APMP/TCRI Key Comparison Report of Measurement of Air Kerma for Medium-Energy X-Rays (APMP.RI(I)-K3.2013)

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Abstract

The APMP/TCRI Dosimetry Working Group initiated the APMP.RI(I)-K3.2013 key comparison of measurement of air kerma for medium-energy x-rays (100 kV to 250 kV); measurements took place between 2015 and 2017. In total, 11 institutes took part in the comparison, among which 8 were APMP member laboratories, two from AFRIMETS and one from SIM. Three commercial cavity ionization chambers were used as transfer standards circulated among the participants. All the participants established 100, 135, 180 and 250 kV x-ray beam qualities equivalent to those of the BIPM. The ARPANSA and the NMIJ were linking laboratories and two participants subsequently made comparisons with the BIPM. The 7 other participants' degrees of equivalence fell within 11 parts in 10^3 of unity, well within the relevant expanded uncertainty (k = 2) in all cases. Excluding the BARC, the results were within 5.7 parts in 10^3, well within the relevant combined standard uncertainty. These results indicated that the calibration capabilities of most laboratories were in very good agreement and there were no serious discrepancies between them. The effect of implementing the recommendations of ICRU Report 90, which occurred on 1 January 2018 (after this comparison), is discussed and we deduce that the effect on the degrees of equivalence is negligible. The increase in the uncertainty in W_{air} has been added to all laboratories so that the degrees of equivalence and the uncertainties published here are applicable to post-ICRU 90 measurement results.

Keywords: APMP Key Comparison, air kerma for medium-energy x-rays, degree of equivalence

1. Introduction

Due to more than 10 years having elapsed since the previous APMP.RI(I)-K3 air kerma for medium-energy x-rays key comparison [1], the Institute of Nuclear Energy Research (INER) was invited by the TCRI chair in 2014 to act as the coordinator of the next APMP.RI(I)-K3 key comparison [2]. Thus, from July 2015, INER designed and delivered a questionnaire to each member laboratory to gauge their intentions with respect to this comparison. Table 1 gives information for the participating laboratories and contact persons for this APMP.RI(I)-K3 key comparison.

Table 1. Participating laboratories and contact persons for the APMP.RI(I)-K3.2013 key comparison

Participating Laboratory	Abbreviation, Economy	Contact Person	Comment
Australian Radiation Protection and Nuclear Safety Agency	ARPANSA, Australia	Duncan.Butler	Link 1
Bhabha Atomic Research Centre	BARC, India	V. Sathian	
National Nuclear Energy Agency of Indonesia	BATAN, Indonesia	C. Tuti Budiantari	
Institute of Nuclear Energy Research	INER, Taiwan	Chien-Hau Chu	Pilot
Korea Research Institute of Standards and Science	KRISS, Republic of Korea	Chul-Young Yi	
Brazilian Metrology Laboratory of Ionizing Radiations	LNMRI-IRD, Brazil	Karla Patrao, Paulo Rosado	SIM
National Metrology Institute of South Africa	NMISA, South Africa	Sibusiso Jozela, Sonwabile Ngcezu	AFRIMETS
National Institute of Metrology	NIM, China	Jinjie Wu	
National Institute of Standards	NIS, Egypt	Ahmed Rashad El-Sersy, Eman, S. A., N. R. Khaled and Mohmed H. Hassan	AFRIMETS
National Metrology Institute of Japan	NMIJ, Japan	Takahiro Tanaka	Link 2
Malaysian Nuclear Agency	Nuclear Malaysia, Malaysia	Mohd Taufik Dolah	

2. Procedure and protocol

2.1 Comparison methodology

In this comparison, there was a star-shaped circulation of the transfer chambers among the participants. Before the transfer chambers were delivered to the first participant, they were tested at the INER to check that the chambers were stable. After being circulated to 2-4 participants, the chambers were sent back to the INER for constancy tests, which included a ^{60}Co air kerma measurement. Every participant was asked to provide air kerma calibration coefficients, N_K, and uncertainties $u(N_K)$ for each transfer standard, for each of the four x-ray beam qualities.

Two participating laboratories the ARPANSA and the NMIJ that had completed the BIPM.RI(I)-K3 comparison with the Bureau International des Poids et Mesures (BIPM) were used to link the results to the BIPM Key Comparison Reference Value. Two further participants, the KRISS and the NIM, subsequently participated in the BIPM.RI(I)-K3 comparison. For this reason their results obtained in the present comparison are not used to evaluate degrees of equivalence. While in principle they could have served as additional linking laboratories, this was not possible because their results in the BIPM.RI(I)-K3 comparison were not finalized at the time of analyzing the present data. Nevertheless, their results in both comparisons can be used to assess consistency.

2.2 Transfer standards

Photographs of the equipment provided by the INER for this comparison are shown in Figure 1 and the main characteristics of the three transfer chambers are listed in Table 2. The collecting voltage stated in the table, consistent with the manufacturer specification, was applied to each chamber, and the equipment was allowed to settle during a warm-up period, according to local procedures, before starting the measurement.

Table 2. Specifications of the transfer chambers

Type	Cavity volume /cm^3	Geometry	Wall material	Bias voltage*	Connector
NE 2571 S/N 3716	0.69	Cylindrical (24 mm long, 3.2 mm radius)	Graphite	250 V	TNC
PTW 30001 S/N 2340	0.6	Cylindrical (23 mm long, 3.1 mm radius)	Acrylic /graphite	400 V	BNT
EXRADIN A3 S/N XR143432	3.6	Spherical (9.7 mm radius)	Shonka air-equivalent plastic C552	300 V	BNT

*Sign of bias voltage chosen such that charge collected by central electrode is negative

All chambers were used without buildup caps in the comparison. However, for the constancy checks in ^{60}Co at the INER, buildup caps were used. We note that the PTW 30001 S/N 2340 chamber was used in the previous APMP.RI(I)-K3 comparison, although the other two chambers had not been used in APMP comparisons.

