APMP key comparison of absorbed dose to water for ^{60}Co, APMP.RI(I)-K4

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Abstract

The APMP/TCRI Dosimetry Working Group performed the APMP.RI(I)-K4 key comparison of absorbed dose to water for ^{60}Co between 2009 and 2010. Fourteen standards laboratories took part in the comparison. Three commercial cavity ionization chambers were used as transfer instruments and circulated among the participants. Nearly all the measured calibration coefficients for each ionization chamber were within one standard uncertainty (as estimated by the laboratory) of the comparison mean for that chamber, indicating reasonable agreement amongst the participants. Three participants (ARPANSA, PTB and NMIJ) were used to link the results to the BIPM through the ongoing bilateral BIPM.RI(I)-K4 comparison. Through this link the degree of equivalence (the ratio to the BIPM Key Comparison Reference Value and its uncertainty) was calculated for each non-linking laboratory to show the calibration capabilities. For the 9 eligible participants, this degree of equivalent ratio fell within 3.3 parts in 10^3 of unity, well within the combined standard uncertainty in all cases.

Keywords: APMP Key Comparison, absorbed dose to water for ^{60}Co, degree of equivalence

1. Introduction

In recent decades, the major emphasis in NMIs around the world has shifted from standards for air kerma to standards for absorbed dose to water. The rationale is to establish a better basis for dosimetry that relates directly to the quantity of interest in radiotherapy, absorbed dose to water (D_w) [1,2]. The need for a regional key comparison for ionization chamber calibration in terms of D_w arose during the APMP/TCRI Workshop in 2006 when the previous attempt in 2000 was abandoned as a major report could not be completed. The measurements for the new comparison were completed on schedule, and an initial draft report was completed in 2013. However, the comparison was then beset by the same problems that forced the abandonment of the 2000 comparison report, namely: the loss of key staff, and difficulties establishing the uncertainty in the linking mechanism, which is surprisingly complex. This latter problem was resolved by a publication by the Consultative Committee for Ionizing Radiation (CCRI) in 2017 [3] which set out a method for calculating the uncertainty in the degrees of equivalence for the general case of multiple transfer instruments and multiple linking laboratories, in a regional dosimetry comparison (updating a previous version [4]). The APMP.RI(I)-K4 was rewritten in 2020 to adopt this method.

Details of the fourteen participating laboratories are listed in Table 1. The comparison was conducted by the pilot laboratory, the Institute of Nuclear Energy Researcher (INER), Taiwan. A comparison for air kerma at ^{60}Co was also carried out at the same time and the results of that comparison are published as APMP.RI(I)-K1.1.

We note that the AECS and BATAN became Designated Institutes in the CIPM MRA after the comparison, in 2014 and 2017, respectively. The NRL has yet to be declared a Designated Institute and will be unable to enter its results into the KCDB. However, the contribution of all the laboratories to the stability and consistency of measurements is included in this report for completeness.

The objective of this key comparison is to establish the degrees of equivalence (D_i) of national standards and to support the Calibration and Measurement Capabilities (CMCs) of the laboratories for ionization chamber calibrations in ^{60}Co, in particular calibrations provided for radiotherapy services. An indirect comparison of the standards of D_w was undertaken using three ionization chambers as transfer instruments. Each participant calibrated each chamber and supplied their measured calibration coefficient and their estimate of the uncertainty. These chambers are the same three used in the APMP.RI(I)-K1.1 comparison. As a pilot laboratory, the INER was responsible for managing the movement of devices around various institutions and collecting the data. Three of the laboratories (the ARPANSA, PTB and NMIJ) maintain primary standards for D_w and had participated in the BIPM.RI(I)-K4 key comparison, allowing the results to be linked to the Key Comparison Reference Value (KCRV) in the Key Comparison Database (KCDB) of the CIPM MRA [5].

Table 1. Participating laboratories and contact persons for the APMP.RI(I)-K4 key comparison

Participating Laboratory	Abbreviation, Economy	Contact Person
Syria Atomic Energy Commission /National Radiation Metrology Laboratory	AECS, Syrian	Mamdouh Bero
Australian Radiation Protection and Nuclear Safety Agency	ARPANSA, Australia	Duncan.Butler
Bhabha Atomic Research Centre	BARC, India	Ashok Kumar Mahant* Sumanth Panyam Vinatha
Center for Technology of Radiation Safety and Metrology, National Nuclear Energy Agency	BATAN, Indonesia	Caecilia Tuti Budiantari
Bureau of Radiation and Medical Devices, Department of Medical Science, Ministry of Public Health	DMSc, Thailand	Siri Srimanoroth
Institute of Nuclear Energy Research	INER, Taiwan	Yi-Chun Lin
Korea Research Institute of Standards and Science	KRISS, Korea	Kook Jin Chun
National Institute of Metrology	NIM, China	Kun Wang
National Institute of Standards	NIS, Egypt	Noha Emad Khaled**
National Metrology Institute of Japan	NMIJ, Japan	Tadahiro Kurosawa & Yuuichirou Morishita
Malaysian Nuclear Agency	Nuclear Malaysia, Malaysia	Taiman Bin Kadni
National Metrology Institute of South Africa	NMISA, South Africa	Zakithi Msimang
National Radiation Laboratory***	NRL, New Zealand	John Laban
Physikalisch-Technische Bundesanstalt	PTB, Germany	Achim Krauss

*Retired in September 2012

**Participants of NIS are N. E. Khaled, A. Elsersy, S. A. Eman and N.R. Khalel

***Closed in 2010

2. Procedure and protocol

2.1 Comparison methodology

In this comparison, there was a ring-shaped circulation of the transfer chambers among the participants. Before the transfer chambers were delivered to the first participant, they were continuously tested at the INER for more than 3 months to check that the chambers were stable. After being circulated to 3 or 4 participating laboratories, the chambers were sent back to the INER for stability tests, which included a ^{60}Co dose to water measurement. Every participant was asked to provide calibration coefficients and uncertainty estimates for each transfer standard in terms of absorbed dose and air kerma for ^{60}Co.

During the circulation period the performance of the chambers was monitored by checking: (1) the dose to water ratios between the chambers; (2) the air kerma ratios between the chambers; and (3) the ratio of the calibration coefficients for absorbed dose and air kerma for each chamber. These ratios were reported to the INER after each participant had completed the calibration. If they were within a suitable range (nominally 1% variation from the INER value) the chambers could be sent directly to the next laboratory. If the ratios were outside the range, the chambers were to be sent back to the INER to be checked for stability.

Three participating laboratories (PTB, ARPANSA and NMIJ) that had completed the BIPMP.RI(I)-K4 comparison with the Bureau International des Poids et Mesures (BIPM) for D_w in ^{60}Co were linking laboratories.

2.2 Transfer standards

Photographs of the equipment provided by INER for this comparison are shown in Figure 1 and the main characteristics of the three transfer chambers are listed in Table 2. These chambers are representative of those commonly used in clinical radiotherapy dosimetry. The chambers were circulated without an electrometer. At each laboratory, the transfer chambers were positioned with the stem perpendicular to the beam direction and with appropriate markings on both the chamber and the envelope (engraved lines or serial numbers) facing the source. A collecting voltage from the manufacturer specifications supplied at each laboratory was applied to each chamber at least 30 min before starting the measurement. Each chamber has its own build-up cap for calibration in terms of air kerma, which was removed for use in water.

Two custom PMMA sleeves made by INER were supplied for use with the NE 2571 and PTW 30001 chambers. The PTW 30013 waterproof chamber was used without a sleeve.

