key role in detecting and eliminating systematic errors that might go unnoticed within a single laboratory. For example, deviations in the conversion coefficient (N_H) when using the N-40 and N-100 X-ray series may be caused by incorrect positioning of the ionization chamber in the X-ray beam or improper filtration of the initial X-ray radiation (due to incorrect selection of filters or materials). Participation in interlaboratory comparisons helps to identify these issues and adjust procedures accordingly. This, in turn, contributes to an improvement in the quality of dosimetry, which is especially important when using ionizing radiation in medicine [3, 4].

Methodology and approach to the comparisons

Interlaboratory comparisons were conducted using standardized methods and conditions to ensure the comparability of the results. The studies covered five types of radiation, which are divided into two main categories:

- X-ray series (N-40, N-100, N-200). Energy range: from low (N-40, approximately 40 keV) to high (N-200, approximately 200 keV). The key parameter is the conversion coefficient (N_H), which depends on the radiation spectrum and the positioning of the ionization chamber;
- Gamma series. These series are implemented using radioisotope gamma radiation sources: cesium-137 (S-Cs) and cobalt-60 (S-Co). The high-energy gamma radiation of cobalt-60 (1.25 MeV) is widely used in radiotherapy. Gamma sources are characterized by the stability of their radiation, which simplifies their use in measurements.

For each type of radiation, key parameters were defined, and additional factors were accounted for, including:

- the positioning of the ionization chamber;
- environmental parameters (temperature, pressure, humidity);
- radiation characteristics (spectrum, angle of incidence, etc.).

The comparisons were based on international standards, including ISO 4037 (both the old and new editions) [1, 2] and the recommendations of EURAMET [5].

Each participant submitted their measurement results, including the N_H coefficients and standard uncertainties, which were then compared with the control reference value (CRV).

The CRV and its uncertainty were calculated based on the values from the reference participants with the minimum expanded uncertainty of the measurement results [6, 7].

Comparison and analysis of the participants' results

The uncertainty budget calculations for the comparison participant NSC "Institute of Metrology" (NSC "IM") focused on three key parameters:

- calibration coefficient of the national/reference measurement standard;
- conversion coefficient of the ambient dose equivalent (the conversion coefficient);
- coefficient accounting for the accuracy of the ionization chamber positioning (source-to-chamber distance).

A comparison of the contributions of these parameters to the overall uncertainty was conducted for all the studied radiation qualities (N-40, N-100, N-200, S-Cs, S-Co). The analysis revealed that:

- the conversion coefficient is the primary source of uncertainty;
- a significant contribution is made by the uncertainty of the ambient dose equivalent, as reproduced by the primary measurement standard;
- the positioning of the ionization chamber relative to the radiation source insignificantly contributes to the overall uncertainty.

Differences in the parameters among the radiation qualities demonstrate the influence of energy dependence and the standards applied by the participants [1, 2].

The comparison results enable the identification of methodological "bottlenecks" and the optimization of calibration processes to reduce the uncertainty.

The obtained uncertainty budget values are presented in Tables 1–5 for the NSC "IM" participant.

Table 1

Results obtained by NSC "Institute of Metrology" for N-40 series

Contributions to combined uncertainty			
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	0.11	1.50	1.50
Conversion coefficient	–	2.00	2.00
Source to chamber distance	–	0.14	0.14

Table 2

Results obtained by NSC "Institute of Metrology" for N-100 series

Contributions to combined uncertainty			
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	0.22	1.50	1.52
Conversion coefficient	–	2.00	2.00
Source to chamber distance	–	0.14	0.14

Table 3

Results obtained by NSC "Institute of Metrology" for N-200 series

Contributions to combined uncertainty			
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	0.22	1.50	1.52
Conversion coefficient	–	2.00	2.00
Source to chamber distance	–	0.14	0.14

Table 4

Results obtained by NSC "Institute of Metrology" for S-Cs

Contributions to combined uncertainty			
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
Conversion coefficient	–	2.00	2.00
Source to chamber distance	–	0.14	0.14

