Radiation Measurements 197 (2026) 107750

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Analysis of EURADOS Intercomparison IC2023calib results: $H^*(10)$ irradiation of passive area dosemeters

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ARTICLE INFO

Keywords:
EURADOS
Area dosimetry
Passive dosemeter
Dosemeter calibration
Ambient dose equivalent

ABSTRACT

The EURADOS calibration inter-laboratory exercise called IC2023calib was carried over the year 2023 with the participation of 24 calibration laboratories from 17 different countries. A total of 614 passive area dosemeters from the dosemeter providing laboratory (IRSN, France) were irradiated by the participants in terms of ambient dose equivalent $H^*(10)$ or used as background dosemeters. The irradiation laboratories could choose to participate with one, two, three or four of the proposed standard radiation qualities (N-30, N-150, S-Cs, S-Co). The aim of this article is to analyse the results of this comparison exercise. Mean relative deviation to the reference laboratory (PTB, Germany) was used to evaluate their performance. Participants' results were satisfactory is most cases. The exercise also provided information on the current calibration methodologies throughout Europe.

1. Introduction

The European Radiation Dosimetry Group, EURADOS (www.EURADOS.org), is a network of 83 European institutions from more than 30 (mostly) European countries. EURADOS' activities are performed in Working Groups (WG) and, in particular, Working Group 3 (WG3) carries out research projects and coordinated activities within the field of area dosimetry. Complementary to the use of active dosimetry or spectrometry systems, passive area dosimetry systems are widely used and within WG3 there is a subgroup, WG3 SG2 - Passive environmental dosimetry, which addresses this topic. Passive area dosemeters are used for workplace monitoring and in environmental radiation monitoring of nuclear, research, medical or industrial facilities, providing ambient dose equivalent, $H^*(10)$, measurement results. In environmental dosimetry passive systems are used for long-term monitoring of public areas or e.g. surrounding areas of nuclear installations with corresponding low dose limits (e.g. 1 mSv per year) or even lower regulated dose constraints (e.g. 0.3 mSv per year for photon radiation emitted by a nearby facility).

Currently, the main aims of EURADOS WG3-SG2 are the harmonization of passive area dosimetry within Europe and the organisation of comparison exercises of passive dosemeters used in workplace and environmental radiation monitoring. The initial task of SG2 provided an overview of passive dosimetry practices in Europe (Duch et al., 2017; Duch et al., 2021) and the group organised several intercomparisons in the past (Dombrowski et al., 2017; Dombrowski, 2019; Ruehm et al., 2019, Hranitzky et al., 2022). In previous EURADOS exercises Cs-137 was used to carry out irradiations to check both the capabilities of the dosimetry services to measure low doses above natural background and the calibration of the systems, as Cs-137 is the reference for most area dosimetry services. Besides this kind of exercises, which focused in the measuring capabilities, the calibration of the dosimetry system is an element of utmost importance for an appropriate dose assessment.

Regarding calibration procedures, several comparisons have been organised by EURAMET for National Metrology Institutes (NMI) and Designated Institutes (DI) in terms of $H^*(10)$ (Živanović et al., 2023; Hupe and Díaz, 2018) but there is a need for comparisons for other dosimetry laboratories that perform calibrations of passive dosemeters. The usual procedure in calibration laboratories involves a standard instrument for the air kerma, K_a, free-in-air measurements and then applying the appropriate conversion coefficients to calculate $H^*(10)$, as specified in ISO 4037-3 (ISO 4037-3, 2019c). When EURADOS WG3-SG2 decided to organise a comparison exercise on this topic in 2023, called IC2023calib, a new version of the standard for calibrating dosemeters,

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https://doi.org/10.1016/j.radmeas.2026.107750
Received 5 February 2026; Received in revised form 4 June 2026; Accepted 9 June 2026

ISO 4037 (ISO 4037-1, 2019a; ISO 4037-2, 2019b; ISO 4037-3, 2019c), had recently been released. All parts of this standard were updated from a previous version after a time period of more than 20 years (ISO 4037-1, 1996; ISO 4037-2, 1997; ISO 4037-3, 1999). It can be expected that some laboratories were still using the old version of the standard.