Table 2: Specifications of the transfer chambers

Type	Cavity volume /cm^3	Cavity length /mm	Cavity inside diameter /mm	Wall material	Wall thickness /mg cm^{-2}	Water-proof	Bias voltage*
NE 2571 (S/N 3025)	0.69	24	6.3	Graphite	65	No	+250 V
PTW 30001 (S/N 2340)	0.60	23	6.1	Acrylic /graphite	60	No	+400 V
PTW 30013 (S/N 0348)	0.60	23	6.1	Acrylic /graphite	49	Yes	+400 V

*Sign of charge collected by central electrode: positive

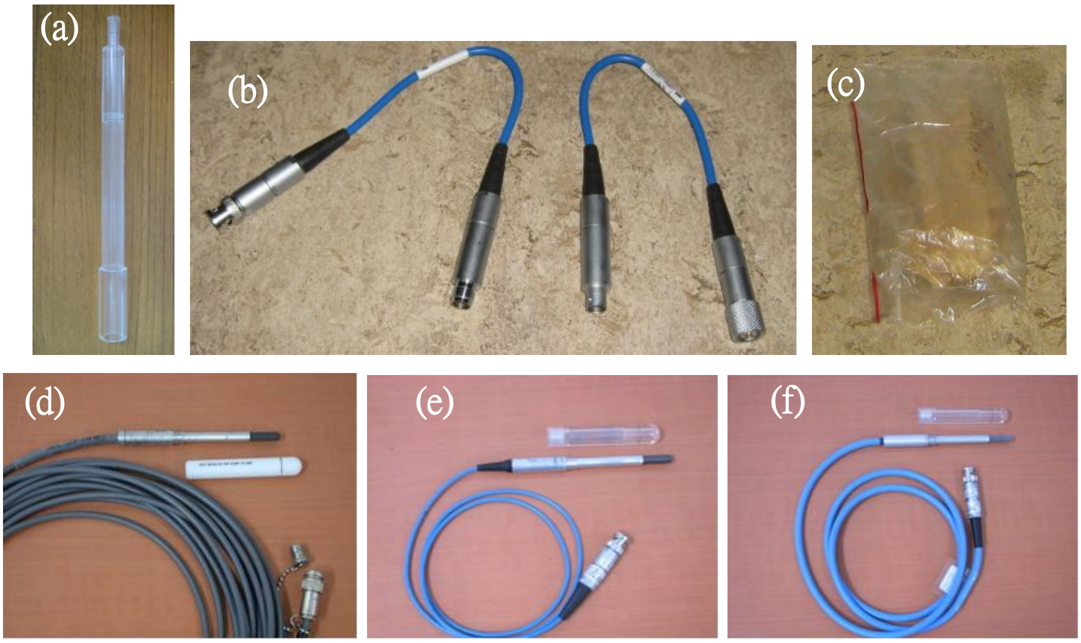

Figure 1: (a) PMMA sleeves made by INER, (b) TNC/BNT adaptors, (c) rubber sheaths which could be used if the PMMA sleeves were incompatible with the laboratory water tank, (d) NE 2571 chamber (S/N 3025, non-waterproof), (e) PTW 30003 chamber (S/N 2340, non-waterproof), and (f) PTW 30013 chamber (S/N 0348, waterproof).

2.3 Reference conditions

The reference conditions for D_w for ^{60}Co are those specified by the BIPM [6]: (1) a distance from the source to the reference plane (the center of the detector) of 1 m; (2) the field size at the reference plane of 10 cm × 10 cm; and (3) a depth in water of 5 g cm^{-2}. However, deviations were allowed – for example several laboratories used 0.8 m for the distance to the detector, and several used 1 m to the water surface. Laboratories were required to specify the conditions if they were different from those of the BIPM.

The calibration coefficients $N_{D,w}$ were expressed in units of Gy/C and referred to standard conditions of 20°C and 101.325 kPa. The traceability of the standard used at each laboratory and the calibration conditions are given in Table 3.

Table 3. Absorbed dose traceability and transfer chamber calibration conditions for each participant.

Participant	Traceability	Primary standard[a] of D_w	Source-detector distance (cm)	Field size
AECS	BIPM (via IAEA)	B	100	10 cm × 10 cm square
ARPANSA	ARPANSA	G1	105	10 cm × 10 cm square
BARC	BIPM	B	80	10 cm × 10 cm square
BATAN	ARPANSA	G1	80	10 cm × 10 cm square
DMSc	BIPM (via IAEA)	B	100	10 cm × 10 cm square
INER	INER	I	100	10 cm × 10 cm square
KRISS	BIPM	B	100	10 cm × 10 cm square
NIM	BIPM	B	100	10 cm in diameter
NIS	BIPM	B	100	10 cm × 10 cm square
NMIJ	NMIJ	G2	100	11 cm in diameter
Nuclear Malaysia	BIPM (via IAEA)	B	100	10 cm × 10 cm square
NMISA	BIPM	B	100	10 cm × 10 cm square
NRL	ARPANSA	G1	100	10 cm × 10 cm square
PTB	PTB	W	100	10 cm × 10 cm square

[a] B = BIPM ionometry standard, I = INER ionometry standard, G1 = ARPANSA graphite calorimeter, G2 = NMIJ graphite calorimeter, W=PTB water calorimeter

2.4 Schedule

The comparison was scheduled to begin in April 2009 and completed in November 2010. The draft comparison protocol was sent to every participant for review and comments, then the revised protocol was submitted to the CCRI(I) for approval. The total time period of chambers delivery and calibrations for each participant was about one month. Each participant was expected to measure the transfer chambers for no longer than 15 days. The comparison schedule is shown in Table 4.

Table 4. Schedule of APMP.RI(I)-K4 comparison

Participant	Date of arrival	Date of departure
INER		27-Apr-2009
PTB	10-May-2009	26-May-2009
Nuclear Malaysia	10-Jun-2009	26-Jun-2009
AECS	10-Jul-2009	26-Jul-2009
INER	10-Aug-2009	16-Aug-2009
KRISS	31-Aug-2009	16-Sep-2009
NMIJ	30-Sep-2009	16-Oct-2009
NMISA	31-Oct-2009	16-Nov-2009
INER	30-Nov-2009	10-Feb-2010
DMSc	28-Feb-2010	16-Mar-2010
BARC	31-Mar-2010	16-Apr-2010
NIM	30-Apr-2010	16-May-2010
BATAN	31-May-2010	16-Jun-2010
INER	30-Jun-2010	31-Jul-2010
ARPANSA	15-Aug-2010	31-Aug-2010
NRL	15-Sep-2010	1-Oct-2010
NIS	15-Oct-2010	31-Oct-2010
INER	15-Nov-2010	

2.5 Calibration results and uncertainty submission

All the participating laboratories submitted calibration results after completing their measurements. The submission included the calibration coefficients (Gy C^{-1}) of the transfer chambers, the absorbed dose rate of the radiation field (mGy s^{-1}), the calibration conditions, traceability, and the relative standard uncertainties of absorbed dose measurements and chamber calibrations. Furthermore, it was requested that the relative humidity conditions at the time of calibration were stated in the results. Ideally, the relative humidity of the participating laboratories at the time of measurement should be within the range from 30% to 70%. To report the results, a “Results” MS-Excel worksheet was provided in which the information about the national (primary) standards used by the participants was stated.

All the participating laboratories were required to provide estimates of their calibration coefficients uncertainty (u_i), including Type A and Type B contributions, according to the criteria of the “Guide to The Expression of Uncertainty in Measurement” [7].

