**ВИМІРЮВАННЯ ХАРАКТЕРИСТИК ІОНІЗУЮЧОГО ВИПРОМІНЮВАННЯ**
**MEASUREMENTS OF IONIZING RADIATION CHARACTERISTICS**

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# Study of the Accuracy and Reliability of Dosimetric Measurements for X-ray Beams with Radiation Qualities N-40, N-100, N-200

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**Abstract**

Radiation dosimetry is a critical aspect of medical, industrial, and scientific applications involving ionizing radiation. Accurate measurements of radiation doses ensure the safety and effectiveness of radiological practices, which is essential for protecting patients in medical procedures, maintaining safety in industrial applications, and ensuring accuracy in scientific research.

Leading international organizations conduct research aimed at improving measurement accuracy and the dissemination of measurement units. One of the methods contributing to this effort is various international projects. The National Scientific Centre "Institute of Metrology" has participated in one such international project.

This international project, involving several National Metrology Institutes (NMIs), aimed to improve the accuracy and consistency of radiation dosimetry across Europe. By standardizing measurement and calibration procedures, the project seeks to create a unified system for measuring radiation doses, thereby improving the reliability of ionizing radiation dosimetry.

This project is particularly significant given the continuous increase in radiation-based technologies across various fields. For example, precise measurements of ionizing quantities are crucial in the medical field, especially for radiotherapy, to ensure that patients receive the necessary dose with minimal exposure to surrounding healthy tissues. Similarly, in industrial radiography, accurate dosimetry is essential for meeting safety standards and preventing excessive radiation exposure to workers.

The international project, with the Physikalisch-Technische Bundesanstalt (PTB) and the Central Office of Measures (GUM) as leading organizations, aims to improve key factors in ionizing radiation dosimetry. These include developing reliable calibration protocols for various types of radiation, establishing traceability chains to ensure measurement accuracy, and sharing best dosimetry practices among project participants. Preliminary comparisons were performed between NMIs, with two control participants serving as references while other NMIs participated anonymously (knowing only their number and the numbers of the reference participants). Each participant had the opportunity to compare their obtained values with the reference values and make adjustments for future measurements. The collaborative nature of such cooperation also promotes knowledge and experience exchange, fostering innovation and improvement in dosimetry techniques.

The NSC "Institute of Metrology", a leading organization in the field of the ionizing radiation metrology, has actively participated in this project as a representative from Ukraine. The paper presents the results of international comparisons for X-ray beams with the radiation qualities N-40, N-100, N-200.

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

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## Materials and Methods

The participants of the international comparisons focused on calibrating dosimeters for a wide range of radiation qualities. Understanding and accurately measuring these different radiation qualities are crucial for ensuring the safety and effectiveness of various radiological practices. Each type of radiation quality has specific characteristics and applications that require precise calibration to maintain measurement accuracy [1].

As part of the project, international comparisons were conducted among the participants for the ionizing radiation qualities such as N-40, N-100, and N-200: narrow-spectrum X-ray beams. The calibration of dosimeters for these X-ray beams involves accurately measuring beam quality and energy spectrum. Dosimeters are exposed to controlled X-ray radiation of a given quality, and their responses are compared with reference measurement standards. This ensures that dosimeters provide accurate readings for different energy levels of X-ray beams. The radiation qualities differ in their energy levels:

- N-40: Low-energy X-ray beams with a peak energy of around 40 keV. These beams are typically used in diagnostic radiology for imaging soft tissues, providing high-contrast images essential for detecting abnormalities such as tumours or fractures.
- N-100: Medium-energy X-ray beams with a peak energy of around 100 keV. This energy range is used in more complex diagnostic procedures, providing a balance between tissue penetration and image resolution, making it suitable for visualizing deeper body structures.
- N-200: High-energy X-ray beams with a peak energy of around 200 keV. High-energy X-ray beams are necessary for imaging dense tissues and bones, as well as for certain therapeutic applications requiring deeper tissue penetration.

Accurate calibration of dosimeters for these varied radiation qualities ensures that measurements are reliable and consistent, regardless of the type of radiation or its energy level. This is crucial for:

- medical imaging and treatment: Ensuring that patients receive the correct dose during diagnostic procedures and radiotherapy, minimizing the risk of overdosing or under-treatment;
- occupational safety: Protecting workers from radiation by accurately monitoring their exposure levels, adhering to safety standards, and minimizing health risks;
- environmental monitoring: Ensuring accurate measurements of radiation levels in the environment, which is important for assessing the impact of nuclear facilities and ensuring public safety.