ISO 4037-1:2019 introduced significant changes for the X-ray radiation qualities, in particular, two types of reference fields were defined: characterised and matched radiation fields. For matched radiation fields there are quite strict requirements (tube potential, filtration, HVL …) allowing the use of tabulated conversion coefficients recommended in ISO 4037-3 (ISO 4037-3, 2019c). Conversely, for characterised reference fields the requirements on some parameters are more flexible, but the appropriate conversion coefficients must be determined individually, e. g. by spectrometry. Especially for low photon energy X-ray radiation spectra the conversion coefficients are influenced by small differences in the energy distribution of the beam (Alberts et al., 1995). Hence, for laboratories carrying out calibrations using characterised fields, the comparison of their methodology is of particular interest. The new version also modified the recommended value of the conversion coefficients for several radiation qualities (ISO 4037-1, 1996c; ISO 4037-3, 2019c), however in most cases the change was smaller than the uncertainty of the conversion coefficient.

The objective of this article is to analyse the results of the IC2023calib comparison exercise. Available data on the adoption of the new version by the calibration laboratories are limited to NMIs and DIs (Živanović et al., 2023) and the proposed EURADOS exercise could also serve to provide information on the use of the new standard by secondary standard dosimetry laboratories and other irradiation entities.

2. Methodology

Technical requirements for passive area dosimetry systems for area dosimetry are specified in ISO 62387:2020 (IEC 62387, 2020). According to this standard the mandatory mean photon energy range is 80 keV to 1.25 MeV, the maximum mean energy range for testing photon radiation is 12 keV up to 7 MeV. The Organisation Group (OG) selected four qualities to cover both low- and medium-energy X-ray qualities and high energy radiation beams: N-30 (mean energy 24.6 keV) and N-150 (mean energy 118 keV) and two gamma radiation qualities: S-Cs (661.7 keV) and S-Co (1173.3 and 1332.5 keV). Each participating laboratory irradiated the same type of dosemeters. The reported dose values of the irradiated dosemeters were compared with the measured dose values based on the calibration irradiation by the reference laboratory, the Physikalisch-Technische Bundesanstalt (PTB), see sections 2.3, 2.4 and 2.5. In addition, the participants were asked by the OG to provide information about their calibration procedure, the irradiation conditions and the uncertainties of the irradiated dose values. The irradiation laboratories could choose to participate with one, two, three or four of the proposed radiation qualities.

2.1. Irradiation conditions

The target ambient equivalent dose value chosen by the OG was 10 mSv to ensure that the influence of transport/background radiation was negligible. Participants were given specific instructions regarding the irradiation conditions to avoid systematic influences on the response of the dosimetry system: the radiation dose had to be between 9.5 mSv and 10.5 mSv in order to limit the possible non-linearity effects, irradiation had to be performed within a strict time schedule to minimize fading influences. The participants also received recommendations for performing the irradiations under the same conditions used by the reference laboratory: for the gamma radiation qualities, S-Cs and S-Co, a setup with a 3 mm PMMA build-up plate directly in front of the dosemeters was recommended, in accordance with ISO 4037. For the x-ray qualities it was recommended to irradiate each dosemeter separately, whilst for gamma irradiations two dosemeters at a time. In all cases the irradiations should be performed free in air.

Each participant received:

- 6 dosemeters to be irradiated per radiation quality;
- 5 background dosemeters not allowed to be irradiated and used for background subtraction;
- At least 2 spare dosemeters to be used in case of wrong irradiations.

2.2. Transfer dosemeter

The dosimetry service of the Institute for Radiation Protection and Nuclear Safety (IRSN, at present CEA dosimétrie) was chosen as the provider of area dosemeters. The service is accredited by COFRAC to conduct measurements of ambient dose equivalent $H^*(10)$ according to the requirements of standard ISO 17025 (ISO/IEC 17025, 2017), and traceable to IRSN standards. The dosemeters are based on radiophotoluminescence (RPL), a property of silver-activated phosphate glass. The main characteristics of the dosimetry system are:

- Photon energy and angular range: 24 keV-6.6 MeV, −60° to +60°
- Linearity range: 0.04 mSv-10 Sv

The objective was to keep the statistical uncertainty of the mean of measurements below 0.5 % in order to minimize the uncertainty related to the use of the passive dosemeter. The dosemeter laboratory distributed the dosemeters to the participants and simultaneously to the reference laboratory and finally performed the readout of all the dosemeters. The corresponding measurement values M provided by IRSN to the OG did not include any energy corrections nor background subtractions, since all calculations were to be managed by the OG. The systematic influences of the irradiations on the response of the dosimetry system were considered negligible assuming similar irradiation conditions of the participants compared with the reference laboratory.