Table 5

Results Obtained by NSC "Institute of Metrology" for S-Co

Contributions to combined uncertainty			
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
Conversion coefficient	–	2.00	2.00
Source to chamber distance	–	0.35	0.35

Table 6

Results obtained by other participants

Contributions to combined uncertainty									
Uncertainties in this Table are stated with k=1									
Results obtained for N-40 series									
Source of uncertainty	Participant № 1			Control participant			Participant № 2		
	$u_{i,A}$, %	$u_{i,B}$, %	$u_{i,C}$, %	$u_{i,A}$, %	$u_{i,B}$, %	$u_{i,C}$, %	$u_{i,A}$, %	$u_{i,B}$, %	$u_{i,C}$, %
Calibration coefficient of the national/reference measurement standard	0.52	0.62	0.81	–	1.00	1.00	1.75	–	1.75
Conversion coefficient	–	2.00	2.00	–	1.00	1.00	–	2.00	2.00
Source to chamber distance	–	0.12	0.12	–	0.09	0.09	–	0.07	0.07
Results obtained for N-100 series									
Calibration coefficient of the national/reference measurement standard	0.52	0.61	0.80	–	1.00	1.00	0.40	–	0.40
Conversion coefficient	–	2.00	2.00	–	1.00	1.00	–	2.00	2.00
Source to chamber distance	–	0.12	0.12	–	0.09	1.00	0.07	–	0.07
Results obtained for N-200 series									
Calibration coefficient of the national/reference measurement standard	0.52	0.60	0.79	–	1.00	1.00	0.40	–	0.40
Conversion coefficient	–	2.00	2.00	–	–	0	–	2.00	2.00
Source to chamber distance	–	0.12	0.12	–	0.09	0.09	–	0.07	0.07
Results obtained for S-Cs									
Calibration coefficient of the national/reference measurement standard	0.52	0.42	0.67	–	0.84	0.84	0.60	–	0.60
Conversion coefficient	–	2.00	2.00	–	1.00	1.00	–	2.00	2.00
Source to chamber distance	–	0.16	0.16	–	0.08	0.08	–	0.07	0.07
Results obtained for S-Co									
Calibration coefficient of the national/reference measurement standard	0.52	0.41	0.66	–	0.84	0.84	0.40	–	0.40
Conversion coefficient	–	2.00	2.00	–	1.00	1.00	–	2.00	2.00
Source to chamber distance	–	0.12	0.12	–	0.20	0.20	–	0.07	0.07

The results of the comparison between the reference participant and two other participants with a status similar to that of the NSC "IM" were analysed. The uncertainty evaluation results for the reference participant and the two other participants are presented in Table 6.

Analysis of the uncertainty budgets of the compared participants

The estimation of uncertainty budgets showed that the two participants and the NSC "IM" have an uncertainty of less than 7% [8]. The reference participant demonstrated a low uncertainty in determining the calibration coefficient, which attests to the high quality of the national measurement standards used.

The sample values of the two other participants showed a larger uncertainty compared to the reference participant, which may indicate non-compliance with the measurement conditions. This could be due to technical peculiarities of the standards or less optimal measurement methods. The values obtained by the NSC "IM" participant also deviated from those of the reference participant, suggesting a possible need for modernization of the primary measurement standards for dosimetry.

The use of spectrometry and modern methods for calculating the conversion coefficient allowed the reference participant to achieve stable and accurate measurements of the ambient dose equivalent. The conversion coefficient values for the selected comparison participants and the NSC "IM" converge with the results of the reference participant. The uncertainty of the conversion coefficient can be reduced by adopting a current standard, as the existing methodology is outdated [1].

Uncertainty in the positioning of the ionization chamber centre relative to the beam axis centre

The uncertainty in positioning the ionization chamber relative to the centre of the beam axis in the installations of the reference participant is negligible, which helps to minimize the uncertainty caused by errors in the distance determination.

One of the comparison participants in this sample achieved positioning results that are practically equivalent to those of the reference participant. For the second participant, as well as for the NSC "IM", the uncertainty due to the chamber positioning is slightly higher than that of the reference participant.