Overall, the calibration of dosimeters for different radiation qualities within the project improves the accuracy of radiation measurements, promoting safer and more effective use of radiation across various fields.

## Calibration coefficients

Calibration coefficients are crucial for converting the primary readings of dosimeters into accurate dose measurements. These coefficients are determined through meticulous calibration procedures and are specific to the type of radiation, energy levels, and characteristics of the dosimeter. The project was focused on obtaining precise calibration coefficients to ensure the reliability and accuracy of radiation dose measurements across various applications [2].

### *Steps in Determining Calibration Coefficients*

1. Standardized Radiation Sources: For the calibration procedure, standardized radiation sources were used, such as narrow-spectrum X-ray beams (N-series), cesium-137 (Cs-series), and cobalt-60 (Co-series). These sources provided controlled and reproducible ionizing radiation fields necessary for accurate calibration. High-precision reference dosimeters, traceable to primary measurement standards, were used to measure the radiation dose. These reference measurements served as the basis for calibrating working dosimeters. Calibration was performed in a controlled environment to minimize exposure to external factors such as temperature, humidity, pressure, and background radiation. This ensured the determination of calibration coefficients under optimal conditions.

2. Calibration Process: Dosimeters were exposed to known amounts of radiation from the standard sources. The exposure was carefully controlled to ensure consistency and reproducibility. The response of the dosimeters was measured and recorded. This response is directly related to the radiation dose received by the dosimeter. Calibration coefficients were calculated by comparing the dosimeter readings with the reference measurements.

## Factors Affecting Calibration Coefficients

Several factors may influence the determination of calibration coefficients, and these variables shall be considered during the calibration process [3]:

1. Energy Dependence. Dosimeters respond differently to radiation of various energy levels. Calibration coefficients shall account for this energy dependence to ensure accurate dose measurements across the spectrum of radiation qualities. For example, the response of a dosimeter calibrated for low-energy X-ray beams (N-40) will differ from its response to high-energy gamma rays (S-Co). Separate calibration coefficients are developed for each energy level to account for these differences.

2. Type of Detectors. Different types of detectors (e.g., ionization chambers, thermoluminescent dosimeters, semiconductor detectors) have unique characteristics that affect their response to radiation. Calibration coefficients are specific to the type of a detector used. For instance, ionization chambers have a linear response to radiation dose over a wide range, while thermoluminescent dosimeters may exhibit nonlinear responses at high doses. Calibration coefficients are accordingly adjusted to ensure accurate dose measurements.

3. Environmental Conditions. Calibration procedures shall account for the influence of environmental conditions such as temperature, pressure, and humidity. These factors may affect the response of the dosimeter and, consequently, the calibration coefficients. A controlled calibration environment helps to minimize these effects, but it is still important to consider potential deviations in environmental parameters when applying calibration coefficients in real-world conditions.

## Method for Calculating the Reference Value and Estimating the International Comparison Results

To estimate the comparison results, a Comparison Reference Value (CRV) was calculated for each radiation quality as the weighted mean of the calibration coefficients (NH) reported by the primary measurement standard laboratories. These laboratories, participants in the study, traced their measurements to their own primary measurement standards for air kerma (Ka) or ambient dose equivalent (H*(10)). The reference participants were numbers 2 and 8 for all the radiation qualities.

According to the equations provided in [4, 5], 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,

$N_{H_i}$ is 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 [4, 5]:

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

By calculating the deviation from the Comparison Reference Value ($d_i$) and the expanded uncertainty of this deviation, the degrees of equivalence with the Comparison Reference Value were assessed. The deviation was calculated according to the formula $d_i = N_{H_i} - \mathrm{CRV}$. Considering that the individual calibration coefficients were compared with the CRV, and that the CRV was calculated based on the calibration coefficients provided by the primary measurement standard laboratories, it is necessary to account for the correlations between the primary measurement standard laboratories and the CRV. If a laboratory contributes to the CRV, the covariance is estimated using the method described in [5], resulting in the equation $u(d_i)^2 = u_i^2 - u(\mathrm{CRV})^2$. In this comparison, the uncertainty due to the stability of the transfer chamber, evaluated as the standard deviation of at least four calibrations performed in VINS ($U_{stab}$), is added to the uncertainty.