2.3. Reference values

The Physikalisch-Technische Bundesanstalt (PTB), primary standards dosimetry laboratory and National Metrology Institute of Germany, volunteered to perform the reference calibration irradiations. PTB provided 10 (k = 1 to n = 10) measurement values per radiation quality (i), and 10 background readings. From the measurements of the irradiated dosemeters ($M_{i,k}$) reported by the IRSN, the OG calculated the average net value by subtracting the average background, ($\overline{M}_{bkg}$), using equation (1):

$$\overline{M}_{\mathrm{ref\ i}} = \frac{\sum_{k=1}^{n}\left(M_{i,k} - \overline{M}_{bkg}\right)}{n} \tag{1}$$

The reference calibration factors ($N_{\mathrm{ref\ i}}$) for each of the four radiation qualities were calculated by the OG as the ratio of the PTB reported ambient dose equivalent values ($H_{\mathrm{irr\ ref\ i}}$) and the corresponding mean net results ($\overline{M}_{\mathrm{ref\ i}}$), equation (2).

$$N_{ref\ i} = \frac{H_{irr\ \ ref\ i}}{\overline{M}_{ref\ i}} \tag{2}$$

The relative combined standard uncertainty of the reference calibration factors ($N_{\mathrm{ref\ i}}$) was calculated in accordance with GUM (JCGM 100, 2008):

$$u^{'}\left(N_{ref\ i}\right) = \sqrt{u^{'2}\left(\overline{M}_{\mathrm{ref\ i}}\right) + u^{'2}\left(H_{\mathrm{irr\ ref\ i}}\right)} \tag{3}$$

Where $u^{'}\left(\overline{M}_{\mathrm{ref\ i}}\right)$ values, type A evaluation of uncertainty, were calculated as the relative statistical uncertainty of the mean net dosemeter indications for each quality. $u^{'}\left(H_{\mathrm{irr\ ref\ i}}\right)$ were the uncertainty values reported by the reference laboratory, type B evaluation of uncertainty.

The uncertainty contribution of the background was not included due to the comparatively low mean background dose value (0.12 mSv).

2.4. Participant's values

Each participant filled in a Microsoft Excel spread sheet protocol for each radiation quality and reported the irradiation conditions, the dosemeter numbers and the corresponding ambient dose equivalent values of the irradiations as well as the associated relative standard uncertainty with coverage factor $k = 1$ by the specified measurement protocol.

For each quality (i) and participant (j) the following calculations were performed:

From the measurements ($M_{i,j,k}$) of the irradiated dosemeters (k) of each participant reported by IRSN, the average net value was calculated by subtracting the average background, ($\overline{M}_{bkg}$), using equation (4), that includes the normalization to the mean irradiated dose value ($\overline{H}_{\text{irr i,j}}$) of the irradiated dosemeters (necessary in case of unequal reported ambient dose equivalent values). The participant's measured ambient dose equivalent values ($H_{\text{meas i,j}}$) were consecutively calculated using the reference calibration factor (Equation (5)).

$$\overline{M}_{\text{meas i,j}} = \frac{\sum_{k=1}^{n}\left(M_{i,j,k} - \overline{M}_{bkg}\right)\cdot\frac{\overline{H}_{\text{irr i,j}}}{H_{\text{irr i,j,k}}}}{n} \tag{4}$$

$$H_{\text{meas i,j}} = N_{\text{ref,i}}\cdot\overline{M}_{\text{meas i,j}} \tag{5}$$

$$u'\left(H_{meas\ i,j}\right) = \sqrt{u'^2\left(N_{\text{ref i}}\right) + u'^2\left(\overline{M}_{\text{meas i,j}}\right)} \tag{6}$$

The relative combined standard uncertainty of the results was calculated according equation (6), where $u'^2\left(\overline{M}_{\text{meas i,j}}\right)$ values were calculated as the relative statistical uncertainty of the average, type A evaluation of uncertainty, and $u'\left(N_{ref\ i}\right)$ values were the relative combined standard uncertainty values of the reference calibration factors, calculated according equation (3). The uncertainty contribution of the subtracted average background was not included due to the comparatively low background dose values < 0.2 mSv for all participants, even for those from outside Europe. The uncertainty contribution associated to the normalization to the mean irradiated dose value was also disregarded. For participants with traceability to the reference laboratory the total uncertainty may be reduced due to correlations in the calibration factor but this analysis was outside the scope of this interlaboratory exercise.