3. Evaluation of degrees of equivalence

The calculation of the degrees of equivalence follows reference [3]. This document describes the calculation of the ratio to the BIPM reference value, taking into account multiple transfer standards and multiple link laboratories. All three linking laboratories conducted indirect comparisons with the BIPM, and in the indirect case:

$$\boldsymbol{R_i = \frac{N_{D,w,i}}{N_{D,w,LINK}} R_{LINK,BIPM} = \frac{D_{w,i}/I_i}{D^{reg}_{w,LINK}/I^{reg}_{LINK}} \frac{D^{inter}_{w,LINK}/I^{inter}_{LINK}}{D_{w,BIPM}/I_{BIPM}}}. \quad (1)$$

Here $N_{D,w,i}$ is the transfer chamber calibration coefficient for laboratory i which has been expanded on the right side to its components D_w/I_i, the ratio of the absorbed dose to water rate to the ionization current of the transfer standard. The dot above D_w used to denote rate has been omitted to keep the notation simple.

Each linking laboratory has two instances of $D_{w,i}/I_i$: one in the regional comparison (superscript *reg*) and one in the BIPM bilateral comparison (superscript *inter*). The $R_{LINK,BIPM}$ is the ratio of the link laboratory in the corresponding BIPM international comparison (superscript *inter*), as described in the relevant comparison report for PTB [8], ARPANSA [9] and NMIJ [10]. The linking ratios are given in Table 5. We note that the result for PTB is taken from their 2015 result. At the time of the APMP comparison their result was taken from 2005. However this result ($R_{\mathrm{LINK,BIPM}}$ = 0.9961 with combined standard uncertainty 0.0037) was replaced in the analysis after the 2015 value was published.

Table 5. Key comparison ratios $R_{\mathrm{LINK,BIPM}}$ of absorbed dose to water for ^{60}Co for the PTB [8], ARPANSA [9] and NMIJ [10]

Link laboratory	Year of comparison	$R_{\mathrm{LINK,BIPM}}$	Combined standard uncertainty
PTB	2015	0.9977	0.0038
ARPANSA	2010	0.9973	0.0053
NMIJ	2009	0.9960	0.0046

Following [3] the uncertainty in R_i is given by

$$u_{R,i}^2 = \left[u_i^2 + u_{BIPM}^2 - \sum_j f_j^2\left(u_{i,j}^2 + u_{BIPM,j}^2\right)\right] + u_{tr}^2 + u_{LINK}^2, \tag{2}$$

where u_i is the combined standard uncertainty in $N_{D,w,i}$ (not including a component for the long-term stability of the transfer standards), and u_{BIPM} is the combined standard uncertainty of the BIPM dose to water realization [8,9,10], of 0.29%. The other terms are discussed in the following sections.

The degree of equivalence, D_i, for each of n participating laboratories i = 1 to n (excluding the linking laboratories) is defined as the difference $D_i = R_i - 1$, and its expanded (k = 2) uncertainty $U_i = 2u_{R,i.}$, expressed in mGy/Gy.

3.1 Correlated uncertainties

The summation in equation (2) contains those components $f_j\, u_{i,j}$ and $fj\ u_{BIPM,j}$ that are correlated between laboratory i and the BIPM, with correlation factor f_j. When laboratory i is traceable to the BIPM (8 laboratories in this comparison, either directly or through the IAEA) the summation contains all of the non-statistical components of u_{BIPM}, each with correlation factor $f_j = 1$. For this case we took the non-statistical component to be equal to the Type B standard uncertainty stated by the BIPM of 0.21% in Table 2 of reference [8]. We note that this is a conservative estimate as some of the Type A uncertainties are not re-evaluated between calibrations, and therefore may also be correlated. INER use the same type of ionometry standard as BIPM, and uncertainties for *W/e* and those arising from interaction coefficients are fully correlated, with a combined value of 0.19% (k=1).

Two laboratories are traceable to ARPANSA and are therefore correlated with the BIPM at the same level as ARPANSA. For this correlation we used Table 6 of the NMIJ BIPM.RI(I)-K4 report [10], which gives the square root of the summation in equation (2) for graphite calorimeters of 1.3 parts in 10^3 for ARPANSA and 1.5 parts in 10^3 for NMIJ. The PTW water calorimeter is considered uncorrelated.

3.2 Estimates of u_{tr}

The uncertainty u_{tr} arises during the measurement of the transfer standards at each participating laboratory i, and as such it is normally included in the estimate of u_i provided by the laboratory, and so can be set to zero in equation (2). However, there is additional information regarding the performance of the transfer standards. The pilot laboratory's stability tests can be used to confirm that the transfer standards are behaving as expected throughout the comparison, and included if the variation is larger than expected. Moreover, the variation between the comparison ratios for the multiple transfer standards can be used to provide an alternative estimate of u_{tr}.

Following [3] for the general case of n laboratories (i = 1 to n), p transfer chambers (j = 1 to p) and q linking laboratories (k = 1 to q), we obtain npq values $R_{i,j,k}$. For each laboratory, and each chamber, we first calculate the ratio of dose to the BIPM reference value, for each linking laboratory, resulting in q=3 ratios for each chamber. When the ratios are averaged over the p =3 chambers, the ratio of the laboratory dose to the BIPM dose is obtained, for each linking laboratory:

$$R_{i,k} = \frac{\sum_j R_{i,j,k}}{p} \tag{3}$$

This approach allows us to estimate of the uncertainty arising from the transfer standards, $u_{\mathrm{tr},k}$, from the spread in the results for different chambers:

$$u_{\mathrm{tr},k}^2 = \frac{\sum_j \left(R_{i,j,k} - R_{i,k}\right)^2}{p(p-1.4)} \,. \tag{4}$$

This leads to q=3 values for $u_{\mathrm{tr},k}$ for each laboratory. As these estimates were slightly larger than those values determined from the laboratory uncertainty budgets, and the estimate based on the pilot stability, we chose to use equation (4) to obtain u_{tr}.

3.3 Estimates of u_{LINK}

The uncertainty u_{LINK} covers the linking measurements, excluding the uncertainty of the BIPM calibration which is already included in u_{BIPM}. It includes statistical (i.e. random) uncertainties in D_{w} and I at the link (included twice, once for each comparison) and the combined uncertainty in the BIPM determination of current (some 0.03%). The estimates for each link can be combined:

$$\frac{1}{u_{\mathrm{LINK}}^2} = \sum_k \frac{1}{u_{\mathrm{LINK},k}^2}. \tag{5}$$

An alternative estimate of u_{LINK} can be obtained from the variation between the ratios calculated for the different linking laboratories. Still following [3], we average over the q=3 links to obtain the final result, R_{i}, as the unweighted mean of $R_{i,k}$:

$$R_i = \frac{\sum_k R_{i,k}}{q}, \tag{6}$$

and then calculate:

$$u_{\mathrm{LINK}}^2 = \frac{\sum_k \left(R_{i,k} - R_i\right)^2}{q(q-1.4)}. \tag{7}$$

The best estimate of u_{LINK} is derived from equation (5) or (7), depending on whichever is larger to prevent fortuitous agreement in unrealistically low value.

4. Results

4.1 Chamber stability

The results of the transfer chamber stability tests made at the pilot laboratory are given in Fig. 2. The graphs confirm that the transfer chambers behaved normally during this comparison, with the standard deviation of the 7 measurements being 0.10% for the NE-2571, 0.09% for the PTW-30001 and 0.07% for the PTW-30013, with no long-term trend.