In the case of primary measurement standard laboratories, the uncertainty $d_i$ is calculated according to equation [5]:

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

Any possible correlations are ignored in the case of laboratories with secondary measurement standards, and $u(d_i)$ is estimated according to equation [5]:

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

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 use the same conversion coefficients, which does not cause correlation, as each laboratory has its own realizations of standard radiation qualities with different “true” values of the conversion coefficients. Thus, the difference between the true values of the conversion coefficients and the recommended values of the conversion coefficients is randomly distributed. The conversion coefficients for monoenergetic radiation are considered to have no uncertainty [6].

As for the tracking of air kerma, several secondary measurement standard laboratories are traceable to the PTB directly or through the IAEA. Generally, the contribution of the calibration coefficient uncertainty of the reference measurement tandard to the uncertainty of the device calibration coefficient is insignificant due to the high uncertainty of the conversion coefficient. In most cases, this contribution is less than 10%, which can be calculated based on the uncertainty budgets of the measurements reported by the participants.

During the comparisons, some participants were unable to achieve the dose rate for certain radiation qualities within the recommended range. These results are shown in Tables 1-6, but were not corrected. Due to the high linearity of the ionization chamber readings, it is expected that any impact of the dose rate on the calibration coefficient will be minor even outside the studied range.

## Results of the comparisons of low-energy X-rays with a peak energy of about 40 keV (N-40)

The results obtained and calculated by the NSC “Institute of Metrology” are presented in Table 1. The NSC “Institute of Metrology” is represented in the final results as participant number 13. The comparison results for the radiation quality N-40 are presented in Table 2. The uncertainties shown in the Tables are expanded uncertainties with a coverage factor of $k$=2. For the purposes of this comparison, it is considered that the uncertainty reported by the participant is confirmed if the following statement is true: $|D_i| \leq U(D_i)$ [7]. Fig. 1 shows a graphical representation of the results. If the uncertainty band for a specific result crosses the zero value of $D$, the uncertainty is considered confirmed.

The X-ray beam quality with a peak energy of around 40 keV (N-40) was mandatory. Two participants could not perform the calibration because of technical problems with the X-ray equipment.

As a reference value for the project, the average value, with the calculated uncertainty, among the primary measurement standard laboratories, was used,

Table 1

Results obtained by the NSC "Institute of Metrology"

| | | | |
|---|---|---|---|
| Radiation quality: | | | N-40 |
| Focus-detector-distance FDD (cm): | | | 200 |
| Field diameter (cm): | | | 34 |
| $K_{a,\mathrm{ref}}$ (mGy/h): | | | 31.566 |
| $H^*(10)_{\mathrm{ref}}$ (mSv/h): | | | 37.248 |
| $N_H$ (µSv/nC) (comparison result): | | | 26.588 |
| Reference $H^*(10)$ determination | | | |
| Uncertainties in this Table are stated with $k$=1 | | | |
| Source of uncertainty | $u_{i,\mathrm{A}}$ | $u_{i,\mathrm{B}}$ | $u_{i,\mathrm{C}}$ |
| Calibration coefficient of the national/reference measurement standard | 0.11% | 1.50% | 1.50% |
| Collected charge | 0.11% | 0.22% | 0.25% |
| 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, $H^*(10)$** | – | – | **2.51%** |
| Transfer chamber measurements | | | |
| Source of uncertainty | $u_{i,\mathrm{A}}$ | $u_{i,\mathrm{B}}$ | $u_{i,\mathrm{C}}$ |
| Collected charge | 0.23% | 0.22% | 0.32% |
| Air density correction | – | 0.05% | 0.05% |
| Source to chamber distance | – | 0.14% | 0.14% |
| Other sources of uncertainty | – | – | – |
| **Combined uncertainty, $Q$** | – | – | **0.35%** |
| | | | |
| **Combined standard uncertainty, $N_H$** | $u=\sqrt{\sum_i\left(u_{i,A}^2+u_{i,B}^2\right)}$ | | **2.54%** |