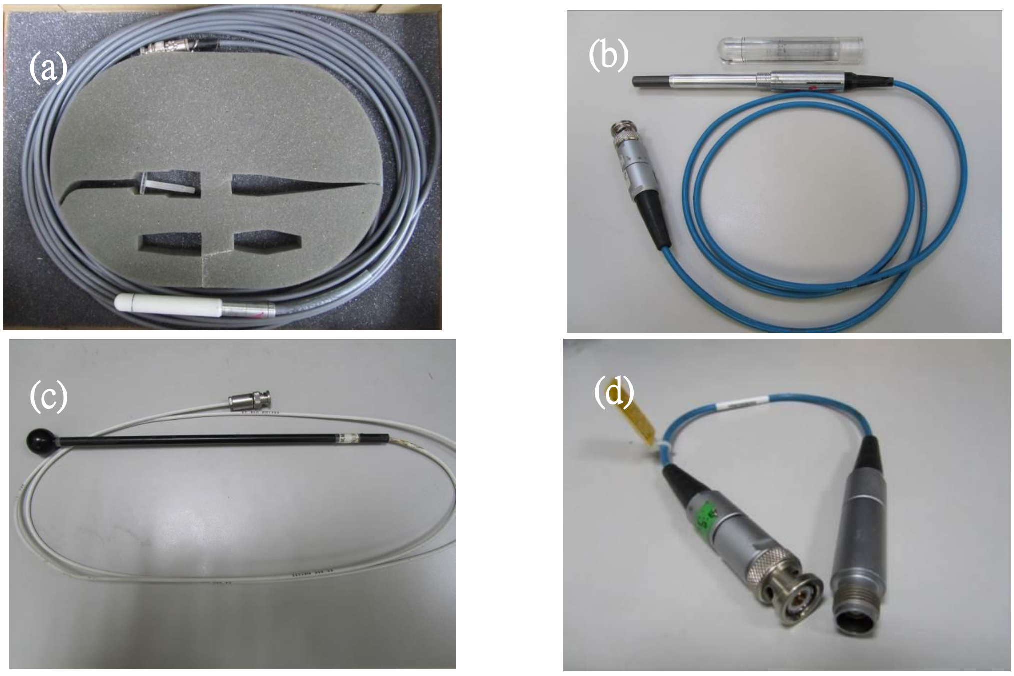


Figure 1: (a) NE 2571 chamber (S/N 3716), (b) PTW 30001 chamber (S/N 2340), and (c) EXRADIN A3 chamber (S/N XR143432), (d) TNC/BNT adaptor

2.3 Reference conditions

The international comparisons for medium-energy x-rays are made on the basis of beam qualities that have been approved by the CCRI and are used at the BIPM. The four beam qualities are indicated in Table 3. All the chamber calibration coefficients were normalized to 20 ℃ and 101.325 kPa and were provided in units of Gy/C. The traceability of the standard used at each laboratory and the calibration conditions are given in Table 4.

Table 3. Reference beam qualities at the BIPM (100 kV to 250 kV)

X-ray tube voltage /kV	100	135	180	250
Al filtration / mm	3.431	2.228	2.228	2.228
Cu filtration / mm	—	0.232	0.485	1.570
Al half-value layer / mm	4.030	—	—	—

Cu half-value layer / mm	0.149	0.489	0.977	2.484
$\bar{\mu}/\rho$ [(1)] / $cm^2\ g^{-1}$	0.290	0.190	0.162	0.137
Air-kerma rate / (mGy s^{-1})	0.50	0.50	0.50	0.50

[(1)] mass air-attenuation coefficient

Table 4. HVL values for the APMP.RI(I)-K3.2013 key comparison for all participants as stated by the laboratory

Participant	HVL (mm Al)	HVL (mm Cu)		
	BIPM-100	BIPM-135	BIPM-180	BIPM-250
ARPANSA	4.06	0.44	0.94	2.42
BARC	4.002	0.493	1.009	—
BATAN	4.030	0.52	1.00	2.51
INER	4.058	0.489	0.983	2.477
KRISS	4.025	0.497	1.004	2.535
LNMRI-IRD	0.15 (Cu)	0.481	0.983	2.479
NMISA	3.998	0.503	0.991	2.521
NIM	4.034	0.491	0.999	2.515
NIS	0.149 (Cu)	0.489	0.984	—
NMIJ	4.031	0.489	0.977	2.484
Nuclear Malaysia	3.954	0.499	0.951	2.521

Table 5. Air kerma traceability and transfer chamber calibration conditions for each participant

Participant	Traceability	Source-detector distance (cm)	Beam diameter (mm)	Air kerma rate (mGy s^{-1})			
				100 kV	135 kV	180 kV	250 kV
ARPANSA	ARPANSA	100	100	2.50	1.90	2.00	2.00
BARC	BARC	120	102	0.95	1.00	0.92	—
BATAN	IAEA[a]	100	100	1.05	0.93	1.38	1.17
INER	INER	100	100	0.49	0.46	0.71	0.84
KRISS	KRISS	100	100	0.47	0.46	0.52	0.51
LNMRI-IRD	IAEA[a]	100	100	0.50	0.50	0.50	0.50
NMISA	BIPM	100	97	0.50	0.50	0.49	0.50
NIM	NIM	100	128	0.83	0.83	0.82	0.81
NIS	BIPM	120	100	0.74	0.66	0.62	—
NMIJ	NMIJ	120	110	0.46	0.45	0.48	0.47
Nuclear Malaysia	IAEA[a]	100	120	0.66	0.71	0.83	1.02

[a] The IAEA Secondary Standards Dosimetry Laboratory, which is traceable to the BIPM.

2.4 Schedule

After discussion with all participating laboratories, the comparison was scheduled to begin in November 2015 and was completed in October 2017. The total time period of chamber delivery and calibration for each participant was about one month. Each participant was expected to measure the transfer chambers for no longer than 15 days. The comparison time schedule is shown in Table 6.

Table 6. Time schedule of APMP.RI(I)-K3.2013 comparison

Participant	Calibration measurements at the participant	Transfer to the next participant or return to INER
INER		
NMISA	11-Nov-15	25-Nov-15
ARPANSA	12-Dec-15	2-Jan-16
BATAN	20-Jan-16	10-Feb-16
NMIJ	27-Feb-16	20-Mar-16
INER	7-Apr-16	27-Apr-16
NIM	16-Jun-16	7-Jul-16
KRISS	24-Jul-16	14-Aug-16
INER	1-Sep-16	22-Sep-16
NIS	9-Oct-16	30-Oct-16
LNMRI-IRD	7-Nov-16	9-Dec-16
INER	27-Dec-16	17-Jan-17
Nuclear Malaysia	9-Aug-17	30-Aug-17
BARC	17-Sep-17	9-Oct-17
INER	27-Oct-17	

2.5 Calibration results and uncertainty evaluations

Participants were requested to submit calibration and uncertainty evaluation results within a month of the calibrations. The format of these results should be identical to that normally used by the participating laboratories. The submission must include at least the air kerma calibration coefficients (Gy C^{-1}) of the transfer chambers, the air kerma rate of the radiation field (mGy s^{-1}), the calibration distance, the field size and the expanded uncertainty (with coverage factor $k = 2$) of the calibration coefficients. To report the results, a MS-Excel worksheet was provided in which the information about the primary standard used by the participants was to be supplied.

