
CCRI(I)-P12

Comparison of absorbed dose to water standards for high-energy electron beams using alanine dosimeters as transfer standards

PILOT STUDY

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M. McEwen *et al* 2026 CIPM MRA Comparison reports 06017

<https://doi.org/10.59161/KKRD7876>

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A comparison of absorbed dose to water standards for high-energy electron beams using alanine dosimeters as transfer standards.

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Abstract

A comparison of therapy-level electron beam absorbed dose to water standards was carried out using alanine as the transfer dosimeter. Participants were LNHB, France, KRISS, Korea and NRC, Canada with the BIPM providing reference Co-60 irradiations to realize a Key Comparison Reference Value (KCRV) in the absence of a BIPM primary standard for electron beams. The alanine system used was that of the NRC, and steps were taken to completely separate the alanine read-out from the alanine irradiations at NRC, to ensure independence of the two steps. Irradiations were carried out in 2023 and final data was received in 2024.

All three participants agreed with the KCRV within 1.1 parts in 10^2 , with combined standard uncertainties in the range 0.9 to 1.6 parts in 10^2 . The two calorimetric standards of the LNHB and NRC agreed, on average, at the level of 1 part in 10^3 . Further work is required to confirm the KCRV for linking comparisons at different times.

1. Introduction

Alanine has been used in reference dosimetry for several decades, initially for dosimetry at industrial processing levels (i.e., in the delivery of kGy doses, [Regulla and Deffner, 1982; ISO, 2013]) and, more recently for radiation therapy dosimetry (where the dose delivered is around 10 Gy [Anton, 2005; Sharpe and Sephton, 2006; Gago-Arias *et al.*, 2015]). Alanine has demonstrated value as an audit dosimeter, providing reduced uncertainties compared to other chemical or solid-state integrating dosimeters [Thomas *et al.*, 2003; Budgell *et al.*, 2011]. Over the last decade or so, the viability of alanine forming the basis of a transfer standard dosimeter for international comparisons at radiation therapy dose levels has been investigated [Garcia *et al.*, 2012]. Such comparisons are typically carried out using high-precision, high-stability ionisation chambers but there are several challenges with this approach when multiple participants are involved in a comparison:

- i) ionisation chambers are sensitive detectors and improper handling and/or transport can lead to equipment failure. Such a failure in the middle of a comparison has the potential to significantly increase the uncertainty of any results (even eliminating participant

measurements) or extending the duration of the comparison to allow for repeat measurements with new detectors.

ii) ionisation chambers are costly devices and this can lead to problems with import/export procedures. Empirical evidence indicates delays of several months are possible with associated costs related to import duties or the complete rejection of a shipment.

Alanine dosimeters are low cost, can be shipped more easily (e.g., no ATA Carnet required) and easily replaced if lost, damaged or destroyed. In addition, the dosimeter only travels between the pilot (hosting) laboratory and a single participant, so there is not the same 'increasing value' (and associated increasing risk) aspect that an ionisation chamber acquires as it proceeds through a comparison.

The disadvantage of alanine dosimetry is that the Type A uncertainties cannot match those of an ion chamber. Although the overall uncertainty of alanine dose measurements can approach that of ion chamber dosimetry in clinical measurements [McEwen *et al.*, 2014; IAEA, 2024], the increased Type A uncertainty – 0.2 % for alanine compared to 0.05 % or less for ion chambers – could limit the information that can be extracted from a comparison that uses alanine as the transfer.

Based on the positive experience gained in previous testing [McEwen *et al.*, 2015], a proposal was made to the CIPM Consultative Committee on Ionizing Radiation (CCRI) that alanine dosimetry could be used to facilitate a Key Comparison for electron beam dosimetry, and so accelerate the adoption of primary standards of absorbed dose to water for high-energy electron beams (i.e., 4 MeV and above) at radiation therapy dose levels. In 2023, a pilot study was initiated between three primary standards dosimetry laboratories to test a comparison protocol and evaluate the overall uncertainties of such an approach.

2. Details of alanine dosimetry system

The NRC alanine dosimetry system was proposed for this comparison. It has been developed over the last 8 years and is described in detail in McEwen *et al.* (2025). As part of validating the alanine capability, a comparison was carried out with the NPL [McEwen *et al.*, 2019] and it was tested as an audit dosimeter, the latter requiring a protocol similar to that required for an international comparison.

The NRC system uses alanine pellets supplied by Harwell Dosimeters (Harwell, UK). The manufacturer provides the following information:

Table 1: Properties of alanine dosimeters

Material	A white cylindrical pellet of alanine in a wax binder. 90.9% Amino acid L-alpha alanine 9.1% Paraffin wax
Dimensions	Diameter: 4.8 mm ± 0.1 mm Height: 2.8 mm ± 0.1 mm Mass: 60 mg ± 2 mg within the overall batch, (standard deviation 0.3 mg within a specific lot)

3. Participants

Table 2 indicates the comparison participants and provides details on the basis for the determination of absorbed dose to water for high energy electron beams. More details on the uncertainties quoted here can be found in Appendix A.