Table 2

Results of N-40 radiation quality comparison
(all uncertainties are reported with $k$=2)

| Participants | $N_H$ (μSv/nC) | | | $H$*(10) (mSv/h) | $h_k$ (Sv/Gy) | $D_i$ (%) | $U(D_i)$ (%) |
|---|---|---|---|---|---|---|---|
| 1 | 26.34 | ± | 1.16 | 6.15 | 1.18 | 0.43 | 5.07 |
| 2 (control participant) | 26.19 | ± | 0.80 | 5.98 | 1.197 | –0.15 | 1.84 |
| 3 | | | | | | | |
| 4 | 26.01 | ± | 1.20 | 6.60 | 1.18 | –0.83 | 5.21 |
| 5 | | | | | | | |
| 6 | 26.38 | ± | 1.23 | 6.43 | 1.20 | 0.58 | 5.31 |
| 7 | 26.76 | ± | 1.14 | 6.14 | 1.20 | 2.03 | 5.01 |
| 8 (control participant) | 26.30 | ± | 1.09 | 5.88 | 1.197 | 0.27 | 3.37 |
| 9 | 26.25 | ± | 1.06 | 1.31 | 1.18 | 0.08 | 4.74 |
| 10 | 26.69 | ± | 1.19 | 6.17 | 1.20 | 1.76 | 5.17 |
| 11 | 26.00 | ± | 1.45 | 6.01 | 1.20 | –0.87 | 6.06 |
| 12 | | | | | | | |
| 13 | 26.59 | ± | 1.36 | 37.25 | 1.18 | 1.38 | 5.75 |

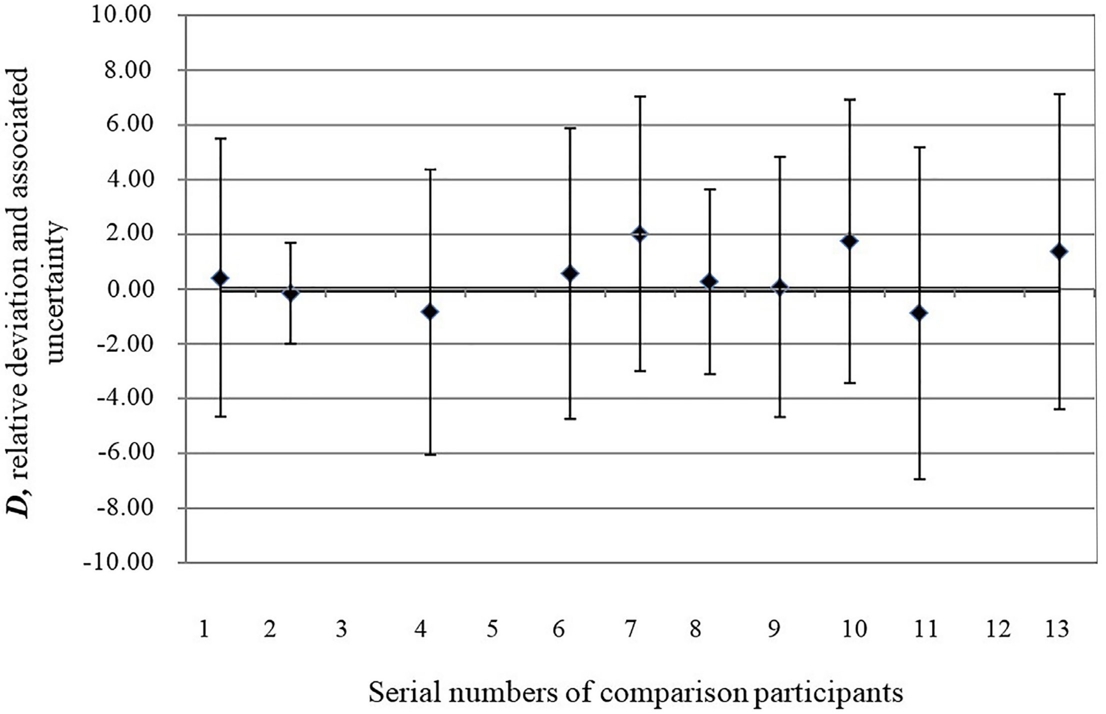

Fig. 1. Relative degrees of equivalence for N-40 radiation quality

calculated according to equations (1–4) mentioned above:

$$\text{CRV} = (26.23 \pm 0.64)\ \mu\text{Sv/nC}\ (k{=}2),$$
$$U_{stab} = 0.094\ \mu\text{Sv/nC}\ (k{=}2).$$

All comparison results for N-40 radiation quality are consistent within the reported measurement uncertainty.