All the laboratories were required to evaluate the uncertainty of calibration coefficients as Type A and Type B according to the criteria of the "Guide to The Expression of Uncertainty in Measurement" issued by the International Organization for Standardization (ISO) [3].

3. Evaluation of degrees of equivalence

The calculation of the degrees of equivalence follows references [4-6]. These documents describe the calculation of the ratio to the BIPM reference value, taking into account multiple transfer standards and multiple link laboratories. Both linking laboratories conducted indirect comparisons with the BIPM, and for this indirect case:

$$R_i = \frac{N_{K,i}}{N_{K,\mathrm{LINK}}} R_{\mathrm{LINK,BIPM}} = \frac{\dot{K}_i / I_i}{\dot{K}^{\mathrm{reg}}_{\mathrm{LINK}} / I^{\mathrm{reg}}_{\mathrm{LINK}}} \frac{\dot{K}^{\mathrm{inter}}_{\mathrm{LINK}} / I^{\mathrm{inter}}_{\mathrm{LINK}}}{\dot{K}_{\mathrm{BIPM}} / I_{\mathrm{BIPM}}} \qquad (1)$$

Here $N_{K,i}$ is the transfer chamber calibration coefficient for laboratory i which has been expanded on the right-hand side to its components $\dot{K}_i/I_i$, the ratio of the air kerma rate to the ionization current of the transfer standard.

Each linking laboratory has two instances of $\dot{K}_i / I_i$: one in this regional comparison (superscript 'reg') and one in the ongoing BIPM intercomparison BIPM.RI(I)-K3 (superscript 'inter'). The latter is denoted $R_{\mathrm{LINK,BIPM}}$ and is described in the relevant comparison report for the ARPANSA [7] and the NMIJ [8]. The linking ratios are given in Table 7.

Table 7. Key comparison ratios $R_{\mathrm{LINK,BIPM}}$ for air kerma in medium-energy x-ray beams for the ARPANSA and the NMIJ

Link Laboratory	Year of comparison	$R_{\mathrm{LINK,BIPM}}$				Combined standard uncertainty
		100 kV	*135 kV*	*180 kV*	*250 kV*	
ARPANSA	2010	1.0037	1.0056	1.0060	1.0053	0.0039
NMIJ	2015	0.9992	0.9986	0.9976	0.9963	0.0031

Following [4] the uncertainty in R_i is given by

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

where u_i is the combined standard uncertainty in $N_{K,i}$ (not including a component for the long-term stability of the transfer standards) and u_{BIPM} is the combined standard uncertainty of the BIPM air kerma realization [7,8] of 0.19 %. When the increase in the uncertainty of W/e recommended in ICRU Report 90 [9] is taken into account, u_{BIPM} increases from 0.19% [7] to 0.37% [10]. The other terms are discussed in the following sections.

The degree of equivalence, D_i, for each of the 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 $f_j\ u_{\mathrm{BIPM},,j}$ that are correlated between laboratory i and the BIPM, with correlation factor f_j. Participants can be divided into two groups according to their traceability: primary and secondary (see Table 4). The primary laboratories all use free air chambers that are correlated with the BIPM due in particular to the use of the same value for W_{air} and its uncertainty of 0.35 % adopted following ICRU 90.

The five secondary laboratories are all traceable to the BIPM, either directly or through the IAEA. So the secondary laboratories are correlated via the use of the same free air chamber, while the primary laboratories are correlated through different (but similar) free air chambers. The Type B standard uncertainty of the BIPM free air chamber is some 0.37% [10] (including ICRU 90) which we take as the correlated component for BIPM-traceable laboratories.

3.2 Estimates of u_{tr}

The uncertainty u_{tr} arises during the measurement of the transfer standards at each participating laboratory i. 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 constancy tests can be used to confirm that the transfer standards are behaving as expected throughout the comparison, and the results included as u_{tr} if the variation is larger than expected. These results are given in Section 1 and indicate that the chambers were stable and behaving normally.

The variation between the comparison ratios for the multiple transfer standards can be used to provide an alternative estimate of u_{tr}. Following [4] 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 $R_{i,j,k}$ to the BIPM reference value according to Equation (1), for each linking laboratory, resulting in $q = 2$ ratios for each chamber. When the ratios for each linking laboratory are averaged over the $p = 3$ chambers, the ratio of the laboratory dose to the BIPM dose is obtained, for each linking laboratory k:

$$R_{i,k} = \frac{\sum_j R_{i,j,k}}{p} \qquad (3)$$

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

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

This leads to $q = 2$ values for $u_{tr,k}$ for each laboratory. The use of p–1.4 rather than the usual p–1 is taken from [4]. We combined the two estimates $u_{tr,k=1}$ and $u_{tr,k=2}$ to obtain u_{tr} from $1/u^2_{tr} = 1/u^2_{tr,k=1} + 1/u^2_{tr,k=2}$. For some laboratories and beam qualities, these estimates were larger than the values determined from the laboratory uncertainty budgets, and so we chose to include the estimates from Equation 4 (for all laboratories) and these values appear later in Tables 12 to 15.