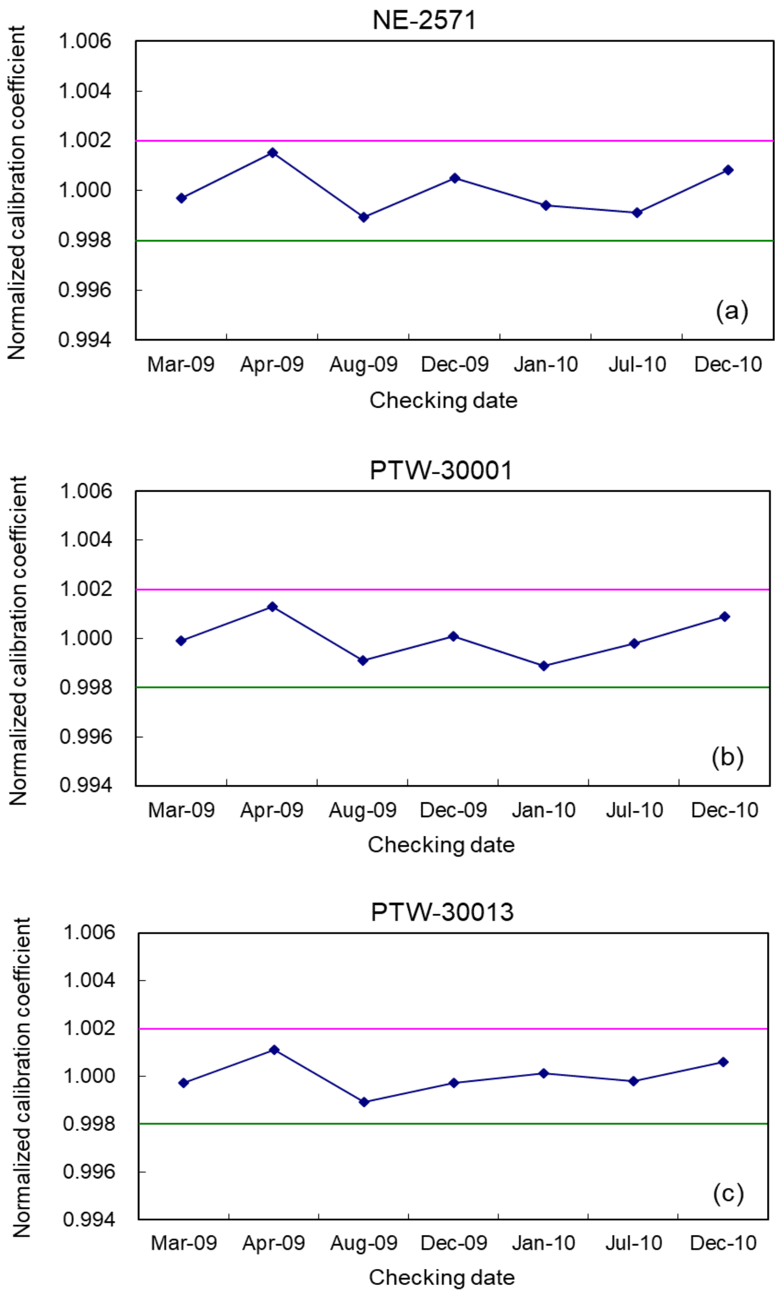

Figure 2. Stability results of transfer chamber measurements made at the INER (a) NE-2571 (S/N 3025) (b) PTW-30001 (S/N 2340) (c) PTW-30013 (S/N 0348)

4.2 Calibration coefficients and reported uncertainties

The calibration coefficients and the reported uncertainty for the transfer chambers are given in Table 6. Laboratories reported the same uncertainty for all three chambers. Detailed uncertainty budgets are given in Appendix I.

Table 6. Reported calibration coefficients ($N_{D,w}$) of the transfer chambers for the APMP RI(I)-K4 key comparison

Participant	$N_{D,w}$ (10^7 Gy C^{-1})			Relative standard uncertainty* $u_i(N_{D,w})$ (%)
	NE-2571 S/N 3025	PTW-30001 S/N 2340	PTW-30013 S/N 0348	
PTB	4.583	5.296	5.294	0.24
Nuc. Malaysia	4.591	5.311	5.312	0.70
AECS	4.595	5.330	5.326	1.14
KRISS	4.583	5.306	5.300	0.38
NMIJ	4.587	5.312	5.303	0.40
NMISA	4.616	5.293	5.326	0.50
DMSc	4.610	5.320	5.337	0.52
BARC	4.622	5.325	5.340	0.53
NIM	4.611	5.310	5.332	0.47
BATAN	4.616	5.323	5.335	0.90
INER	4.592	5.303	5.315	0.36
ARPANSA	4.596	5.297	5.311	0.44
NRL	4.624	5.314	5.342	0.41
NIS	4.592	5.303	5.350	0.61

* The combined standard uncertainty as stated by the laboratory in Appendix I.

These calibration coefficients are plotted in Fig. 3. The standard deviation of the distribution of the calibration coefficients was 0.32% (NE-2571), 0.21% (PTW-30001) and 0.33% (PTW-30013), and twice this value has been indicated on each graph. The error bards show the standard uncertainty in the calibration coefficient, as stated by the participant. The graphs show that the laboratories are in reasonable agreement, with all calibration coefficients within two standard deviations of the mean, and nearly all results within a standard uncertainty of the mean.

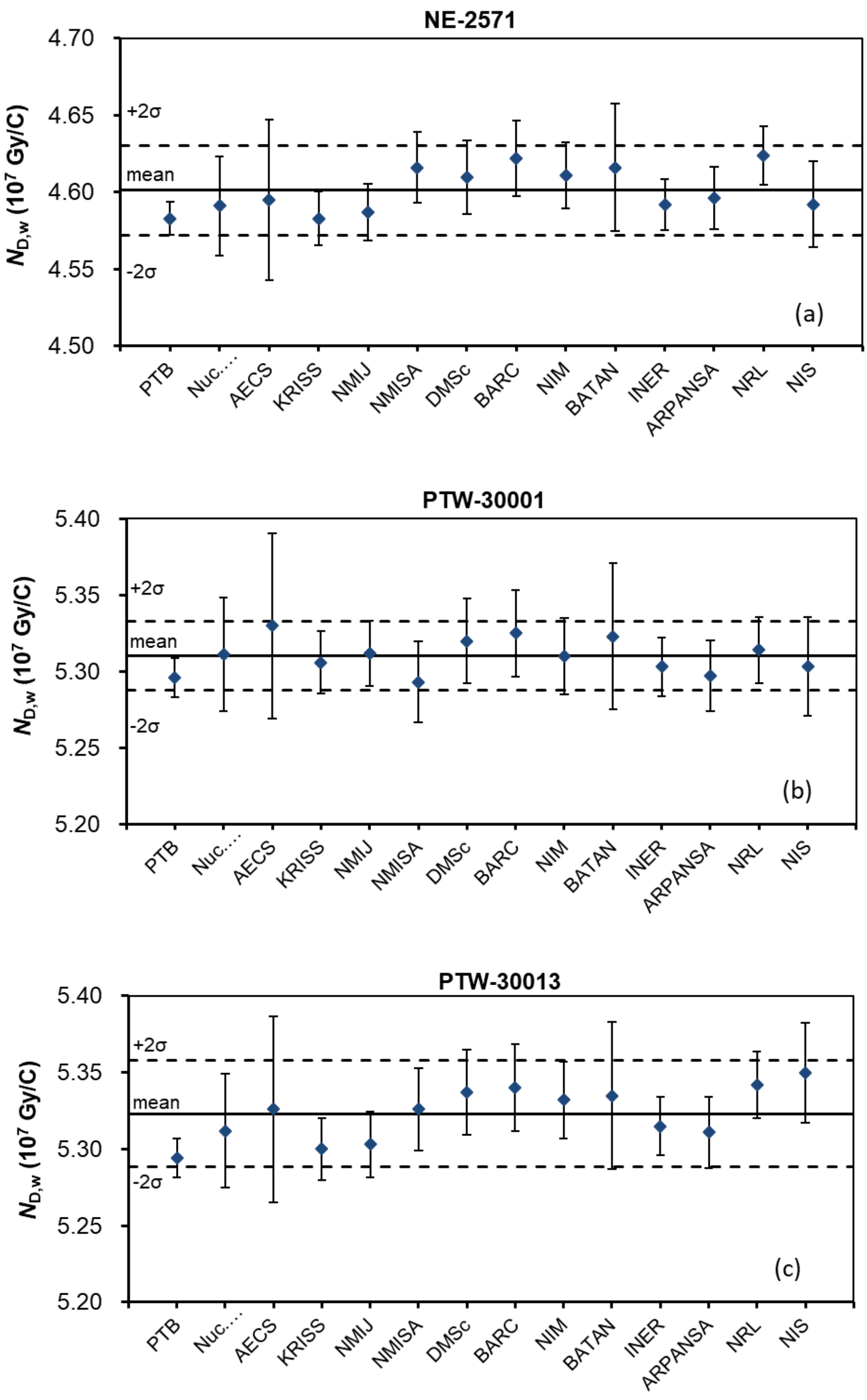

Figure 3. Transfer chamber calibration coefficients ($N_{D,w}$) with twice the standard deviation of the distribution indicated, for (a) NE-2571 (S/N 3025), (b) PTW-30001 (S/N 2340) and (c) PTW-30013 (S/N 0348). The error bars show the laboratory's reported standard uncertainty $u(N_{D,w})$.