2.5. Evaluation of the participant's performance and acceptance criteria

In this article the degree of equivalence of the participant's irradiated ambient dose equivalent values to the measured values for each quality *(i)* and participant (j) was expressed by the relative deviation ($D_{i,j}$) in percentage (Equation (7)). It was derived from the mean ambient dose equivalent ($\overline{H}_{\text{irr i,j}}$) values reported by the participants and the mean measured ambient dose equivalent ($\overline{H}_{\text{meas i,j}}$) both calculated as arithmetic mean values.

$$D_i(\%) = 100\cdot\left(\frac{\overline{H}_{\text{irr i,j}} - \overline{H}_{\text{meas i,j}}}{\overline{H}_{\text{meas i,j}}}\right) = 100\cdot\left(\frac{\overline{H}_{\text{irr i,j}}}{\overline{H}_{\text{meas i,j}}} - 1\right)\ \% \tag{7}$$

The robust average of relative deviation ($D_{i,j}$) values was also calculated for each quality according to Annex C of ISO 13528, algorithm A with iterated scale (ISO 13528, 2022). However, the OG did not define maximum permissible values of the relative deviations but a criterion related to the expanded ($k = 2$) uncertainty.

The uncertainty of the relative deviation ($D_{i,j}$) has been calculated according to equation (8):

$$u(D_{i,j}) = 100\cdot\sqrt{\left(\frac{1}{\overline{H}_{\text{meas i,j}}}\cdot u\left(H_{\text{irr i,j}}\right)\right)^2 + \left(\frac{\overline{H}_{\text{irr i,j}}}{\overline{H}_{\text{meas i,j}}{}^2}\cdot u\left(\overline{H}_{\text{meas i,j}}\right)\right)^2}\ \% \tag{8}$$

Where $u\left(\overline{M}_{\text{meas i,j}}\right)$ values were calculated from equation (6):

$$\text{u}\left(\overline{M}_{\text{meas i,j}}\right) = u'\left(\overline{M}_{\text{meas i,j}}\right)\cdot\overline{M}_{meas\ i,j} \tag{9}$$

$u\left(H_{\text{irr i,j}}\right)$ were the uncertainty values of the ambient dose equivalent values reported by the participants.

3. Results and discussion

24 laboratories from 17 countries took part in the intercomparison. Two of the participants came from distant countries (United Arab Emirates and Japan) in which case higher transport dose contributions were expected. One participant (in all four qualities) was not able to return the dosemeters in due time due to customs problems and therefore their results were not included. A total of 614 passive area dosemeters were irradiated or used as background dosemeters.

3.1. Calibration methodologies

Fig. 1 shows for the x-ray qualities whether the radiation beams of the participants were matched or characterised fields according to ISO 4037-1:2019. For N-150, 50 % of the laboratories stated to have matched fields, 31 % characterised fields, and the remaining 19 % stated to be compliant with the former version ISO 4037:1996. The results can be compared to the information gathered in a recent EURAMET comparison (Živanović et al., 2023), a supplementary comparison in terms of the ambient dose equivalent rate organized as a part of the DOSEtrace project, between 13 NMIs and DIs. In this exercise the mandatory radiation qualities were N-40, N-100 and S-Cs, additional qualities were N-200 and S-Co. According to their reported information, 46 % or the participants used the old version, 39 % declared matched fields and only 15 % characterised fields, values quite similar to those obtained for the laboratories participating in our exercise for N-150. In contrast, for N-30 only 27 % of participants stated to have matched fields, 36 % characterised fields, 27 % compliant with ISO4037:1996, and one participant indicated to have a non-standard radiation quality.