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 (Type A) uncertainties in $\dot{K}_{\mathrm{air}}$ and I at the link (included twice, once for the BIPM international comparison and once for this regional comparison) and the combined uncertainty in the BIPM determination of current. The estimates for each link can be combined:

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

An alternative estimate of u_{LINK} can be obtained from the variation between the ratios calculated for the different linking laboratories. Still following [4], we average over the q = 2 links to obtain the final result, R_i, as the unweighted mean of the $R_{i,k}$:

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

and calculate the corresponding uncertainty:

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

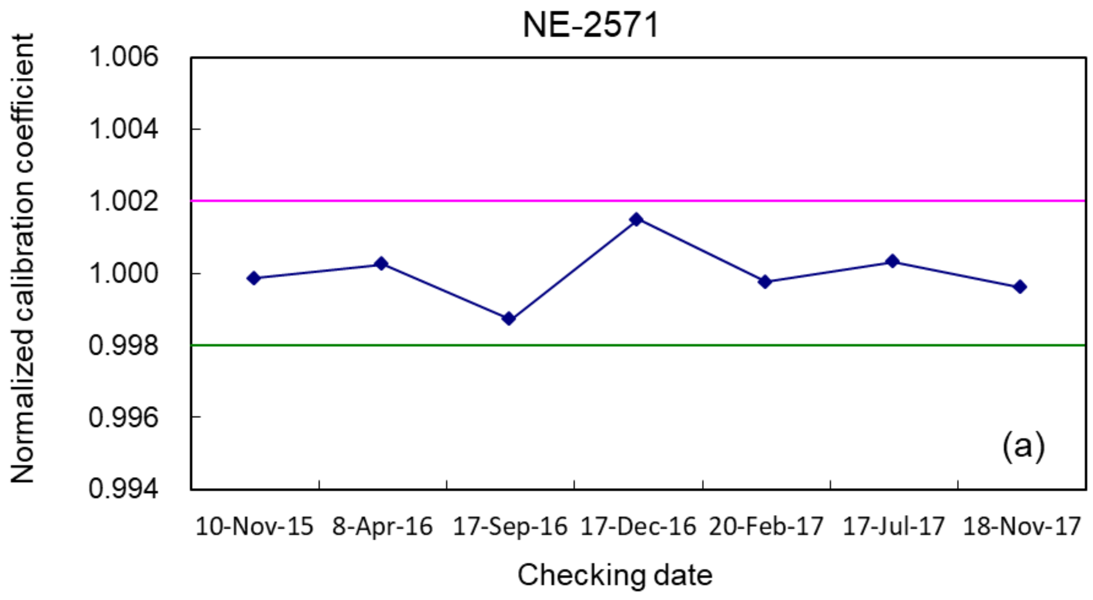
The best estimate of u_{LINK} is derived from Equation (5) or (7), whichever is the larger. In this way, differences in the results for the two linking laboratories are taken into account if they are larger than expected from the statistical uncertainties included in Equation (5).

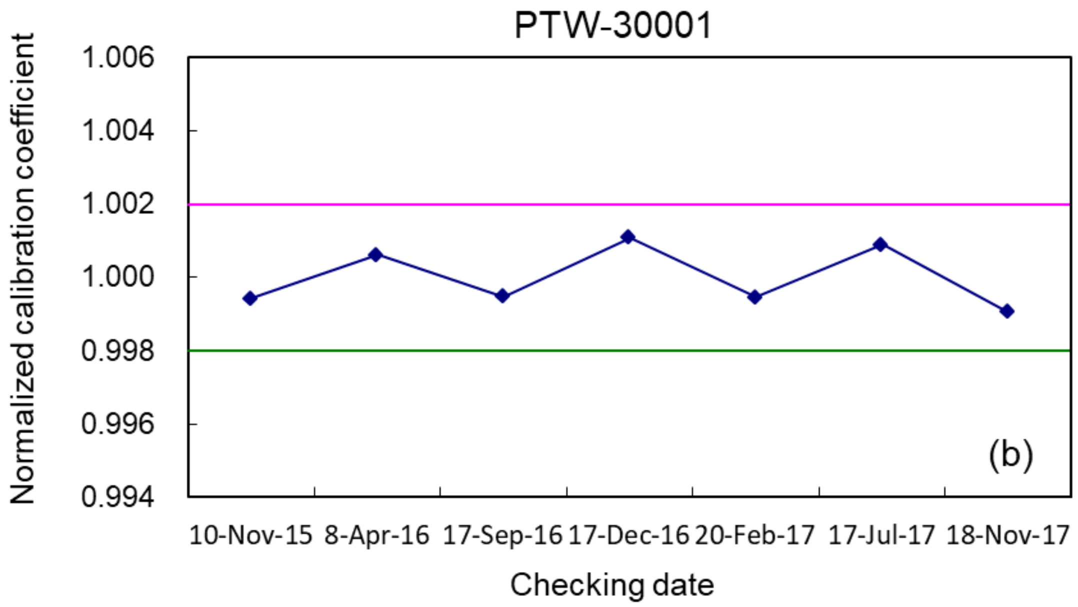
The estimates of u_{LINK} from Equation (7) were 0.16% (100 kV), 0.09% (135 kV), 0.09% (180 kV) and 0.12% (250 kV). These values are larger than the estimate using Equation (5), 0.06%, and so were used for the evaluation of $u_{R,i}$ for each laboratory using Equation (2), as given in Tables 12 to 15.

4. Results and discussion

4.1 Transfer chamber stability

The results of the transfer chamber constancy tests made in the ^{60}Co reference beam at the INER are given in Figure 2. The standard deviation of the chamber response was 0.08%, 0.08% and 0.06% for the NE-2571, PTW-30001 and Exradin A3, respectively. From these values and the lack of a trend on the graphs, we conclude the transfer chambers behaved normally during this comparison.


NE-2571
Normalized calibration coefficient
1.006
1.004
1.002
1.000
0.998
0.996
0.994
(a)
10-Nov-15
8-Apr-16
17-Sep-16
17-Dec-16
20-Feb-17
17-Jul-17
18-Nov-17
Checking date