4.3 Ratios between chambers

The ratios of the calibration coefficients between the chambers at each laboratory are shown in Fig. 4. The ratios of the two PTW chambers relative to the NE2571 chamber did not change by more than 1% from an expected value of 1.155. While the larger deviations (NMISA and NIS) suggest issues with either the chamber stability or laboratory setup, in both cases the chambers were already scheduled to be returned to INER, and the INER results did not indicate any problems with the chambers. There is the suggestion of a step change in response for the PTW-30001 chamber between the first 5 and last 9 participants. However, as the INER stability checks did not show any change, no attempt was made to account for this.

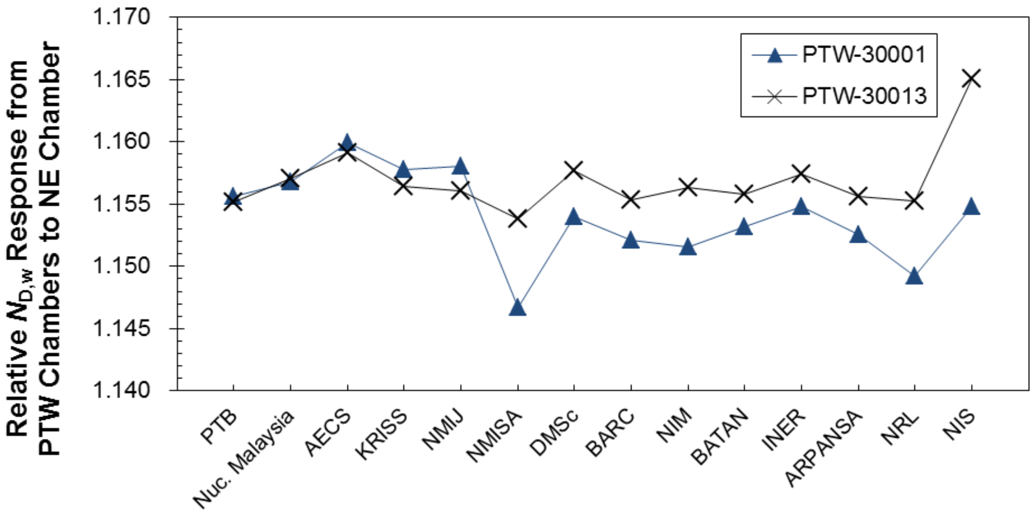

Figure 4. Relative responses of dose to water calibration factor for PTW chambers 30001 (▲) and 30013 (×) with respect to the NE 2571 chamber.

4.4 Ratio to the BIPM

The results have been analyzed as described in Section 3. Tables 7, 8 and 9 give the ratios of each participant to the BIPM absorbed dose, for each chamber, one table per link laboratory. Each table includes the estimate of u_{tr} derived from the spread in the results.

Table 7. Ratio of NMI absorbed dose to BIPM linked through PTB, $R_{i,\text{PTB}}$, and the uncertainty $u_{\text{tr,PTB}}$, estimated from the spread in results.

Participant, i	$R_{i,j,\text{PTB}}$			$R_{i,\text{PTB}}$	$u_{\text{tr,PTB}}$ (%)
	NE-2571 S/N 3025	PTW-30001 S/N 2340	PTW-30013 S/N 0348		
PTB	N/A	N/A	N/A	N/A	N/A
Nuc. Malaysia	0.9994	1.0005	1.0011	1.0004	0.05
AECS	1.0003	1.0041	1.0037	1.0027	0.13
KRISS	0.9977	0.9996	0.9988	0.9987	0.06
NMIJ	0.9986	1.0007	0.9994	0.9996	0.07
NMISA	1.0049	0.9971	1.0037	1.0019	0.27
DMSC	1.0036	1.0022	1.0058	1.0039	0.12
BARC	1.0062	1.0032	1.0064	1.0052	0.12
NIM	1.0038	1.0003	1.0049	1.0030	0.15
BATAN	1.0049	1.0028	1.0054	1.0044	0.09
INER	0.9997	0.9990	1.0017	1.0001	0.09
ARPANSA	1.0005	0.9979	1.0009	0.9998	0.11
NRL	1.0066	1.0011	1.0067	1.0048	0.21
NIS	0.9997	0.9990	1.0083	1.0023	0.33

Table 8. Ratio of NMI absorbed dose to BIPM linked through ARPANSA, $R_{i,\text{ARPANSA}}$, and the uncertainty, $u_{\text{tr,ARPANSA}}$, estimated from the spread in results.

Participant, i	$R_{i,j,\text{ARPANSA}}$			$R_{i,\text{ARPANSA}}$	$u_{\text{tr,ARPANSA}}$ (%)
	NE-2571 S/N 3025	PTW-30001 S/N 2340	PTW-30013 S/N 0348		
PTB	0.9945	0.9971	0.9941	0.9952	0.11
Nuc. Malaysia	0.9962	0.9999	0.9975	0.9979	0.12
AECS	0.9971	1.0035	1.0001	1.0002	0.21
KRISS	0.9945	0.9990	0.9952	0.9962	0.16
NMIJ	0.9953	1.0001	0.9958	0.9971	0.17
NMISA	1.0016	0.9965	1.0001	0.9994	0.17
DMSC	1.0003	1.0016	1.0022	1.0014	0.06
BARC	1.0029	1.0026	1.0027	1.0028	0.01
NIM	1.0006	0.9997	1.0012	1.0005	0.05
BATAN	1.0016	1.0022	1.0018	1.0019	0.02
INER	0.9964	0.9984	0.9981	0.9976	0.07
ARPANSA	N/A	N/A	N/A	N/A	N/A
NRL	1.0034	1.0005	1.0031	1.0023	0.10
NIS	0.9964	0.9984	1.0046	0.9998	0.28

Table 9. Ratio of NMI absorbed dose to BIPM linked through NMIJ, $R_{i,\mathrm{NMIJ}}$, and the uncertainty $u_{\mathrm{tr,\,NMIJ}}$, estimated from the spread in results.