**Comparison results for medium-energy X-ray beams with a peak energy of around 100 keV (N-100)**

The results obtained and calculated by the NSC "Institute of Metrology" are presented in Table 3. The comparison results for the radiation quality N-100 are presented in Table 4. The uncertainties shown in the Tables are expanded uncertainties with a coverage factor of $k$=2. For the purposes of this calculation, the uncertainty reported by a participant is considered confirmed if the following statement is true: $|D_i| \le U(D_i)$ [7].

Fig. 2 shows a graphical representation of the results. If the uncertainty band for a specific result crosses the zero value of $D$, the uncertainty is considered confirmed.

The X-ray beam quality with a peak energy of around 100 keV (N-100) was mandatory. Two participants could not perform the calibration because of technical problems with the X-ray equipment.

As a reference value for the project, the average value, with the calculated uncertainty, among the primary measurement standard laboratories, was used, calculated according to equations (1–4) mentioned above:

$$\text{CRV} = (29.12 \pm 0.72)\ \mu\text{Sv/nC}\ (k = 2),$$
$$U_{stab} = 0.21\ \mu\text{Sv/nC}\ (k = 2).$$

Table 3

Results obtained by the NSC "Institute of Metrology"

| | | | |
|---|---|---|---|
| Radiation quality: | | | N-100 |
| Focus-detector-distance FDD (cm): | | | 200 |
| Field diameter (cm): | | | 34 |
| $K_{a,\text{ref}}$ (mGy/h): | | | 5.712 |
| $H^*(10)_{\text{ref}}$ (mSv/h): | | | 9.768 |
| $N_H$ (μSv/nC) (comparison result): | | | 30.199 |
| Reference $H^*(10)$ determination | | | |
| Uncertainties in this table are stated with $k$=1 | | | |
| Source of uncertainty | $u_{i,\text{A}}$ | $u_{i,\text{B}}$ | $u_{i,\text{C}}$ |
| Calibration coefficient of the national/reference measurement standard | 0.22% | 1.50% | 1.52% |
| Collected charge | 0.22% | 0.10% | 0.24% |
| 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)** | – | – | **2.52%** |
| Transfer chamber measurements | | | |
| Source of uncertainty | $u_{i,\text{A}}$ | $u_{i,\text{B}}$ | $u_{i,\text{C}}$ |
| Collected charge | 0.15% | 0.10% | 0.18% |
| Air density correction | – | 0.05% | 0.05% |
| Source to chamber distance | – | 0.14% | 0.14% |
| Other sources of uncertainty | – | – | – |
| **Combined uncertainty, *Q*** | – | – | **0.23%** |
| | | | |
| **Combined standard uncertainty, $N_H$** | $u = \sqrt{\sum_i \left(u_{i,A}^2 + u_{i,B}^2\right)}$ | | **2.53%** |

Table 4

Results of N-100 radiation quality comparison
(all uncertainties are reported with $k$=2)

| Participants | $N_H$ (µSv/nC) | | | $H$*(10) (mSv/h) | $h_k$ (Sv/Gy) | $D_i$ (%) | $U(D_i)$ (%) |
|---|---|---|---|---|---|---|---|
| 1 | 29.66 | ± | 1.30 | 6.11 | 1.71 | 1.84 | 5.15 |
| 2 (control participant) | 29.31 | ± | 0.90 | 5.99 | 1.707 | 0.64 | 1.98 |
| 3 | | ± | | | | | |
| 4 | 29.05 | ± | 1.34 | 7.20 | 1.71 | –0.25 | 5.27 |
| 5 | | ± | | | | | |
| 6 | 29.37 | ± | 1.35 | 6.93 | / | 0.85 | 5.30 |
| 7 | 29.84 | ± | 1.27 | 5.81 | 1.71 | 2.46 | 5.06 |
| 8 (control participant) | 28.79 | ± | 1.20 | 5.71 | 1.710 | –1.14 | 3.37 |
| 9 | 30.00 | ± | 1.22 | 0.99 | 1.71 | 3.01 | 4.92 |
| 10 | 29.19 | ± | 1.29 | 5.90 | 1.71 | 0.23 | 5.12 |
| 11 | 28.84 | ± | 1.27 | 5.96 | 1.71 | –0.97 | 5.06 |
| 12 | 28.62 | ± | 1.40 | 6.58 | 1.71 | –1.73 | 5.45 |
| 13 | 30.20 | ± | 1.53 | 9.77 | 1.71 | 3.70 | 5.85 |