Concerning the air kerma to ambient dose equivalent conversion coefficients, $h_K^*(10)$, for the low-energy N-30 x-ray quality the range of the applied conversion coefficients was 0.800 - 0.826 Sv/Gy. According to ISO 4037-3, the corresponding matched field recommended conversion coefficient is 0.810 Sv/Gy (at 1 m calibration distance) and 0.814 (at 2.5 m calibration distance), hence, the use of a different conversion coefficient could influence the result up to a maximum of a 2 %. For the N-150 X-ray radiation quality and for Cs-137 and Co-60 gamma radiation, almost all participants used the ISO 4037-3 (ISO 4037-3, 2019c) tabulated conversion coefficients, i.e. 1.58 Sv/Gy (N-150), 1.21 Sv/Gy (S-Cs) and 1.16 Sv/Gy (S-Co), respectively. One participant used an alternative method with a directly $H^*(10)$ calibrated ionization chamber.

Regarding the use of the 3 mm PMMA build-up plate recommended by ISO 4037 for Cs-137 and Co-60 gamma radiation, as expected, the majority of the participating laboratories (80 %) reported the use of the recommended 3 mm PMMA plate, however some participants still use different thicknesses of PMMA plates (from 2 mm to 8 mm-thick plates). The previous version of the ISO 4037 standard recommended two different PMMA build-up plate thicknesses, 2 mm for Cs-137 and 4 mm for Co-60. This may explain the different thickness values currently used by the laboratories.

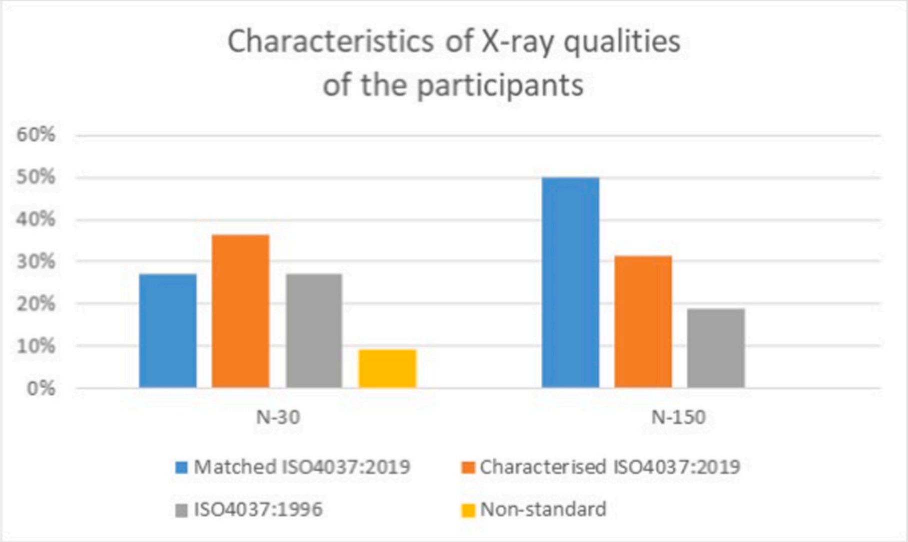

Fig. 1. Characteristics of the participants' reported x-ray radiation qualities.

3.2. Comparison results

Regarding the reference calibration factors, $u'(\overline{M}_{\text{ref i}})$ uncertainty values were in all cases below 0.1 % (coverage factor k = 1). Subsequently the calculated relative combined standard uncertainty (equation (3), coverage factor k = 1) for X-ray qualities was dominated by the PTB reported uncertainty, i.e. 2 %, and 1.5 % for S-Cs and S-Co qualities respectively.

Figs. 2–5 show the results in terms of the relative deviation *D* in sorted order. Relative deviation diagrams include individual combined standard uncertainty bars (coverage factor k = 2). Table 1 provide further details on the comparison. The statistical uncertainty contribution of the 6 RPL readings per participant was generally low, below 0.2 %, so the passive area dosemeters from IRSN did not influence the total uncertainty in the results.