Participant, i	$R_{i,j,\mathrm{NMIJ}}$			$R_{i,\mathrm{NMIJ}}$	$u_{\mathrm{tr,NMIJ}}$ (%)
	NE-2571 S/N 3025	PTW-30001 S/N 2340	PTW-30013 S/N 0348		
PTB	0.9951	0.9930	0.9943	0.9941	0.07
Nuc. Malaysia	0.9969	0.9958	0.9977	0.9968	0.06
AECS	0.9977	0.9994	1.0003	0.9991	0.08
KRISS	0.9951	0.9949	0.9954	0.9951	0.02
NMIJ	N/A	N/A	N/A	N/A	N/A
NMISA	1.0023	0.9924	1.0003	0.9984	0.34
DMSC	1.0010	0.9975	1.0024	1.0003	0.16
BARC	1.0036	0.9984	1.0029	1.0017	0.18
NIM	1.0012	0.9956	1.0014	0.9994	0.21
BATAN	1.0023	0.9981	1.0020	1.0008	0.15
INER	0.9971	0.9943	0.9983	0.9966	0.13
ARPANSA	0.9980	0.9932	0.9975	0.9962	0.17
NRL	1.0040	0.9964	1.0033	1.0012	0.27
NIS	0.9971	0.9943	1.0048	0.9987	0.35

4.5 Uncertainties u_{tr} and u_{LINK}

Estimates of u_{tr} based on the spread of ratios for different chambers ranged from 0.02% to 0.35%. For any given participant, these estimates were consistent when compared across the three link laboratories, and when averaged were higher or at least consistent with the pilot laboratory's estimates of the stability. The averages ranged from 0.08% to 0.32% and these values were used in equation (2).

Except three link laboratories, the estimate of u_{LINK} from equation (7) has the same value, 0.12%, for other participating laboratory linked by all three link laboratories. This value gave an estimate that was almost larger than estimate using equation (5) and then it was used in equation (2) for all laboratory.

4.6 Degrees of equivalence

The ratios $R_{\mathrm{i,PTB}}$, $R_{\mathrm{i,ARPANSA}}$ and $R_{\mathrm{i,NMIJ}}$ are the unweighted mean of the three chambers. These are then averaged to get the final comparison result R_{i} for each laboratory relative to the BIPM, as given in Table 10 and Fig. 5.

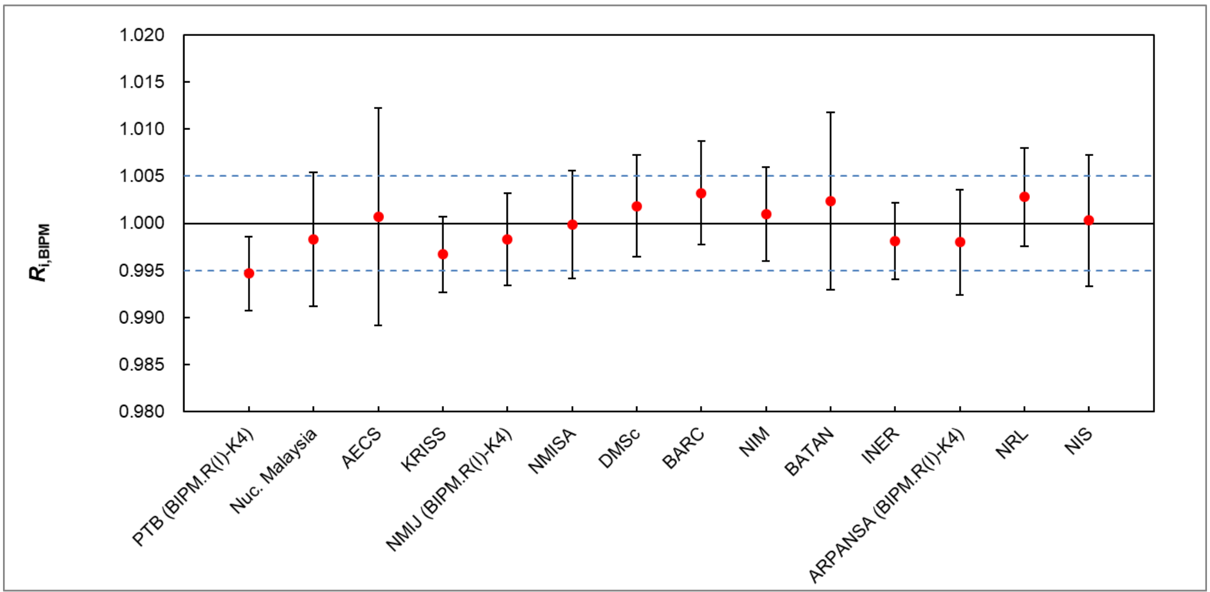

Figure 5. All results $R_{i,\mathrm{BIPM}}$ for each participating laboratory for the APMP.RI(I)-K4 comparison. Error bars show the combined standard uncertainty u_{Ri}. The three linking laboratories (linked via the other two link laboratories and indicated with brackets) are included for completeness.

Table 10. Final result: the ratio $R_{i,\mathrm{BIPM}}$ and combined relative standard uncertainty u_{Ri} (equation 2).

Participant	R_i	u_i (%)	u_{BIPM} (%)	u_{corr} * (%)	u_{tr} average (%)	u_{LINK} eq.7 (%)	**Combined $u_{R,i}$ (%)**
PTB	(0.9947) [a]	0.24	0.29	0.00	0.09	0.07	(0.39)
Nuc. Malaysia	**0.9983**	0.70	0.29	0.21	0.08	0.12	**0.71**
AECS	**1.0007**	1.14	0.29	0.21	0.14	0.12	**1.15**
KRISS	**0.9967**	0.38	0.29	0.21	0.08	0.12	**0.40**
NMIJ	(0.9983) [a]	0.40	0.29	0.15	0.12	0.16	(0.49)
NMISA	**0.9999**	0.50	0.29	0.21	0.26	0.12	**0.57**
DMSc	**1.0018**	0.52	0.29	0.21	0.11	0.12	**0.54**
BARC	**1.0032**	0.53	0.29	0.21	0.10	0.12	**0.55**
NIM	**1.0010**	0.47	0.29	0.21	0.14	0.12	**0.50**
BATAN	**1.0023**	0.90	0.29	0.13	0.09	0.12	**0.94**
INER	**0.9981**	0.36	0.29	0.19	0.10	0.12	**0.41**
ARPANSA	(0.9980) [a]	0.44	0.29	0.13	0.14	0.23	(0.56)
NRL	[1.0028] [b]	0.41	0.29	0.13	0.19	0.12	[0.52]
NIS	**1.0003**	0.61	0.29	0.21	0.32	0.12	**0.70**

[a] Link laboratories cannot change their degrees of equivalence as the result of a regional comparison. However, for each link we have used the other two link laboratories to calculate a value, for the purpose of checking the consistency of the analysis.
[b] The NRL is yet to be declared a Designated Institute and therefore cannot enter degree of equivalent in the KCDB.
[*] The combined correlated uncertainty component in equation 2, to be squared and subtracted twice (once for the NMI and once for the BIPM).

Results have been included for the link laboratories, where they have been calculated using the other two link laboratories. Although the link laboratories cannot update their values in the KCDB, the calculation is a useful check that the analysis is free of errors. The ratios (PTB, NMIJ, ARPANSA) of (0.9947, 0.983, 0.9980) differ by (-0.30%, 0.23%, 0.07%) from the Table 5 linking ratios (0.9977, 0.9960, 0.9973). We note that the differences sum to zero, as they must.

The results for all of the non-linking participants ranged from -0.33% to +0.32%, and all fell within one standard uncertainty of unity. The degrees of equivalence were calculated for eligible laboratories, and they are presented in Table 11.

Table 11. Degrees of Equivalence for the APMP.R(I)-K4 comparison.