PTW-30001
Normalized calibration coefficient
1.006
1.004
1.002
1.000
0.998
0.996
0.994
(b)
10-Nov-15
8-Apr-16
17-Sep-16
17-Dec-16
20-Feb-17
17-Jul-17
18-Nov-17
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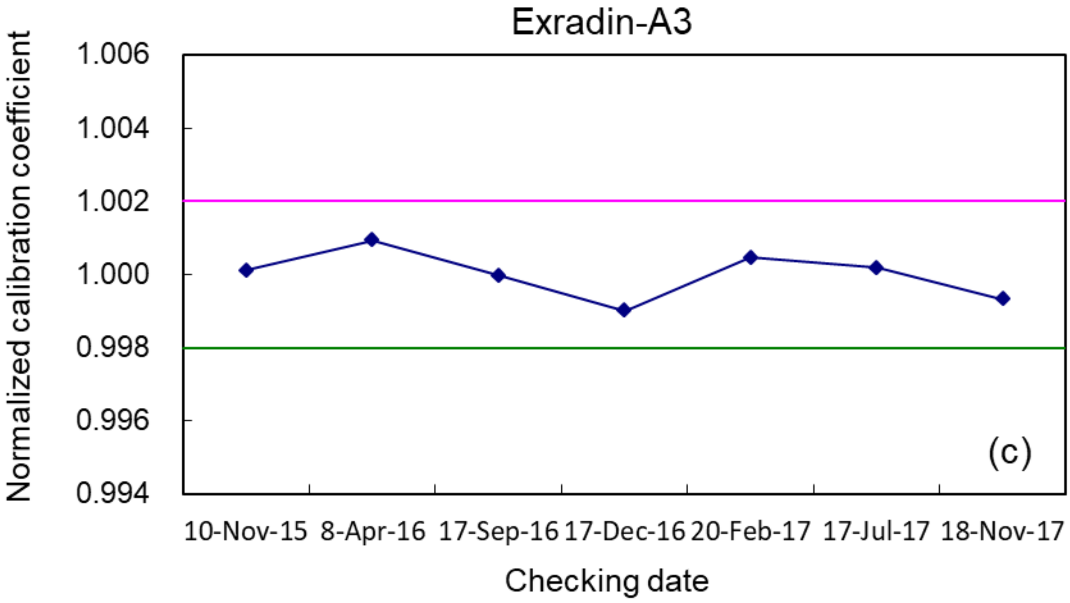

Figure 2. Constancy results of transfer chamber measurements made in the ^{60}Co beam at the INER (a) NE-2571 (S/N 3716) (b) PTW-30001 (S/N 3240) (c) Exradin-A3 (S/N XR143432)

4.2 Calibration coefficients and uncertainties

The calibration coefficients and uncertainties for the transfer chamber calibrations are given in Table 8 to Table 11. Each laboratory chose to report the same relative uncertainty for all three chambers. Two laboratories, the BARC and the NIS, did not provide results for the 250 kV_p beam quality. Detailed uncertainty budgets are given in Appendix A.

Before the report was written the pilot laboratory noticed that the results of the BARC appeared to be anomalous. In line with the procedures for key comparisons, the pilot asked the BARC to check their results, without indicating the magnitude or direction of the possible discrepancy. The BARC subsequently found a transcription error and provided corrected results.

Table 8. Reported BIPM-100 calibration coefficients of the transfer chambers for the APMP RI(I)-K3.2013 key comparison

Participant	*BIPM-100* N_K (10^7 Gy C^{-1})			Relative standard uncertainty* $u_i(N_K)$ (%)
	NE-2571 S/N 3716	PTW-30001 S/N 2340	Exradin A3 S/N XR-143432	
ARPANSA	4.175	4.674	0.7913	0.49
BARC	4.209	4.742	0.7945	0.71
BATAN	4.181	4.662	0.7884	0.73
INER	4.186	4.663	0.7902	0.58
KRISS	4.195	4.670	0.7933	0.43
LNMRI-IRD	4.161	4.676	0.7910	0.58
NMISA	4.173	4.657	0.7835	0.53
NIM	4.187	4.677	0.7891	0.58
NIS	4.187	4.677	0.7936	0.86
NMIJ	4.182	4.651	0.7890	0.52
Nuclear Malaysia	4.121	4.663	0.7929	0.56

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

Table 9. Reported BIPM-135 calibration coefficients of the transfer chambers for the APMP RI(I)-K3.2013 key comparison

Participant	*BIPM-135* N_K (10^7 Gy C^{-1})			Relative standard uncertainty* $u_i(N_K)$ (%)
	NE-2571 S/N 3716	PTW-30001 S/N 2340	Exradin A3 S/N XR-143432	
ARPANSA	4.158	4.708	0.7963	0.49
BARC	4.209	4.752	0.7912	0.71
BATAN	4.157	4.695	0.7947	0.73
INER	4.151	4.693	0.7980	0.58
KRISS	4.156	4.694	0.7963	0.43
LNMRI-IRD	4.132	4.698	0.7937	0.58
NMISA	4.141	4.692	0.7913	0.53
NIM	4.142	4.690	0.7911	0.58
NIS	4.150	4.717	0.7982	0.86
NMIJ	4.142	4.674	0.7919	0.52
Nuclear Malaysia	4.121	4.712	0.7963	0.56

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

Table 10. Reported BIPM-180 calibration coefficients of the transfer chambers for the APMP RI(I)-K3.2013 key comparison

Participant	*BIPM-180* N_K (10^7 Gy C^{-1})			Relative standard uncertainty*
	NE-2571 S/N 3716	PTW-30001 S/N 2340	Exradin A3 S/N XR-143432	$u_i(N_K)$ (%)
ARPANSA	4.143	4.747	0.7997	0.49
BARC	4.165	4.787	0.7950	0.71
BATAN	4.111	4.714	0.7942	0.73
INER	4.133	4.730	0.7980	0.58
KRISS	4.136	4.726	0.7983	0.43
LNMRI-IRD	4.114	4.728	0.7956	0.58
NMISA	4.122	4.725	0.7943	0.53
NIM	4.129	4.729	0.7946	0.58
NIS	4.118	4.738	0.7981	0.86
NMIJ	4.120	4.707	0.7941	0.52
Nuclear Malaysia	4.102	4.727	0.7962	0.56

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

Table 11. Reported BIPM-250 calibration coefficients of the transfer chambers for the APMP RI(I)-K3.2013 key comparison

Participant	*BIPM-250* N_K (10^7 Gy C^{-1})			Relative standard uncertainty*
	NE-2571 S/N 3716	PTW-30001 S/N 2340	Exradin A3 S/N XR-143432	$u_i(N_K)$ (%)
ARPANSA	4.121	4.786	0.8009	0.49
BARC	N/A	N/A	N/A	N/A
BATAN	4.107	4.788	0.7986	0.73
INER	4.113	4.769	0.8002	0.58
KRISS	4.114	4.758	0.7981	0.43
LNMRI-IRD	4.103	4.770	0.7963	0.58
NMISA	4.096	4.767	0.7960	0.53
NIM	4.113	4.776	0.7969	0.58
NIS	N/A	N/A	N/A	N/A
NMIJ	4.097	4.747	0.7951	0.52
Nuclear Malaysia	4.066	4.733	0.7939	0.56

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

The calibration coefficients for the BIPM 100, 135, 180 and 250 kV_p qualities are plotted in Figures 3-6. The standard deviation of the distribution of the calibration coefficients was 0.58 % (NE-2571), 0.49 % (PTW-30001) and 0.51 % (Exradin-A3) and twice this value has been indicated on each graph. The uncertainty bars 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 one standard uncertainty of the mean.