Table 2: Summary of absorbed dose to water standards at participant laboratories

Institution	Country	Reference field	Standard of absorbed dose to water in high energy electron field	Nominal dose rate (Gy min ⁻¹)	<i>u</i> (%) [†]	Reference
LNHB	France	High-energy electron beam from linear accelerator: Varian TrueBeam	Water calorimeter	4	0.5	Rapp (2019)
KRISS	South Korea	High-energy electron beam from linear accelerator: Elekta Synergy [®] Platform	Ionisation chamber calibrated in Co-60 combined with protocol [§]	4	1.3	Agassy <i>et al</i> , 2025
NRC	Canada	High-energy electron beam from linear accelerator: Elekta Precise	Water calorimeter	5	0.4 to 0.6	Muir <i>et al</i> , 2017 Surensen, 2022
BIPM		Co-60 irradiator	Primary standard ionisation chamber [†]	0.2	0.2	Kessler and Burns (2024), Burns and Kessler (2018)

[†] This is just the uncertainty of the standard, not the irradiation procedure.

[§] KRISS used the modified TG-51 formalism by Muir [2020], which dispenses with a positional shift for the ionisation chamber effective point of measurement.

[†] Irradiations in Co-60 combined with a consensus conversion factor from Co-60 to high energy electrons [McEwen *et al*, 2020] provides the reference irradiations to make the alanine dosimetry independent of the NRC primary standard. It also enables a direct link to the BIPM Key Comparison BIPM.RI(1)-K4 (www.bipm.org/kcdb).

4. Key Comparison Reference Value

Since there is currently no Key Comparison for absorbed dose to water in high-energy electron beams and no primary standard operated at the BIPM, the default option for defining the KCRV – taking the BIPM value of the quantity of interest as the reference in any comparison – was not

available. However, it was concluded that a KCRV could be provided by the BIPM through irradiations in a Co-60 reference field and the application of a consensus-developed conversion factor [McEwen *et al.*, 2020] to yield an equivalent absorbed dose in an electron beam. Choosing this KCRV provides a stable basis for future electron beam comparisons, independent of the number of participants or the development of their specific primary absorbed dose standards, and is similar to the approach taken for BIPM.RI(I)-K8 (bipm.org/kcdb). It also provides separation in activities if an NMI/DI is the source of the alanine transfer dosimeters and is also participating in the comparison (similar to the protocol for CCRI(I)-S3 (bipm.org/kcdb)).

5. Comparison procedures

5.1 Comparison protocol

The following protocol was used for the comparison. The primary features are i) irradiation in water, ii) use of hermetically-sealed dosimeters to reduce impact of transport and handling, and iii) adoption of a cylindrical geometry for the alanine dosimeters. In regard to the latter, it is common to use a disk geometry for electron beams [Zeng *et al.*, 2005], but a number of investigations have indicated that a cylindrical geometry would not negatively impact measurements down to 6 MeV [McEwen *et al.*, 2006; Vörös *et al.*, 2012].

- i. A hermetically-sealed holder containing six alanine pellets (hereafter referred to as the “dosimeter”) was developed to mitigate the effect of environmental changes, since humidity, in particular, can affect the alanine free-radical signal. The holder is made out of Delrin® (polyoxymethylene, POM) and is designed to replicate the outer dimensions of a Farmer-type ionisation chamber. The central axis of the dosimeter is defined to be the point of measurement and this is to be placed at the reference depth where the absorbed dose is determined.
- ii. The energy range of interest is that of clinical electron beam radiation therapy. International Dosimetry Protocols generally cover energies from 4 MeV to 25 MeV but the use of cylindrical dosimeters meant that the energy range is limited to 6 MeV and above. To reduce the number of beams investigated, the energy range is limited to 6 MeV to 18 MeV.
- iii. Each participant receives sufficient dosimeters to perform irradiations in a minimum of 3 electron energies. Dosimeters are to be irradiated to a nominal dose of 25 Gy, with irradiations performed in a water phantom. All irradiations (except those at the BIPM) must be completed using a clinical linear accelerator.
- iv. Each lab receives 3 control dosimeters – one “blank” (zero dose) and 2 pre-irradiated in the NRC Co-60 beam to known dose levels in the 20-50 Gy range. These are to be kept with the measurement dosimeters but must not receive any additional dose, since they act as controls to monitor shipping and/or environmental effects. Three control dosimeters (irradiated to similar doses) remain at NRC as additional, non-travelling controls.
- v. Dosimeters are provided to the BIPM, to be irradiated in a range of doses from 20-50 Gy in Co-60. As for the electron measurements, irradiations are to be carried out in water.
- vi. Delays in irradiation of the dosimeters after receipt, and in shipping back to NRC should be minimized. However, the alanine free-radical signal is very stable post-irradiation

[Arber and Sharpe, 1993; Nagy and Desrosiers, 1996], so extended timelines, due to shipping issues, facility availability, etc., should not impact the comparison.

vii. The information required from each participant is as follows:

Dose delivered	(Gy)
Irradiation temperature	(°C)
Nominal beam energy	(MeV)
R ₅₀ (beam quality specifier)	(g cm ⁻²)
z _{ref} (reference depth)	(g cm ⁻²)
<u>Irradiation geometry (SSD, field size)</u>	

viii. The choice of field size and SSD is not specified, but it should be the same as used in the participant's realization of absorbed dose to water.

ix. At the NRC, participant dosimeters will be read-out at the same time as control dosimeters. Since the alanine read-out is non-destructive and signal drift is small, repeat measurements will be used to monitor system drift and interpolate results between participants. protocol/equipment.