For the low energy radiation quality N-30 the relative deviations of the participants are between −1.7 % and +37.1 % (robust mean + 1.3 %) and 2.5 % was the median of participant's irradiation uncertainties (coverage factor k = 1). As previously stated, for N-30 only 27 % of participants stated to have matched fields, 36 % have characterised fields, 27 % compliant with ISO4037:1996. One participant indicated to have a non-standard radiation quality and reported a high uncertainty (10 %, k = 1) compared to the median value of all participants (2.5 %, k = 1). As expected, no significant differences were observed among the results from laboratories that have characterised, matched or compliant with the previous version of the standard. However, the maximum

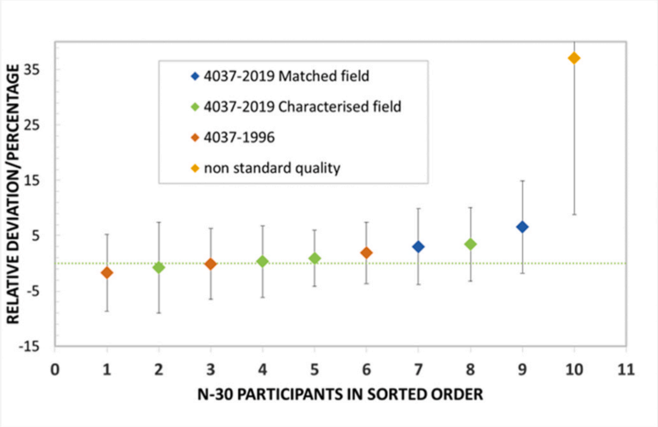

Fig. 2. N-30 results in terms of relative deviation (uncertainty bars, coverage factor k = 2).

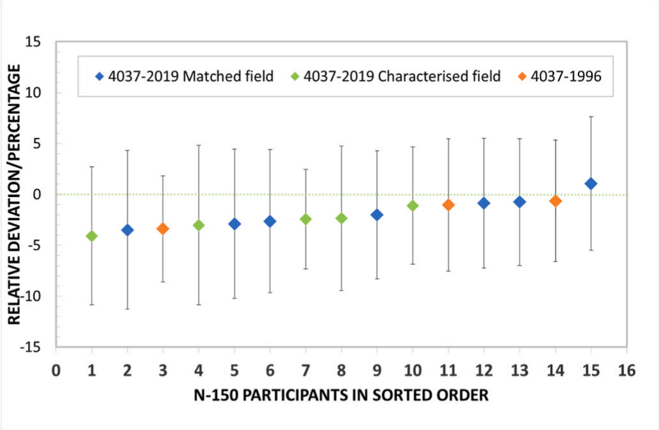

Fig. 3. N-150 results in terms of relative deviation (uncertainty bars, coverage factor k = 2).

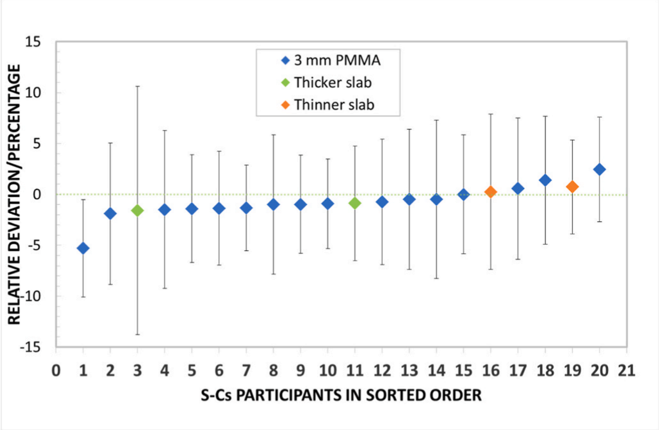

Fig. 4. S-Cs results in terms of relative deviation (uncertainty bars, coverage factor k = 2).

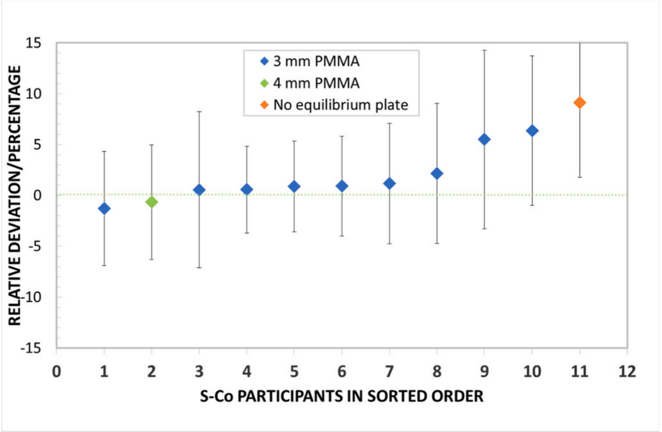

Fig. 5. S-Co results in terms of relative deviation (uncertainty bars, coverage factor k = 2).