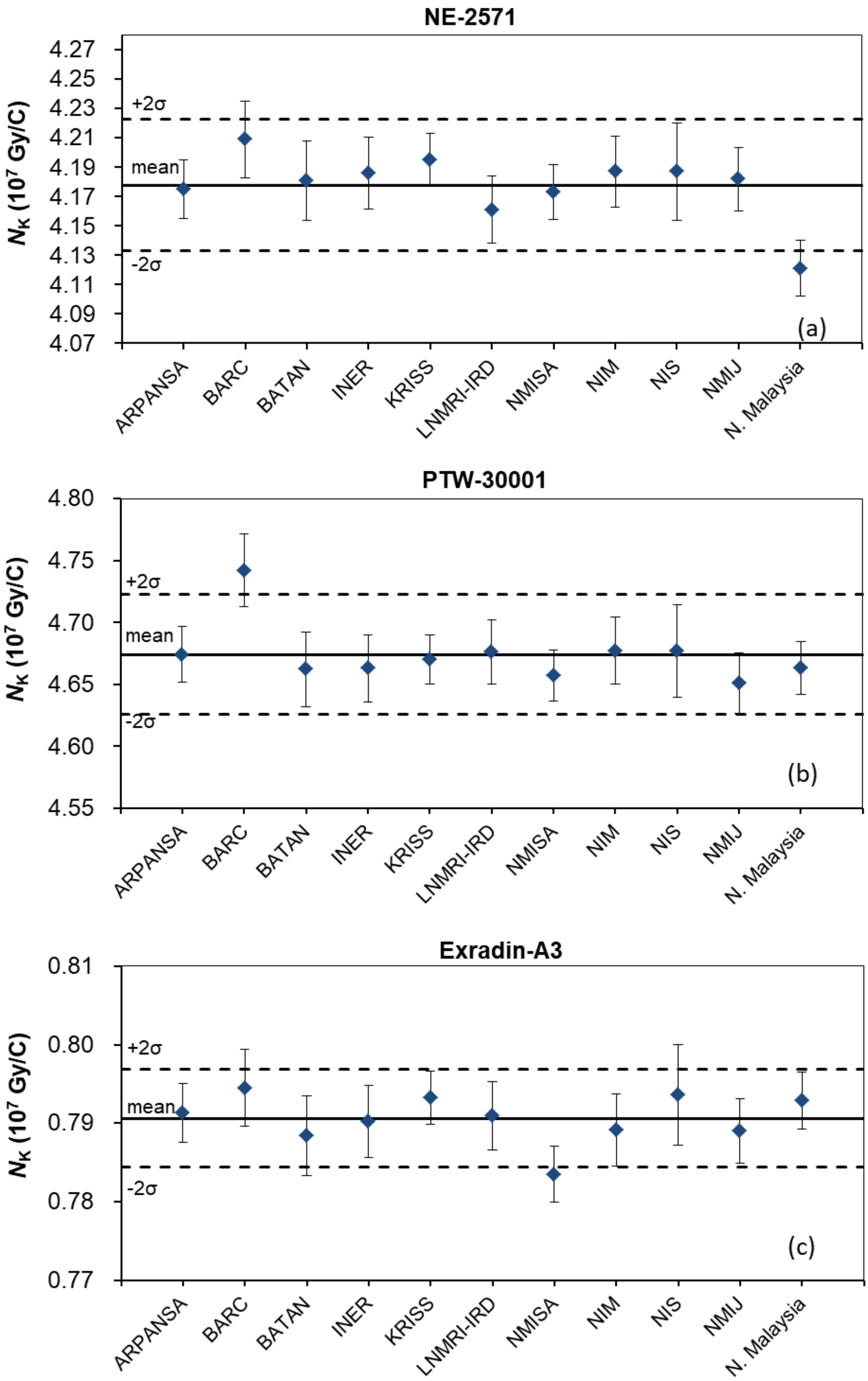

Figure 3. Calibration coefficients (N_K) of each transfer chamber for BIPM-100 with twice the standard deviation of the distribution indicated, for (a) NE-2571 (S/N 3716), (b) PTW-30001 (S/N 2340) and (c) Exradin-A3 (S/N 143432). The uncertainty bars show the laboratory's reported standard uncertainty $u(N_K)$.