5.2 Irradiation procedure at the BIPM

Irradiations were carried out in the standard water phantom at the BIPM, as used for comparisons and calibrations in terms of absorbed dose to water. The dose rate was determined to be 0.234 Gy min⁻¹ at the time of irradiation (2023-10-16).

5.3 Irradiation procedure at the KRISS

Five dosimeters were irradiated at each of three electron energies – 6 MeV, 12 MeV, 18 MeV. The beam qualities are given in Table 3. A vertical beam geometry was used and the SSD was 100 cm.

5.4 Irradiation procedure at the LNHB

Five dosimeters were irradiated at each of three electron energies – 9 MeV, 12 MeV, 18 MeV. The beam qualities are given in Table 3. A horizontal beam geometry was used and the water equivalent thickness of the entrance window (0.4 cm PMMA) was taken into account in determining R₅₀ and setting the reference depth for irradiations. The SSD was 100 cm.

5.5 Irradiation procedure at the NRC

Five dosimeters were irradiated at each of three electron energies – 8 MeV, 12 MeV, 18 MeV. The beam qualities are given in Table 3. A horizontal beam geometry was used and the water equivalent thickness of the entrance window (1.8 mm PMMA) was taken into account in determining R₅₀ and setting the reference depth for irradiations. The SSD was 100 cm (nominal, based on manufacturer pointer).

Table 3. Beam qualities of the electron beams of the participants.

Energy label	R ₅₀ , KRISS (g cm ⁻²)	R ₅₀ , LNHB (g cm ⁻²)	R ₅₀ , NRC (g cm ⁻²)
Low	2.34	3.65	3.25
Medium	4.69	5.08	4.59
High	7.17	7.67	7.09

6. Analysis and presentation of results

In the BIPM Key Comparison for high energy photon beams, the range of possible beams was split into three regions – ‘low’, ‘medium’, ‘high’. This reflects the key clinical beam energies of 6 MV, 10 MV, 18 MV. Clinically, the majority of electron beam treatments use 6 MeV or 9 MeV, whereas a common energy for the cross-calibration of ionisation chambers is 18 MeV [IAEA, 2024]. This would suggest a similar delineation of ‘low’ (up to 9 MeV), ‘medium’ (>9 MeV to 15 MeV) and ‘high’ (>15 MeV and higher) could be considered for the presentation of results.

For each participant a dose ratio is obtained for each energy:

$$R_{NMI,BIPM}(E_{del}) = \frac{D_{w,del}^{NMI}(E_{del})}{D_{w,meas,BIPM}^{NMI}} \quad (1)$$

where the subscript *NMI* refers to a participant, *del* indicates the delivered dose reported by the participant, and *meas* indicates the alanine dose as measured using the alanine dosimeters, traceable to the BIPM Co-60 reference irradiations. The alanine reading yields a “Co-60” dose value, which must be converted to a value appropriate for high-energy electron beams. Since it is assumed that alanine has no energy dependence across the range of electron energies considered, there is only reference to the energy in the participant beam (E_{del}). The reference (alanine) dose is given by:

$$D_{w,meas,BIPM}^{NMI} = M_{alanine} \cdot C_{w,Co} \cdot f_{Co \rightarrow e} \quad (2)$$

where $M_{alanine}$ is the read-out of the alanine pellet by the EPR spectrometer, $C_{w,Co}$ is the alanine calibration coefficient to yield absorbed dose to water in a Co-60 beam, and $f_{Co \rightarrow e}$ is the factor to convert the Co-60-based dose reading to yield the dose delivered in a high energy electron beam [McEwen *et al*, 2020].

7. Uncertainty budgets

Uncertainty budgets are given in Appendix A, as provided by the participants. The standard uncertainty in the delivery of dose to the alanine dosimeters is in the range of 0.6 % to 1.5 %. The components of uncertainty for the determination of dose using alanine have been described in McEwen *et al*. (2025) but it is useful for this comparison to provide the specific components that are relevant for the interpretation of participant results.

Table 4. Uncertainty components related to alanine dosimeters. All values are quoted as standard uncertainties ($k=1$).