Procedures for reducing the uncertainty of the considered parameters

After analysing and evaluating the obtained comparison results, the following conclusions can be drawn regarding the reduction of the uncertainty:

- the use of spectrometry methods for determining the calibration coefficient of X-ray radiation;
- adoption of the practice of regular interlaboratory comparisons involving participants with the highest measurement accuracy;
- implementation of ISO 4037:2019 in place of its outdated version.

ISO 4037:2019 offers a more detailed description of spectra considering modern X-ray sources [2]. It introduces new reference beams for more accurate dosimeter calibration and provides increased flexibility in selecting radiation parameters to replicate real irradiation conditions. The practical advantage lies in the use of a new classification that better accounts for the characteristics of radiation fields, thereby reducing calibration uncertainty.

Furthermore, ISO 4037:2019 has refined the procedures for measuring the scattered radiation and introduced stricter requirements for the geometry of the installations [2]. It defines methods for minimizing the scattered radiation (e.g., through the use of collimators and shields). The practical advantage of controlling the scattered radiation is an increase in accuracy, especially in the low-energy range. Additionally, the standard refines the calculation of conversion coefficients by separating coefficients for different types of dosimeters. In practice, the use of updated coefficients reduces the uncertainty.

ISO 4037:2019 also introduces new requirements for controlling the stability of radiation sources, the metrological control of dosimeters, and procedures for evaluating uncertainties [2].

Conclusion

The analysis showed that the comparison results presented by the NSC "Institute of Metrology" are consistent with the results of the reference participant and other comparison participants, and the measurement uncertainty does not exceed the upper limit.

Ways for enhancing the calibration capabilities have been identified through the modernization of national measurement standards for dosimetry and implementation of advanced measurement methods and uncertainty evaluation techniques.

Transitioning to the new regulatory framework (ISO 4037:2019) and modernizing the reference measurement standard base will reduce the uncertainty in determining the conversion coefficient, which in turn will lower the combined uncertainty for the NSC "IM" reference instruments. Following these changes, participation in repeated international comparisons is required.

Дослідження складових бюджету невизначеності при дозиметрії рентгенівського та гамма-випромінювання

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Анотація

Дозиметрія рентгенівського та гамма-випромінювання широко використовується в медицині, де точність і відтворюваність вимірювань безпосередньо впливають на ефективність і безпеку променевої терапії та клінічної діагностики. Помилки при відпуску дози пацієнту можуть згодом негативно впливати на його здоров'я. Однак невизначеності вимірювань можуть виникати через нестабільність джерел випромінювання, вплив параметрів навколишнього середовища та складність калібрування дозиметричних камер. Незважаючи на постійне вдосконалення методик, ці проблеми залишаються невирішеними і потребують подальшого вивчення для забезпечення надійного дозиметричного контролю.

В умовах зростаючої необхідності уніфікації дозиметричних вимірювань рентгенівського та гамма-випромінювання міжнародні та національні лабораторії проводять міжлабораторні звірення. Це дозволяє оцінити можливості лабораторії та розробити практичні шляхи для покращення уніфікації стандартів і мінімізації величини невизначеності.

Були проаналізовані результати міжнародних звірень щодо рентгенівського та гамма-випромінювання. Проведено порівняння складових часток бюджету невизначеності при вимірюванні величин рентгенівського та гамма-випромінювання. Надано рекомендації щодо зниження невизначеностей та підвищення точності вимірювань. Проведено порівняння бюджету невизначеності ННЦ "Інститут метрології" з бюджетами невизначеності інших лабораторій, що брали участь у звіренні. Порівнявши отримані невизначеності ННЦ "Інститут метрології" з невизначеностями інших лабораторій-учасників звірення, зроблено висновок про необхідність впровадження актуальної нормативної бази та модернізації еталонної бази, що дозволить знизити складові частини невизначеності до рівня лабораторій, які є лідерами у цьому виді вимірювань.

Запропоновані рекомендації та практичні підходи до зниження невизначеності вимірювань сприяють підвищенню точності в дозиметрії, що є важливим для медичного та наукового застосування іонізуючого випромінювання.

Ключові слова: звірення; невизначеність; рентгенівська та гамма-дозиметрія; іонізуюче випромінювання.

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