Participant	D_i (mGy/Gy)	U_i (mGy/Gy)
Nuc. Malaysia	-1.7	14.2
AECS	0.7	23.1
KRISS	-3.3	8.0
NMISA	-0.1	11.4
DMSc	1.8	10.8
BARC	3.2	11.0
NIM	1.0	10.0
BATAN	2.3	18.8
INER	-1.9	8.1
NIS	0.3	13.9

5. Conclusion

A regional key comparison has been carried out by the Asia Pacific Metrology Program for standards of absorbed dose to water in ^{60}Co gamma rays. Three thimble type ionization chambers were used as transfer standards and circulated among the 14 laboratories for calibration. Regular stability tests at the pilot laboratory indicated that they were well behaved throughout the comparison. The ratio between chambers deviated on two occasions by as much as 1%, however if this was a problem with setup or chamber behavior it was not evident in the final results. Nearly all of the calibration coefficients fell within the stated standard uncertainty of the chambers' mean calibration coefficients, as evaluated from the comparison results. All coefficients were within two standard uncertainties of the mean, indicating reasonable agreement between all 14 participants. Three participants PTB, NMIJ and ARPANSA were used to link the results to the BIPM Key Comparison Reference Value. Thus, the degrees of equivalence were calculated for the non-linking eligible laboratories. The absorbed dose was found to be within 3.3 parts in 10^3 of the BIPM value, well within the relative expanded uncertainty which ranged from 8.0×10^{-3} to 2.3×10^{-2}. The results have not been adjusted for any changes to primary standards that may have resulted from the adoption of ICRU Report 90 [11], which was published after the measurements and linking data for this comparison were finalized.

References

[1] P. Andreo, “Absorbed dose beam quality factors for the dosimetry of high-energy photon beams,” Phys. Med. Biol. 37, 2189-2211 (1992)

[2] D.W.O. Rogers, “The advantages of absorbed-dose calibration factors,” Med. Phys. 19, 1227-1239 (1992)

[3] D. T. Burns and D.J. Butler, “Updated report on the evaluation of degrees of equivalence in regional dosimetry comparisons”, CCRI(I)/17-09 (2017)

[4] D. T. Burns and P. J. Allisy-Roberts, “The evaluation of degrees of equivalence in regional dosimetry comparisons”, CCRI(I)/07-04 (2007)

[5] P. J. Allisy-Roberts and D. T. Burns, “Summary of the BIPM.RI(I)-K4 comparison for absorbed dose to water in ^{60}Co gamma radiation”, Metrologia 42, Tech. Suppl., 06002 (2005)

[6] P. J. Allisy-Roberts, D. T. Burns and C. Kessler, “Measuring condition and uncertainties for the comparison and calibration of national dosimetric standards at BIPM,” Rapport BIPM-11/04 (2011)

[7] “Guide to the Expression of Uncertainty in Measurement,” International Organization of Standards, Switzerland (1995)

[8] C. Kessler, D.T. Burns, R.-P. Kapsch and A. Krauss, “Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the PTB, Germany and the BIPM in ^{60}Co gamma radiation”, Metrologia 53, Tech. Suppl., 06003 (2016)

[9] C. Kessler, D. T. Burns, P. J. Allisy-Roberts, D. Butler, J. Lye, D. Webb, “Comparison of the standards for absorbed dose to water of the ARPANSA and the BIPM for ^{60}Co γ radiation”, Metrologia 49, Tech. Suppl., 06009 (2012)

[10] C. Kessler, P. J. Allisy-Roberts, Y. Morishita, M. Kato, N. Takata, T. Kurosawa, T. Tanaka, N. Saito, “Comparison of the standards for absorbed dose to water of the NMIJ and the BIPM for ^{60}Co γ-ray beams”, Metrologia 48, Tech. Suppl., 06008 (2011)

[11] ICRU Report 90, Key Data For Ionizing-Radiation Dosimetry: Measurement Standards And Applications, *Journal of the International Commission on Radiation Units and Measurements*, Volume 14, Issue 1, April 2016

Appendix I: Uncertainty budgets

<u>PTB Uncertainty budget</u>

Uncertainty associated with the primary standard water calorimeter

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
1. Relative resistance change	0.02	
2. Thermistor calibration		0.07
3. Specific heat capacity of water / (J g^{-1} K^{-1})		0.03
4. Positioning		
Source to surface distance		0.01
Detector position		0.03
5. Heat conduction effects		
Detector cylinder		0.04
Pipettes		0.05
Depth-dose distribution		0.02
Lateral dose distribution		0.03
6. Chemical heat defect, h		0.14
7. Lateral dose distribution		0.01
8. Perturbation effect		0.05
9. Transfer to reference field		0.08
Quadratic sum	0.020	0.202
Combined standard uncertainty	0.21	

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
1. absorbed dose to water (D_w)	0.02	0.2
2. Ionization charge	0.01	0.02
3. Air density (temperature, pressure and humidity correction)		0.045
4. Depth in water		0.061
5. Reference distance		0.02
6. Recombination		0.09
7. Radial non-uniformity		0.01
8. Decay correction		0.01
Quadratic sum	0.022	0.234
Combined standard uncertainty	0.24	

Nuclear Malaysia Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	**Type B**
Absorbed dose rate to water		
1. Calibration coefficient of reference chamber		0.548
2. Ionization charge	0.014	
3. Air density (temperature, pressure and humidity correction)		0.036
4. Reference distance		0.058
5. Accuracy of charge measurement		0.289
6. Decay correction		0.013
Transfer chamber calibration		
1. Ionization charge	0.008	
2. Air density (temperature, pressure and humidity correction)		0.036
3. Reference distance		0.058
4. Accuracy of charge measurement		0.289
Quadratic sum	0.016	0.691
Combined standard uncertainty	0.70	

AECS Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Absorbed dose rate to water		
1. Calibration coefficient of secondary standard chamber		0.76
2. Ionization charge	0.096	0.12
3. Air density (temperature, pressure and humidity correction)		0.036
4. Depth in water		0.58
5. Reference distance		0.058
Transfer chamber calibration		
1. Ionization charge	0.097	
2. Air density (temperature, pressure and humidity correction)		0.036
3. Depth in water		0.58
4. Reference distance		0.058
Quadratic sum	0.136	1.122
Combined standard uncertainty	1.14	

KRISS Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Absorbed dose rate to water		
*KRISS reference chamber (NE2571 #261) with BIPM sleeve		
1.Calibration factor of absorbed dose to water ($N_{D,w}$)		0.3
2. Ionization current of reference chamber	0.01	0.12
3. Air density (temperature and pressure correction)		0.06
4. Humidity correction		0.03
5. Repeatibility of source position		0.01
6. Long term stability of reference chamber		0.12
Transfer chamber calibration		
*Transfer chamber with INER sleeve		
7. Ionization current of transfer chamber	0.01	0.12
8. Air density (temperature and pressure correction)		0.06
9. Humidity correction		0.03
10. Repeatability of source position		0.01
11. Depth in water		0.02
12. Decay correction		0.02
Quadratic sum	0.01	0.38
Combined standard uncertainty	0.38	

NMIJ Uncertainty budget

Uncertainty associated with the primary standard graphite calorimeter

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
1. Measurement of absorbed dose to graphite		
Power calculation (including repeatability)	0.15	0.022
Core mass (g)		0.0003
Calorimeter gaps		0.1
Graphite depth		0.06
Radial non-uniformity		0.01
Axial non-uniformity		0.02
Source decay		0.036
Impurity		0.05
Heat defect		0.1
Distance from source to reference point		0.06
2. Transfer absorbed dose rate from graphite to water		
Distance from source to reference point for the graphite phantom		0.06
Graphite depth in the graphite phantom		0.06
Distance from source to reference point for the water phantom		0.06
Water depth in the water phantom		0.1
Ionization current ratio (I_w/I_G)	0.09	
Scaling theorem $(\bar{\mu}_{en}/\rho)_{w,c}$ Water phantom window Air attenuation		0.14
Dose to kerma ratio (β)		0.05
Fluence ratio (Ψ)		0.15
Sleeve of ionization chamber in water phantom		0.1
Quadratic sum	0.175	0.328
Combined standard uncertainty	0.371	

Uncertainty associated with the calibration of the transfer chambers

Source of component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
1. Absorbed dose to water (D_w)	0.175	0.328
2. Ionization charge	0.03	0.05
3. Air density (temperature, pressure and humidity correction)		0.05
4. Depth in water		0.1
5. Reference distance		0.06
6. Radial non-uniformity		0.01
Quadratic sum	0.177	0.355
Combined standard uncertainty	0.40	