Component	KRISS	LNHB	NRC	Type
Read out	0.13%	0.13%	0.13%	A
EPR drift (see 8.2)	0.14%	0.14%	0.14%	A
Transport (see 8.2)	0.30%	0.14%	0.14%	B
Calibration (sensitivity, see 8.3)	0.13%	0.13%	0.13%	B
Consistency (repeat, see 8.3)	0.29%	0.29%	0.29%	B
Temperature	0.05%	0.05%	0.05%	B
Overall	0.48%	0.40%	0.40%	

Alanine dosimeters exhibit a small temperature dependence ($\sim 0.15 \% K^{-1}$) [Desrosiers *et al.*, 2004; Sharpe *et al.*, 2009] and therefore an additional parameter is required from the participants – the temperature at irradiation. It is assumed that all the participants measure the temperature of the alanine (or water) during irradiation with an uncertainty better than 0.3 °C.

8. Results

8.1 Performance of alanine read-out system

All irradiated dosimeters from the participating laboratories were read out using the NRC EPR spectrometer system during October and November 2023. The system consists of a Bruker EMX spectrometer with a high-Q cavity and Xenon upgrade. Beyond the standard NRC QA processes used to monitor system performance, pellets from the BIPM were re-read in January 2024 and the rms difference between the 1st and 2nd measurements was 0.12 %, consistent with the Type A uncertainty for read-out of pellets (i.e., no significant drift in response was seen over three months).

8.2 Control dosimeters

Nine irradiated control dosimeters A-I were used for this comparison. Controls D, E, F remained at NRC and were read with every participant's dosimeters. These were then used as the stable references against which the travelling controls (A, B, C, G, H, I) were compared.

The relative standard deviations on the readings for D, E, F across the read-out campaign were 0.17 %, 0.11 % and 0.14 % respectively. These values are consistent with historical data on re-reading alanine pellets in the 20-50 Gy range. The relative difference between the travelling dosimeters and the reference dosimeters are given in Table 5

Table 5. Potential effect of transport on control dosimeters

Dosimeter	Participant	Relative difference
A	LNHB	0.14%
B	KRISS	0.36%
C	BIPM	-0.10%
G	BIPM	-0.17%
H	KRISS	0.44%
I	LNHB	0.14%
rms value		0.26%

As can be seen in Table 5, the relative differences are the same, or larger than the repeatability of the reference dosimeters, indicating a small effect due to transport. No correction factor was applied, but an uncertainty component (participant-specific) was included to take account of the differences in controls seen (Table 4).

8.3 BIPM reference irradiations

The dose response of the alanine dosimeters is shown in Figure 1. The Type A uncertainty bars for the read out – representing the standard uncertainty on the set of six pellets in a single dosimeter – are smaller than the symbols and amounted to 0.25 % on average. The root mean squared (rms) value of the deviations from the expected linear fit is 0.05 % for the first read of the pellets (Nov-2023) and 0.11 % for the re-read (Jan-2024). The standard uncertainty in the gradient is estimated to be 0.07% and 0.19 % respectively, and the difference in the gradient between the two reads was 0.40 %.