Table 1

Median values of the statistical uncertainty of the mean net readings; participant's irradiation uncertainties (coverage factor k = 1), range and median; robust average and median uncertainty (coverage factor k = 1) of the relative deviations.

Quality	Number of participants	$u'(\widetilde{\overline{M}_{\mathrm{meas}}})$/%	$u'(H_{\mathrm{irr}})$/%		$\overline{D}$/%	$\widetilde{u(\overline{D})}$/%
			Range	Median		
N-30	10	0.2	1.5-10	2.5	1.3	3.2
N-150	15	0.2	1.5-3.5	2.5	2.0	3.3
S-Cs	20	0.2	1.5-6	2.5	0.6	2.9
S-Co	11	0.2	1.5-3.5	2.5	1.4	2.9

relative deviation observed (+37.1 %) corresponds to the laboratory with a non-standard quality. For the other participants the results agree well within the criterion $2{\cdot}u(D)$.

Regarding N-150, the relative deviations of the participants ranged from −4.1 % up to +1.1 % (robust mean −2.0 %). No significant differences were observed among the results from laboratories that have characterised, matched or compliant with the previous version of the standard and all results agree well within $2{\cdot}u(D)$. Interestingly, the majority of reported values were below the reference dose value, but conclusions regarding the PTB reference value and the traceability of the participants would need further investigation. Fig. 4 shows the results for the most widely used S-Cs radiation quality. The relative deviation calculated values are between −5.3 % and +2.5 % (robust mean −0.6 %). No significant differences were observed among the results from laboratories that used PMMA plates of different thicknesses. The results agree well within $2{\cdot}u(D)$ except for one laboratory. For this participant (#1) the result is very close to $2{\cdot}u(D)$, which can be interpreted as a warning. One participant (#3) reported a greater uncertainty (6 %, k = 1) compared to the median value of all participants (2.5 %) suggesting a review of its uncertainty assessment.

As can be seen in Fig. 5 for the Co-60 radiation quality, the calculated relative deviation values are between −1.3 % and +9.1 % (robust mean + 1.4 %). The highest deviation of a laboratory (#11) is because it is routinely irradiating active dosemeters without any secondary electronic equilibrium build-up plate. The significant difference is highlighting the need to follow the international recommendations. The results of the other participants agree well within $2{\cdot}\ u(D)$. A detailed EURADOS report including all available data will be prepared.

4. Conclusions

The IC2023calib intercomparison was successfully carried out for all but one participant who was not able to return the dosemeters in due time due to customs problems. The information provided by the participant's allowed to analyse the degree of adoption of ISO4037:2019 as well as the use of the reference field types (matched/characterised) among laboratories that provide calibration services in terms of $H^*(10)$. Regarding the comparison results in terms of relative deviations (D), in most cases the participant's results were acceptable (within the $2{\cdot}u(D)$ criterion), unacceptable results were linked to the use of non-standard qualities or not following the standard ISO 4037 recommendations, highlighting the need for standardisation. The results obtained within the IC2023calib comparison series are important not only for the quality assurance systems of the participants but also for the European harmonization of calibration methods of passive dosimetry systems and contribute to build confidence in the metrology network. The use of passive dosemeters as compared to ionization chamber transfer standards is also of interest for other dosimetry networks e.g. EURAMET and future intercomparisons.

CRediT authorship contribution statement

Maria A. Duch: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Christian Hranitzky:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Christian Naber:** Conceptualization, Methodology, Project administration, Writing – review & editing. **Julia Aslan:** Methodology, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been performed by the IC2023calib intercomparison organization group within the scientific network of EURADOS notably within WG3 SG2 “Passive Environmental Dosimetry”. The authors thank all EURADOS working group members and intercomparison participants for their interest and feedback with special thanks to the colleagues from IRSN and PTB for the collaboration.

Data availability

The data that has been used is confidential.

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