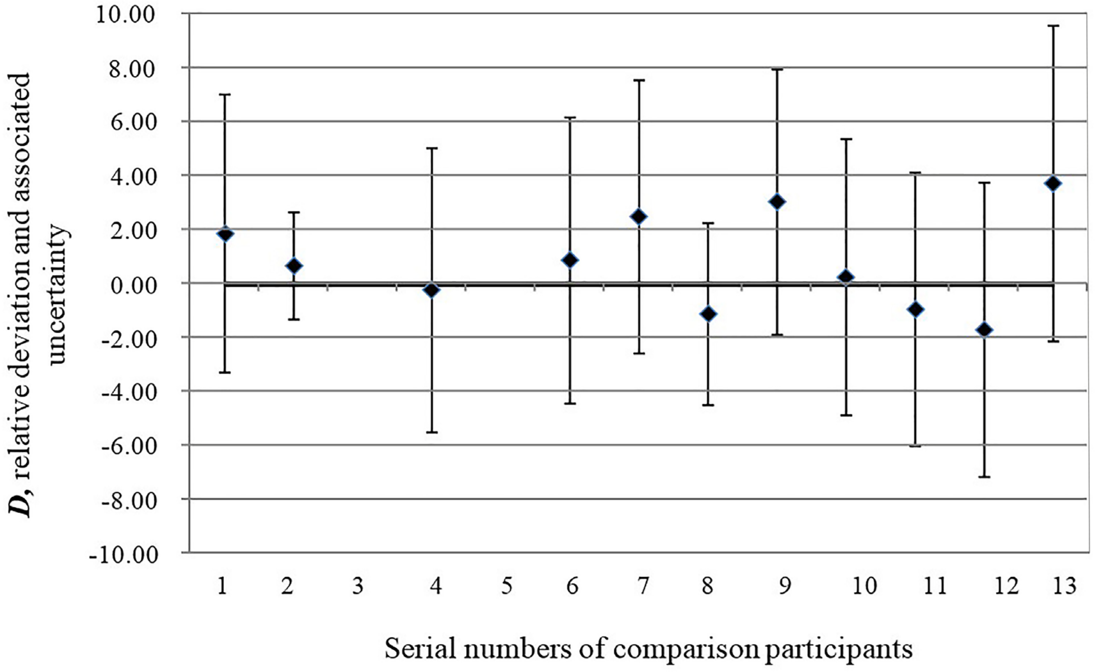

Fig. 2. Relative degrees of equivalence for the radiative quality of N-100

### Comparison results for high-energy X-ray beams with a peak energy of around 200 keV (N-200)

The results obtained and calculated by the NSC "Institute of Metrology" are presented in Table 5. The comparison results for the radiation quality N-200 are presented in Table 6. The uncertainties shown in the Tables are expanded uncertainties with a coverage factor of $k$=2. For the purposes of this comparison, the uncertainty reported by a participant is considered confirmed if the following statement is true: $|D_i| \leq U(D_i)$ [7].

Fig. 3 shows a graphical representation of the results. If the uncertainty band for a specific result crosses the zero value of $D$, the uncertainty is considered confirmed.

As a reference value for the project, the average value, with the calculated uncertainty, among the primary measurement standard laboratories, was used, calculated according to equations (1–4) mentioned above:

$$\text{CRV} = (29.35 \pm 0.72)\ \mu\text{Sv/nC}\ (k=2),$$
$$U_{stab} = 0.19\ \mu\text{Sv/nC}\ (k=2).$$

Table 5

Results obtained by the NSC "Institute of Metrology"