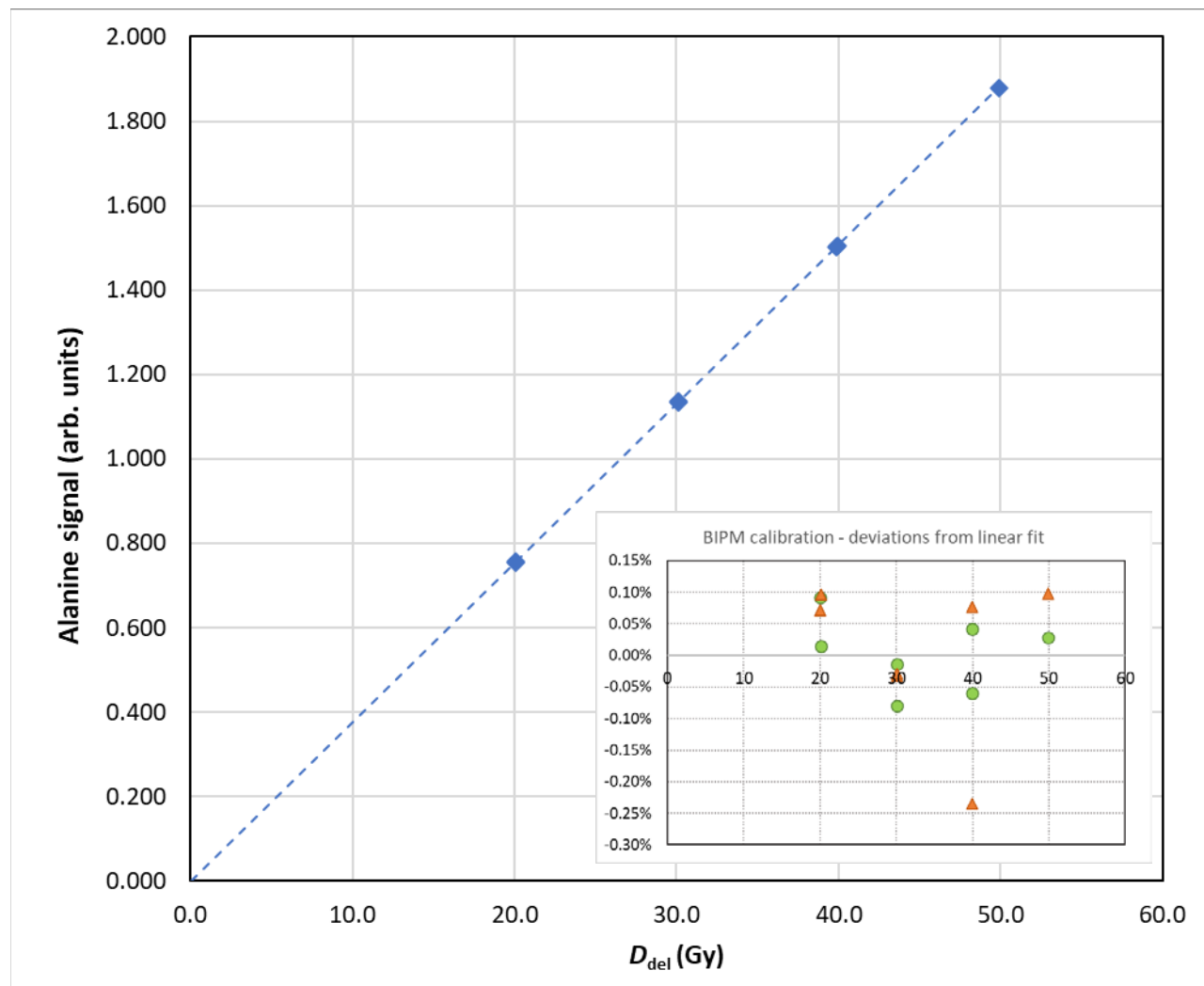


Figure 1. Alanine dose response, obtained from irradiations in Co-60 at the BIPM. The inset shows the deviation of the individual points from a linear fit – circles: Nov-2023 read; triangles: Jan-2024 read.

When reading alanine pellets irradiated in high-energy electron beams, the BIPM calibration curve above is used and then the 'Co-60' dose is multiplied by the conversion factor 1.014, as recommended by McEwen *et al* (2020) to give the absorbed dose to water for high-energy electron beams. The conclusion of that consensus analysis was that there was no evidence for any significant energy dependence, and therefore a single conversion factor is appropriate for all the energies used in this comparison.

8.4 Participant results

The results for KRISS, LNHB and NRC are given in Tables 6, 7 and 8 respectively. In the final column, values of R are collated for each energy to provide mean values for determining degrees of equivalence.

Table 6. Results for KRISS irradiations. The percentage value in the right-hand column is the standard deviation of the set of 5 dosimeters. The value s is the standard deviation of the values of $R_{\text{NMI/BIPM}}$ for each beam energy.

E (MeV)	D_{del} (Gy)	M_{alanine} (arb. units)	$D_{\text{w, meas, BIPM}}$ (Gy)	$R_{\text{KRISS/BIPM}}$	$\bar{R}$ s (%)
6	25.02	0.9178	24.71	1.0127	1.0136 0.18%
6	25.02	0.9149	24.63	1.0159	
6	25.02	0.9191	24.74	1.0113	
6	25.02	0.9160	24.66	1.0147	
6	25.02	0.9171	24.69	1.0135	
12	25.03	0.9276	24.97	1.0024	0.9998 0.19%
12	25.03	0.9292	25.01	1.0006	
12	25.03	0.9323	25.10	0.9973	
12	25.03	0.9311	25.07	0.9986	
12	25.03	0.9297	25.03	1.0001	
18	24.96	0.9216	24.81	1.0061	1.0087 0.18%
18	24.96	0.9190	24.74	1.0090	
18	24.96	0.9189	24.74	1.0090	
18	24.96	0.9196	24.75	1.0083	
18	24.96	0.9170	24.69	1.0111	

Table 7. Results for LNHB irradiations. The percentage value in the right-hand column is the standard deviation of the set of 4 or 5 dosimeters. The value s is the standard deviation of the values of $R_{\text{NMI/BIPM}}$ for each beam energy.

E (MeV)	D_{del} (Gy)	M_{alanine} (arb. units)	$D_{\text{w, meas, BIPM}}$ (Gy)	$R_{\text{LNHB/BIPM}}$	$\bar{R}$ s (%)
9	25.02	0.9298	25.03	0.9994	0.9963 0.38%
9	24.98	0.9313	25.07	0.9963	
9	24.97	0.9291	25.01	0.9985	
9	24.98	0.9363	25.20	0.9909	
12	24.98	0.9385	25.26	0.9888	0.9861 0.25%
12	24.99	0.9407	25.32	0.9867	
12	24.99	0.9415	25.34	0.9860	
12	24.99	0.9409	25.33	0.9867	
12	25.00	0.9456	25.45	0.9820	
18	25.09	0.9458	25.46	0.9856	
18	25.10	0.9471	25.49	0.9845	

18	25.09	0.9491	25.55	0.9822	0.9839
18	25.04	0.9454	25.45	0.9837	0.13%
18	25.04	0.9458	25.46	0.9835	

* Only 4 readings were used for the 9 MeV analysis due to a problem with the read-out of one of the dosimeters.