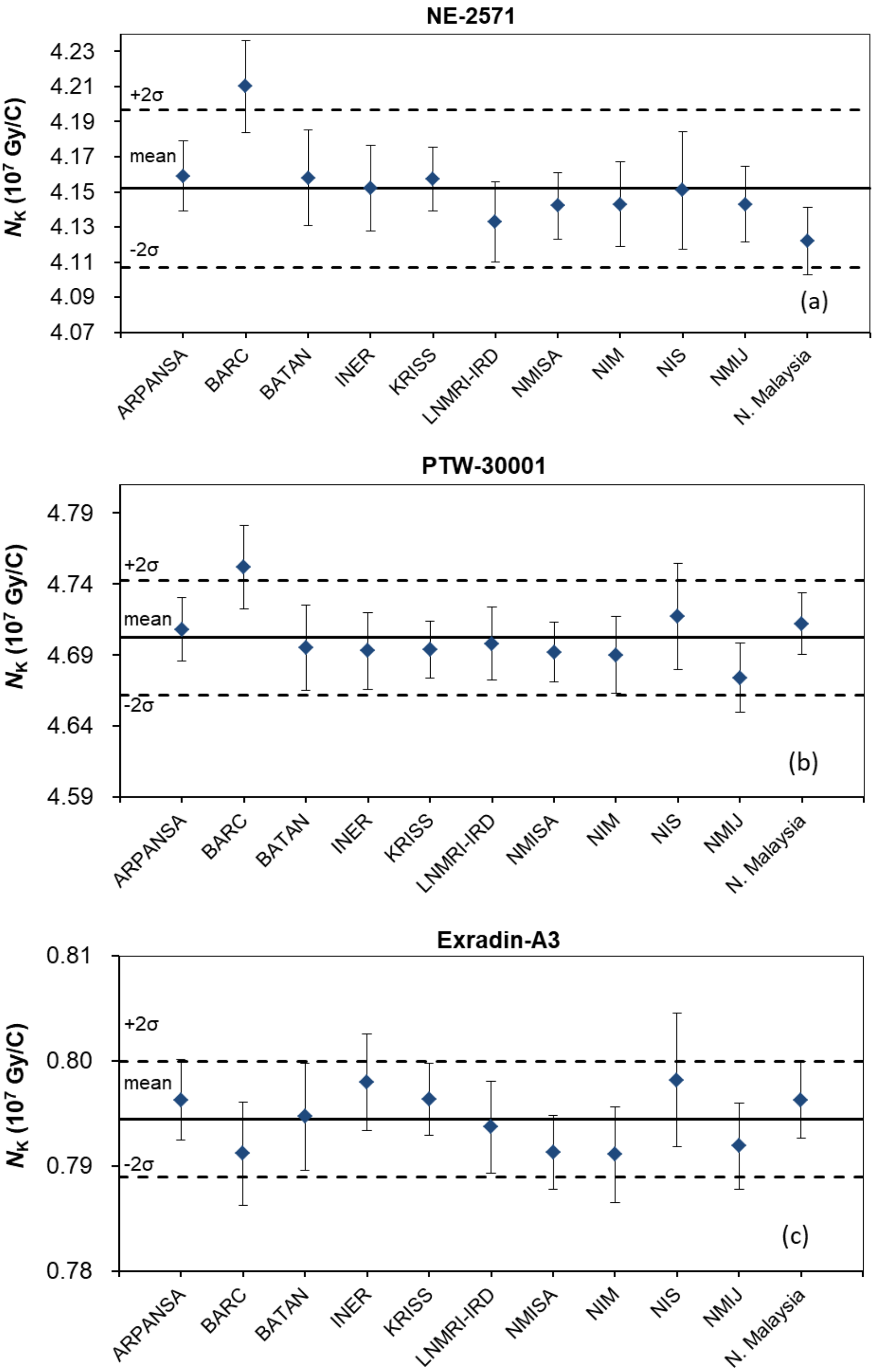

Figure 4. Calibration coefficients (N_K) of each transfer chamber for BIPM-135 with twice the standard deviation of the distribution indicated, for (a) NE-2571 (S/N 3716), (b) PTW-30001 (S/N 2340) and (c) Exradin-A3 (S/N 143432). The uncertainty bars show the laboratory's reported standard uncertainty $u(N_K)$.

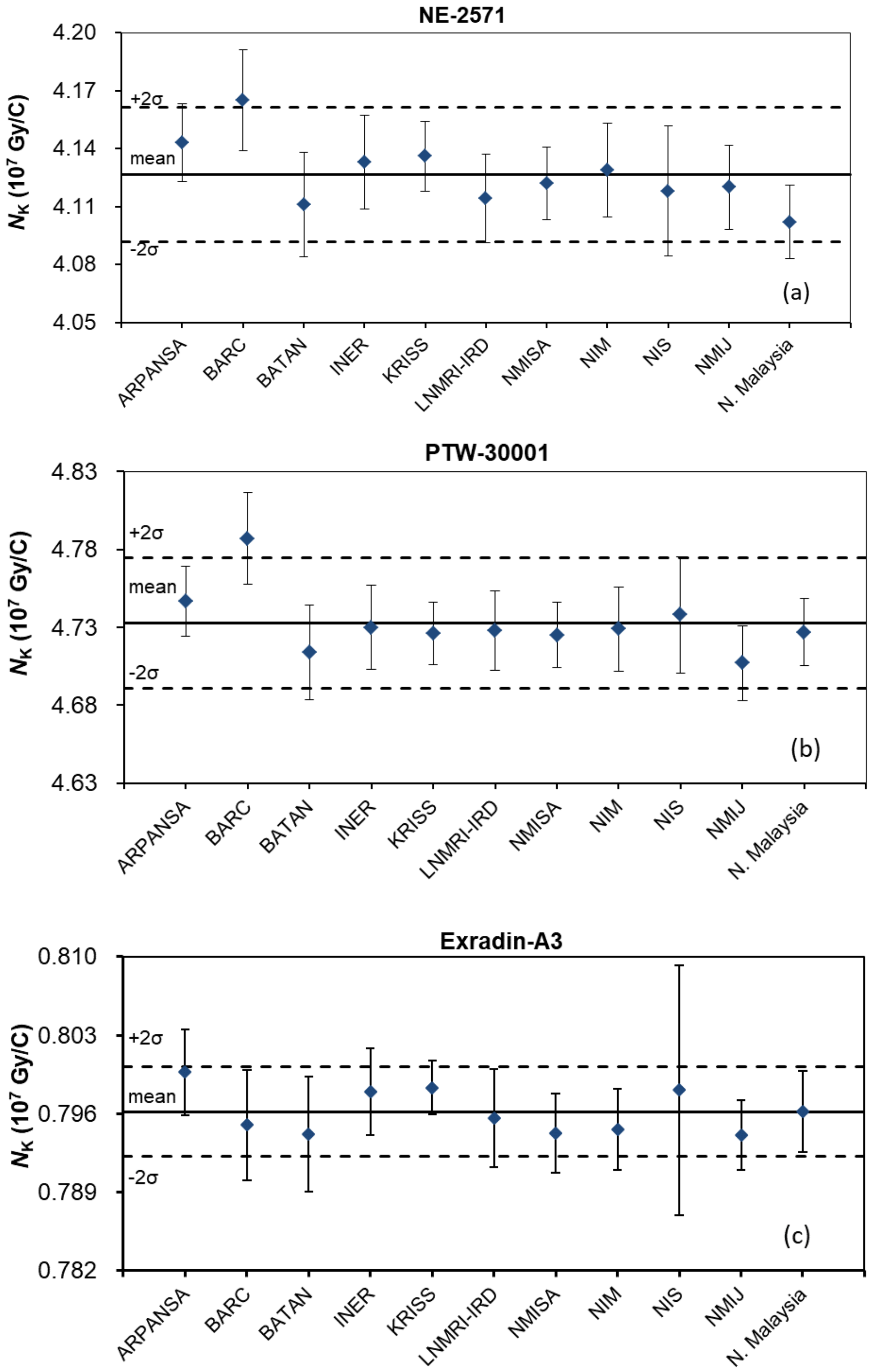

Figure 5. Calibration coefficients (N_K) of each transfer chamber for BIPM-180 with twice the standard deviation of the distribution indicated, for (a) NE-2571 (S/N 3716), (b) PTW-30001 (S/N 2340) and (c) Exradin-A3 (S/N 143432). The uncertainty bars show the laboratory's reported standard uncertainty $u(N_K)$.