| | | | |
|---|---|---|---|
| Radiation quality: | | | N-200 |
| Focus-detector-distance FDD (cm): | | | 200 |
| Field diameter (cm): | | | 34 |
| $K_{a,\text{ref}}$ (mGy/h): | | | 9.157 |
| $H^*(10)_{\text{ref}}$ (mSv/h): | | | 13.37 |
| $N_H$ (µSv/nC) (comparison result): | | | 30.354 |
| Reference $H^*(10)$ determination | | | |
| Uncertainties in this table are stated with $k$=1 | | | |
| Source of uncertainty | $u_{i,\text{A}}$ | $u_{i,\text{B}}$ | $u_{i,\text{C}}$ |
| Calibration coefficient of the national/reference measurement standard | 0.22% | 1.50% | 1.52% |
| Collected charge | 0.22% | 0.07% | 0.23% |
| 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, $H^*(10)$** | – | – | **2.52%** |
| Transfer chamber measurements | | | |
| Source of uncertainty | $u_{i,\text{A}}$ | $u_{i,\text{B}}$ | $u_{i,\text{C}}$ |
| Collected charge | 0.14% | 0.07% | 0.16% |
| Air density correction | – | 0.05% | 0.05% |
| Source to chamber distance | – | 0.14% | 0.14% |
| Other sources of uncertainty | – | – | – |
| **Combined uncertainty, $Q$** | – | – | **0.22%** |
| | | | |
| **Combined standard uncertainty, $N_H$** | $u = \sqrt{\sum_i \left(u_{i,A}^2 + u_{i,B}^2\right)}$ | | **2.53%** |

Table 6

Results of N-200 radiation quality comparison
(all uncertainties are reported with $k$=2)

| Participants | $N_H$ (µSv/nC) | | | $H^*(10)$ (mSv/h) | $h_k$ (Sv/Gy) | $D_i$ (%) | $U(D_i)$ (%) |
|---|---|---|---|---|---|---|---|
| 1 | 29.95 | ± | 1.32 | 6.02 | 1.46 | 2.03 | 5.16 |
| 2 (control participant) | 29.34 | ± | 0.90 | 5.97 | 1.46 | –0.05 | 1.93 |
| 3 | | ± | | | | | |
| 4 | | ± | | | | | |
| 5 | | ± | | | | | |
| 6 | 29.12 | ± | 1.34 | 6.64 | / | –0.80 | 5.22 |
| 7 | 29.79 | ± | 1.27 | 5.60 | 1.46 | 1.48 | 5.02 |
| 8 (control participant) | 29.38 | ± | 1.21 | 5.85 | 1.460 | 0.09 | 3.37 |
| 9 | 29.74 | ± | 1.21 | 1.30 | 1.46 | 1.31 | 4.84 |
| 10 | 29.20 | ± | 1.29 | 6.04 | 1.46 | –0.53 | 5.08 |
| 11 | 29.52 | ± | 1.30 | 5.95 | 1.46 | 0.56 | 5.10 |
| 12 | 29.63 | ± | 1.45 | 6.23 | 1.46 | 0.94 | 5.55 |
| 13 | 30.35 | ± | 1.54 | 13.37 | 1.46 | 3.39 | 5.83 |

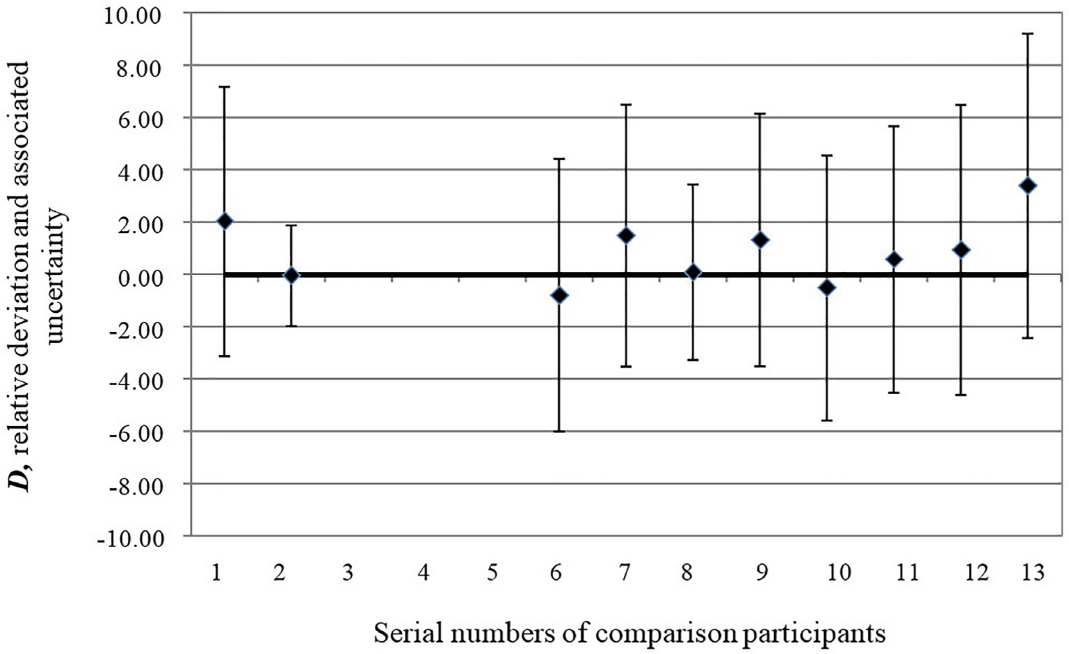

Fig. 3. Relative degrees of equivalence for the radiative quality of N-200

All comparison results for N-200 radiation quality are consistent within the reported measurement uncertainty.