Table 8. Results for NRC irradiations. The percentage value in the right-hand column is the standard deviation of the set of 5 dosimeters. The value s is the standard deviation of the values of $R_{\text{NMI/BIPM}}$ for each beam energy.

E (MeV)	D_{del} (Gy)	M_{alanine} (arb. units)	$D_{\text{w, meas, BIPM}}$ (Gy)	$R_{\text{NRC/BIPM}}$	$\bar{R}$ s (%)
8	25.01	0.9349	25.17	0.9937	
8	25.01	0.9354	25.18	0.9932	
8	25.01	0.9372	25.23	0.9913	0.9929
8	25.01	0.9369	25.22	0.9915	0.14%
8	25.01	0.9341	25.14	0.9946	
12	25.01	0.9420	25.36	0.9863	
12	25.01	0.9416	25.35	0.9868	
12	25.01	0.9451	25.44	0.9832	0.9854
12	25.01	0.9422	25.36	0.9861	0.15%
12	25.01	0.9436	25.40	0.9847	
18	25.01	0.9410	25.33	0.9873	
18	25.01	0.9388	25.27	0.9896	
18	25.01	0.9386	25.27	0.9898	0.9897
18	25.01	0.9378	25.24	0.9907	0.14%
18	25.01	0.9376	25.24	0.9909	

8.5 Summary of results and degrees of equivalence

Table 3 indicates that there are differences in the beam qualities of the participants, even for the same nominal energy. The KRISS and the NRC operate linear accelerators from the same manufacturer but even there the difference in R_{50} can be as large as 0.1 g cm^{-2} . However, the lack of energy dependence of alanine means that this should not introduce any significant uncertainty in comparing participant results and determining degrees of equivalence.

The results are summarized in Figure 2. There is a suggestion of an energy dependence but this is not statistically significant, based on the uncorrelated uncertainties. It therefore makes sense, at least for this initial comparison, to determine a single DoE (degree of equivalence) for each participant.

Table 9. Summary of comparison data. The overall standard uncertainty (u_i) is the combination of the data in Table 4 with the participant specific uncertainties of the standard and dose delivery (Appendix A) and the reference irradiations of the BIPM.

Participant	Mean value of $R_{\text{NMI,BIPM}}(E_{\text{del}})$	Standard deviation of $R_{\text{NMI,BIPM}}(E_{\text{del}})$	u_i
KRISS	1.0074	0.70 %	1.6 %
LNHB	0.9887	0.67 %	0.9 %
NRC	0.9893	0.38 %	1.0 %