NMISA Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Absorbed dose rate to water		
1. Calibration of the standard at BIPM		0.31
2. Electrometer		0.1
3. Uncertainty related to pressure measurements (STD)		0.02
4. Uncertainty related to temperature measurements (STD)		0.17
5. Relative positioning of chamber		0.12
6. Drift of the standard		0.25
7.Charge measurements (ESDM)	0.02	
Transfer chamber calibration		
1. Electrometer		0.1
2. Relative positioning of chamber		0.12
3. Uncertainty related to pressure measurements (UUT)		0.02
4. Uncertainty related to temperature measurements (UUT)		0.17
5. Charge measurements (ESDM)	0.02	
Quadratic sum	0.03	0.49
Combined standard uncertainty	0.50	

<u>**DMSc Uncertainty budget**</u>

Uncertainty associated with the calibration of the transfer chambers

Source of component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Absorbed dose rate to water		
1. Reference calibration ($N_{D,w}$)		0.5
2. Stability of Reference chamber		0.087
3. Change in Co-60 source position		0.0065
4. Ref. measurement	0.0115	
5. Ref. recombination		0.035
6. Ref. temperature correction for cavity thermometer difference		0.0346
7. Ref. pressure correction		0.0018
Transfer chamber calibration		
1. User measurement	0.0147	
2. User recombination		0.048
3. User temperature correction for cavity thermometer difference		0.0346
4. User pressure correction		0.0018
5. User variation in depth in water		0.025
Quadratic sum	0.02	0.51
Combined standard uncertainty	0.52	

BARC Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	**Type B**
Absorbed dose rate to water		
1.Calibration coefficient of secondary standard chamber		0.43
2.Ionization charge	0.01	0.1
3.Air density (temperature, pressure and humidity correction)	0.01	0.01
4. Depth in water		0.01
5. Reference distance		0.01
6. Recombination		0.01
7. Radial non-uniformity		0.01
8. Decay correction		0.01
Transfer chamber calibration		
1. Ionization charge	0.02	0.01
2.Air density (temperature, pressure and	0.01	0.01
3. Depth in water		0.28
4. Reference distance		0.05
5. Recombination		0.01
6. Radial non-uniformity		0.01
7. Decay correction		0.01
Quadratic sum	0.026	0.526
Combined standard uncertainty	0.53	

NIM Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Absorbed dose rate to water		
1. $N_{D,w}$ of NIM reference chamber		0.30
2. Long-term stability of reference chamber		0.20
3. Ionization charge	0.04	0.08
4. Position of reference chamber		0.1
5. Air density (temperature, pressure and humidity correction)		0.06
6. Depth in water		0.1
7. Recombination	0.03	0.06
8. Radial non-uniformity	0.03	0.05
9. Influence of field size		0.05
Transfer chamber calibration		
10. Ionization charge	0.04	0.08
11. Air density (temperature, pressure and humidity correction)		0.07
12. Depth in water		0.12
13. Reference distance		0.08
14. Recombination	0.02	0.06
15. Radial non-uniformity	0.03	0.05
16. Decay correction		0.02
17. Influence of field size		0.05
Quadratic sum	0.079	0.458
Combined standard uncertainty	0.47	

BATAN Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Absorbed dose rate to water		
1. Calibration coefficient for the reference chamber		
·Uncertainty of calibration at ARPANSA		0.400
·Stability of the reference instrument		0.578
2. Correction for change in source position		0.220
3. Raw reading of the reference instrument	0.007	
4. Temperature during reference measurement		
·Thermometer calibration		0.263
·Resolution of thermometer		0.304
5. Pressure during reference measurement		
·Barometer calibration		0.066
·Resolution of barometer		0.076
Transfer chamber calibration		
1. Raw reading of the instrument to be calibrated		0.058
2. Temperature during user measurement		0.263
3. Pressure during user measurement		0.066
4. Deviation in chamber depth in phantom		0.05
Quadratic sum	0.007	0.891
Combined standard uncertainty	0.90	

INER Uncertainty budget

Uncertainty associated with the primary standard parallel-plate graphite cavity ionization chamber

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
1. Physical constants		
· ρ_a [a] (g cm^{-3})		0.01
· W/e (J C^{-1}) · $\bar{S}_{c,a}$		0.11
2. Perturbation correction factor		
k_{cav} (air cavity)	0.03	0.04
$(\bar{\mu}_{en}/\rho)_{w,c}$	0.01	0.14
$\psi_{w,c}$ (photon fluences ratio)	0.04	0.06
$(1+\varepsilon)_{w,c}$ (dose to kerma ratio)		0.06
3. Other correction factors		
k_s (recombination losses)		0.02
k_{pf} (phantom window)		0.01
k_{ps} (PMMA envelope)		0.02
k_{rn} (radial non-uniformity)	0.01	0.03
k_h (humidity)		0.03
4. V (cm^3)	0.08	
5. I (ionization current)	0.04	0.01
6. Long-term stability	0.17	
7. Air density correction		0.10
Quadratic sum	0.198	0.231
Combined standard uncertainty	0.30	

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
1. absorbed dose to water (D_w)	0.198	0.231
2. Ionization charge	0.12	0.05
3. Air density (temperature, pressure and humidity correction)		0.10
4. Depth in water		0.04
5. Reference distance		0.06
6. Radial non-uniformity		0.04
7. Decay correction		0.02
Quadratic sum	0.232	0.270
Combined standard uncertainty	0.36	

ARPANSA Uncertainty budget

Uncertainty associated with the primary standard graphite calorimeter

Source of component	Relative standard uncertainty (%)	
	Type A	**Type B**
1. Determination of absorbed dose to graphite		
·Electrical power	0.08	
·Mass of the core		0.01
·Repeatability	0.07	
·Radial non-uniformity		0.05
2. Conversion to absorbed dose rate to water by calculation $(D_w/D_{core})_{MC}$ conversion from graphite to water	0.21	0.32
Quadratic sum	0.24	0.32
Combined standard uncertainty	0.40	

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	**Type B**
1. Absorbed dose to water (D_w)	0.24	0.32
2. Ionization current of the transfer chamber	0.07	
3. Distance		0.10
4. Depth in water		0.11
5. Normalization T, P		0.05
6. Electrometer calibration factor		0.05
7. Ion recombination		0.01
8. Polarity		0.01
9. Source decay		0.02
10. Radial non-uniformity		0.05
11. Phantom window		0.02
Quadratic sum	0.25	0.36
Combined standard uncertainty	0.44	

NRL Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	**Type B**
1. absorbed dose to water (D_w)		0.4
2. Ionization charge	0.01	0.05
3. Air density (temperature, pressure and humidity correction)		0.05
4. Recombination		0.01
Quadratic sum	0.010	0.406
Combined standard uncertainty	0.41	

NIS Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Absorbed dose rate to water		
1.Calibration coefficient of secondary standard chamber		0.17
2.Ionization charge	0.1	0.205
3.Air density (temperature, pressure and humidity correction)	0.1	0.09
4. Depth in water		0.15
5. Reference distance	0.01	0.1
6. Recombination	0.1	0.125
7. Radial non-uniformity	0.1	0.15
8. Decay correction		0.005
Transfer chamber calibration		
1. Ionization charge		0.0034
2.Air density (temperature, pressure and	0.1	0.09
3. Depth in water		0.15
4. Reference distance	0.01	0.1
5. Recombination	0.1	0.125
6. Radial non-uniformity	0.1	0.15
7. Decay correction		0.0005
8. Repeatability of measurements	0.27	
Quadratic sum	0.378	0.478
Combined standard uncertainty	0.61	