## Conclusions

The conducted international comparison revealed some shortcomings and approaches for improving international cooperation and standardization in radiation dosimetry. A thorough review of the protocols of all the NMIs participating in this study and adjustments to the calibration protocols will further improve the reliability and validity of the calibration procedures. The project comprehensive approach to calibration, measurement accuracy, and statistical analysis has significantly advanced the field, providing a model for future initiatives. Continued application and improvement of the project procedures will ensure that dosimetric measurements remain the foundation of protection and safety from the exposure to radiation.

The participation in this project and the data obtained by the NSC “Institute of Metrology” compared to other participants indicate a probable presence of systematic error. These errors will be further studied and accounted for in subsequent works.

The harmonization of measurement practices and the development of standardized protocols have contributed to the global consistency of dosimetric measurements. These efforts ensure the comparability of measurements conducted in different laboratories, enhancing the reliability of dosimetric data used for regulatory and safety purposes.

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# Дослідження точності та достовірності дозиметричних вимірювань рентгенівських пучків з якістю випромінення N-40, N-100, N-200

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**Анотація**

Дозиметрія випромінювання є критично важливим аспектом медичних, промислових та наукових застосувань, що включають іонізуюче випромінювання. Точне вимірювання доз випромінювання забезпечує безпеку та ефективність радіологічних практик, що є надзвичайно важливим для захисту пацієнтів у медичних процедурах, безпеки в промислових застосуваннях та точності в наукових дослідженнях.

Провідні міжнародні організації проводять дослідження, направлені на підвищення точності вимірювань. Одним із методів, який використовується в цьому напрямку, є міжнародні проєкти. В одному з них узяв участь ННЦ “Інститут метрології”.

Міжнародний проєкт, до якого було залучено декілька національних метрологічних інститутів (NMI), мав на меті підвищити точність та узгодженість дозиметрії випромінювання по всій Європі. Стандартизуючи методики вимірювання та процедури калібрування, проєкт прагнув удосконалити систему для вимірювання доз випромінювання, тим самим підвищуючи надійність дозиметрії іонізуючого випромінювання.

Цей проєкт є особливо значущим з огляду на постійне збільшення використовуваних технологій, заснованих на випромінюванні, у різних сферах. Наприклад, високоточне вимірювання іонізуючих величин є важливим у медичній галузі, особливо в радіотерапії, щоб пацієнти отримували необхідну дозу з мінімальним опроміненням навколишніх здорових тканин. Аналогічно, у промисловій радіографії точна дозиметрія є важливою для виконання стандартів безпеки та запобігання перевищенню дози опромінення працівників.

Міжнародний проєкт, у якому Фізико-технічний федеральний інститут (PTB, Німеччина) та Головне управління мір (GUM) брали участь як провідні організації для підвищення рівня контролю, ставив за мету поліпшити ключові фактори в дозиметрії іонізуючого випромінювання. Серед них – розробка надійних протоколів калібрування для різних типів випромінювання, встановлення ланцюгів простежуваності для забезпечення точності вимірювань та поширення найкращих методів дозиметрії серед учасників проєкту. Для цього були проведені попередні звірення між NMI, в яких були два контрольних учасники як опорні, інші NMI брали участь анонімно (знали тільки свій номер та номери опорних учасників). Кожен з учасників мав змогу звірити отримані значення з контрольними значеннями та внести корективи для участі в подальших звіреннях. Такий формат співпраці також сприяв обміну знаннями та досвідом, стимулюючи інновації та вдосконалення в техніках дозиметрії.

Від України в цьому проєкті активну участь узяв ННЦ “Інститут метрології” як провідна організація з метрології в галузі іонізуючого випромінювання. У статті наведені результати міжнародних звірень для рентгенівських пучків з якістю випромінення N-40, N-100, N-200.

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

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