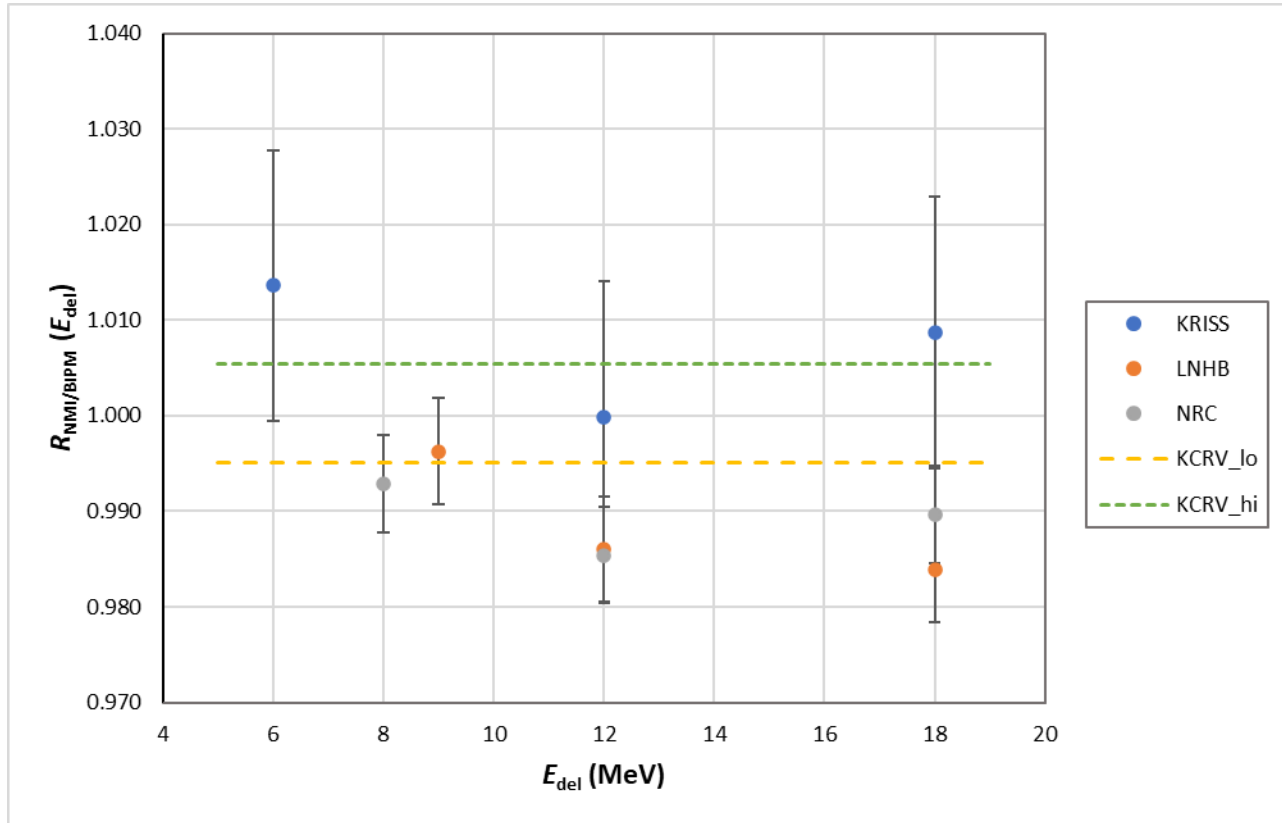


Figure 2. Ratio of dose values – participant relative to KCRV (see equation 1). The dotted lines represent the $k=1$ uncertainty of the alanine irradiations at the BIPM to produce the KCRV for this comparison. Uncertainty bars are given as $k=1$ standard uncertainties.

9. Discussion

Protocol: the comparison was completed successfully, with no reported challenges to the irradiation of the alanine dosimeters. Additionally, no issues were reported with import/exports of the dosimeters.

All three participants used ionisation chambers to realize absorbed dose to water – LNHB and NRC used chambers calibrated against their respective primary standard water calorimeters in high-energy electron beams, KRISS used an ionisation chamber calibrated in Co-60. This approach makes it relatively easy to decouple the standard from the irradiations to allow, for example, application of the same Co-60-based formalism for each participant as a secondary investigation.

The effort required to carry out the protocol has a baseline cost related to the realization of the KCRV (i.e., irradiation of alanine at the BIPM) but is otherwise scalable, allowing for a range of possible future comparisons from a single participant to numbers consistent with typical RMO comparison projects.

Transport: any transport/environmental effects were less than 0.5 % for all participants. It is not possible to separate transport and environmental impacts on the alanine response without additional monitoring but the data from this comparison would suggest further efforts beyond the control dosimeters used is not necessary.

Precision: the precision obtained with the alanine pellets was independent of participant, independent of beam modality (Co-60 versus high-energy electrons) and consistent with NRC experience with national dosimetry audit measurements for high-energy photon beams [McEwen *et al.*, 2025]. The standard deviations of the dosimeters shown in Tables 6-8 are similar to the standard uncertainties for the six alanine pellets within a single dosimeter, indicating consistent data sets (i.e., no temporal drift in linac output or significant impact of dosimeter positioning).

Uncertainties: Appendix A provides the uncertainty budgets of each of the participants. The combined uncertainties in Table 9 for LNHB and NRC can be compared with the results for the BIPM.RI(I)-K6 Key Comparison for high-energy photon beams (www.bipm.org/kcdb), which can be viewed as providing the target performance level for this electron comparison. The average standard uncertainty in the dose ratio NMI/BIPM for the K6 comparison is 0.6 %, significantly lower than the 0.9 % obtained here. However, a sub-1 % value still provides confidence for participants and can support CMC claims. The uncertainty could be reduced further by improving the determination of the conversion factor, $f_{Co \rightarrow e}$, between Co-60 and high-energy electron beams used in the KCRV.

Participant standards: The results of the LNHB and the NRC agree closely with a mean dose ratio within 0.1 % of unity, which is perhaps to be expected given that both laboratories use calorimetric standards. There is a significant offset of 1.5 % between the two calorimetric measurements and the KRISS dosimetry based on a Co-60 and the TG-51 formalism, with the formalism approach leading to a higher delivered dose. This difference is within the combined standard uncertainty but should be investigated further.

KCRV: it was expected that the participant/BIPM ratio would be close to unity for the calorimetric-based participants since the reference value is derived from calorimetry measurements in electron beams and Co-60 irradiations that have previously been validated through the BIPM.RI(I)-K4 Key Comparison. The offset from unity in both of the LNHB/BIPM and NRC/BIPM ratios, of around 1 %, is therefore somewhat surprising. A detailed analysis of the data did not reveal any reason for this discrepancy but fortunately it does not impact the comparison of national standards, since the KCRV cancels in any NMI-to-NMI comparison. Further work is required to investigate this apparent

offset to establish a long-baseline KCRV and allow the linking of laboratories across different electron comparisons using this protocol.

Alanine system: the design of the protocol does not require a specific laboratory to provide the alanine dosimetry, but the provider must meet the performance specifications shown in Table 4. For independence, it is preferable to use a laboratory not directly involved in the comparison, but this experience has shown that is not a requirement.

Conclusion

An indirect comparison of primary standards for therapy-level high-energy electron beam dosimetry was carried out between the NRC, Canada and the LNHB, France using alanine as the transfer dosimeter, traceable to Co-60 irradiations at the BIPM to provide a KCRV. In addition, KRISS, Korea participated using a protocol-based dose determination based on an ionisation chamber Co-60 absorbed dose calibration coefficient. All three participants agreed with the KCRV within the combined expanded uncertainties and the two calorimetric standards of the LNHB and NRC agreed, averaged across the electron energies investigated, at the 0.1 % level.

The comparison protocol proved successful and is ready to be used by other NMIs seeking to validate their electron beam primary standards.

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APPENDIX A

Table A-1. KRISS Uncertainty components: irradiation of alanine dosimeters in terms of absorbed dose to water in high-energy electron beams

Component	u (%)	
	Type A	Type B
<u>Dose measurement</u>		
$N_{D,w}^{60Co}$, calibration coefficient under ^{60}Co gamma-ray		0.5
$M_{Q,raw}$, chamber reading without corrections	0.03	
P_i , correction for influence quantities for chamber measurement		0.22
P_{Tp} , temperature and pressure correction		0.04
P_H , humidity correction		0.05
P_{ion} , ion recombination correction		0.04
P_{pol} , polarity correction		0.2
P_{elec} , electrometer calibration		0.02
P_{rp} , lateral non-uniformity of the beam		0.03
P_{depth} , chamber depth and positioning		0.05
k_Q , beam quality correction		1.2
P_{stb} , long term stability of the ionisation chamber		0.12
<u>Beam delivery</u>		
Stability of the reference chamber for beam monitoring		0.1
Stability of the beam monitoring chambers		0.5
Square root quadratic sum	0.03	1.42
Relative combined standard uncertainty	1.4	

Table A-2. LNHB Uncertainty components: irradiation of alanine dosimeters in terms of absorbed dose to water in high-energy electron beams

	<i>u</i> (%)
<i>Calibration of the monitor ionisation chamber with the Top ionisation chambers</i>	
$N_{D,w}$, calibration coefficient of the Top ionisation chambers	0.47 to 0.50
3 Top ionisation chambers drifts (on their average value)	0.06 to 0.27
Interpolation to new R_{50}	0.04
Top ionisation chambers signals / Monitor signals (corrected for T, p and H)	0.06
Top ionisation chambers Ion Recombination correction	0.02 to 0.03
Top ionisation chambers Polarity correction	0.02
Top ionisation chambers Radial Anisotropy correction	0.04 to 0.09
Capacitors (electrometers)	0.13
<i>Irradiation of the alanine dosimeter</i>	
Monitor Signal	0.02
T, p and H correction factors	0.08
<u>Alanine dosimeter radial anisotropy</u>	0.02 to 0.10
Alanine dosimeter depth	0.07
Phantom distance	0.03
Relative combined standard uncertainty	0.53 to 0.59

The uncertainties are similar but not identical for different beam energies.

Further information on the irradiation procedure:

$N_{Dw}^*(Top)$: calibration coefficient of a Top ionisation chamber with a signal corrected for T, p, H , polarity, ion recombination and radial anisotropy

Q_{Top} : charge measured by the Top ionisation chamber and corrected for T, p, H

Q_{mon} : charge measured by the monitor ionisation chamber and corrected for T, p, H

$N_{D,w}(mon)$: calibration coefficient of a monitor ionisation chamber with a signal corrected for T, p, H

$$N_{D,w}(mon) = N_{Dw}^*(Top) \frac{Q_{Top}}{Q_{mon}} [k_{pol} k_{rec} k_{prof}](Top)$$

3 different Top ionisation chambers have been used to calibrate the monitor chambers and their results averaged. The maximum discrepancies were 0.12 %, 0.10% and 0.47% at 9 MeV, 12 MeV and 18 MeV respectively.

$$D_w(dosimeter) = < N_{D,w}(mon) > Q_{mon}/k_{prof}(dosimeter)$$

As the absorbed dose at the reference point on the right of the equation ($< N_{D,w}(mon) > Q_{mon}$) is divided by the radial anisotropy correction factor, the absorbed dose at the left of the equation corresponds to the averaged absorbed dose in the alanine dosimeter.

Table A-3. NRC Uncertainty components: irradiation of alanine dosimeters in terms of absorbed dose to water in high-energy electron beams

Component	Source	<i>u</i> (%)
Calibration coefficient of reference chamber	Muir <i>et al</i> , 2017* Surensen, 2022§	0.62 [¶]
Stability of reference chamber	Internal QA procedures	0.15
Chamber experimental uncertainty	Muir <i>et al</i> , 2017	0.19
Linac stability during irradiations	Analysis of linac performance	0.19
Alanine positioning	Same as for ion chamber	0.14
Total, combined (k=1)		0.71

* See Muir et al, 2017 for details on the various uncertainty components related to calorimetry and ionisation chamber measurements.

§ See Surensen, 2022 for details of the measurements at lower electron energies, where alanine is used as a transfer detector from the calorimetry measurements at higher energy.

[¶] This is the value for energies less than 18 MeV, at higher energies the uncertainty is ~ 0.4 % because of direct calibration against the primary standard water calorimeter.