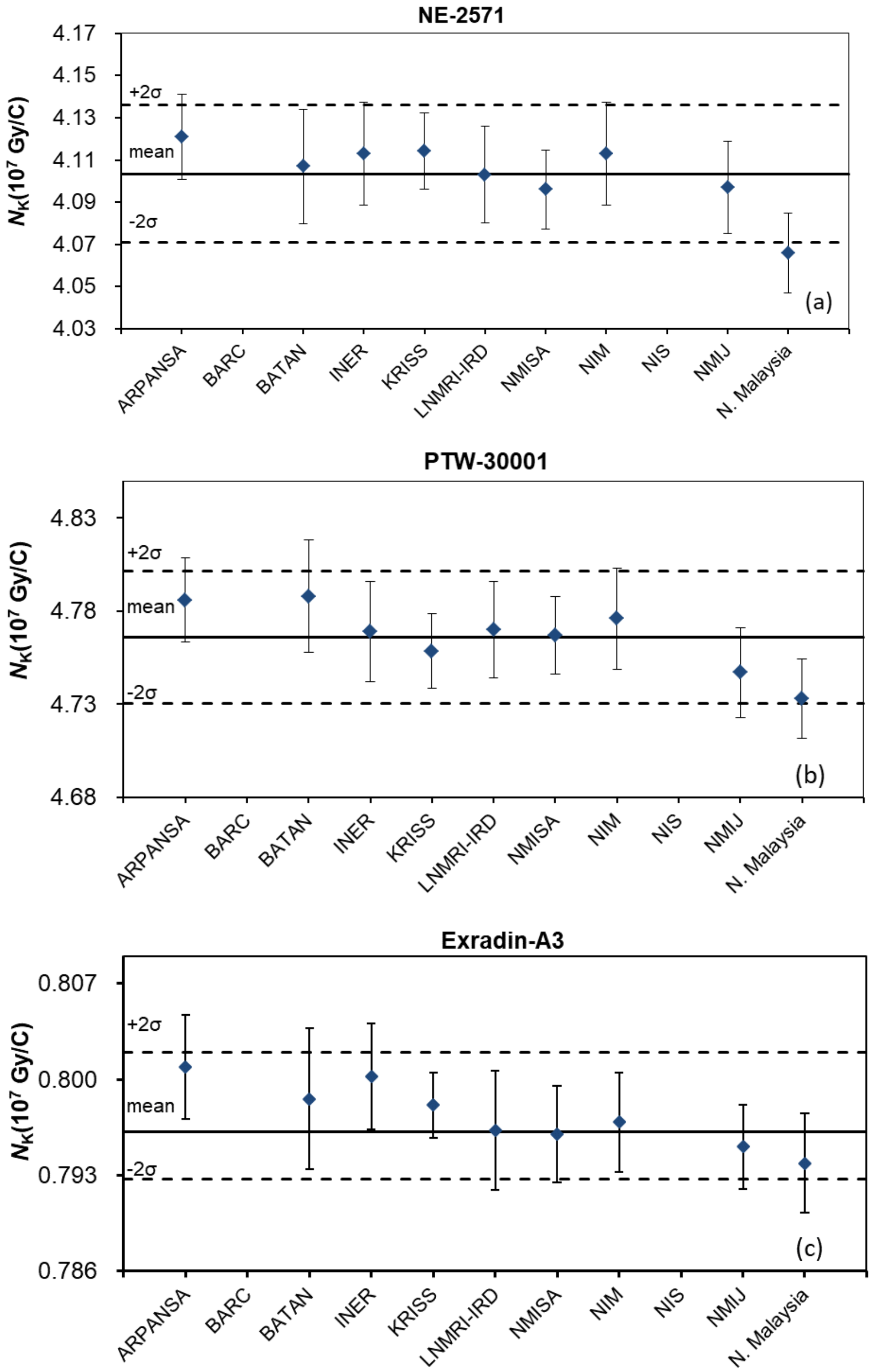

Figure 6. Calibration coefficients (N_K) of each transfer chamber for BIPM-250 with twice the standard deviation of the distribution indicated, for (a) NE-2571 (S/N 3716), (b) PTW-30001 (S/N 2340) and (c) Exradin-A3 (S/N 143432). The uncertainty bars show the laboratory's reported standard uncertainty $u(N_K)$.

4.3 Degrees of equivalence

The ratios $R_{i,\mathrm{ARPANSA}}$ and $R_{i,\mathrm{NMIJ}}$ obtained using Equation (3) are the unweighted mean for the three chambers. These are then averaged to get the final comparison result R_i for each laboratory relative to the BIPM 100, 135, 180 and 250 kVp beams, as given in Tables 12-15 and Figure 7.

In the following analysis we have chosen to include the link laboratories ARPANSA and NMIJ in the graphs and tables, even though the degrees of equivalence are not changed for the linking laboratories. The ratio R_{ARPANSA} has been evaluated using only the NMIJ as the link, and likewise R_{NMIJ} has been evaluated using the ARPANSA as the link, while all the other laboratories use the average of both.

We have also included R_{KRISS} and R_{NIM} although as noted in Section 2.1 these results will not be used to update more recent results obtained in the BIPM.RI(I)-K3 comparison. For the KRISS, these more recent results for the four beams, respectively, are 1.0041, 1.0051, 1.0043 and 1.0028, which are within around 0.2 % of the values from the present comparison (1.0046, 1.0037, 1.0027, 1.0007) given in Tables 12-15. For the NIM the BIPM.RI(I)-K3 results are 1.0072, 1.0054, 1.0061 and 1.0060, which are around 0.5 % higher than the APMP comparison (1.0027, 1.0001, 1.0008, 1.0013).

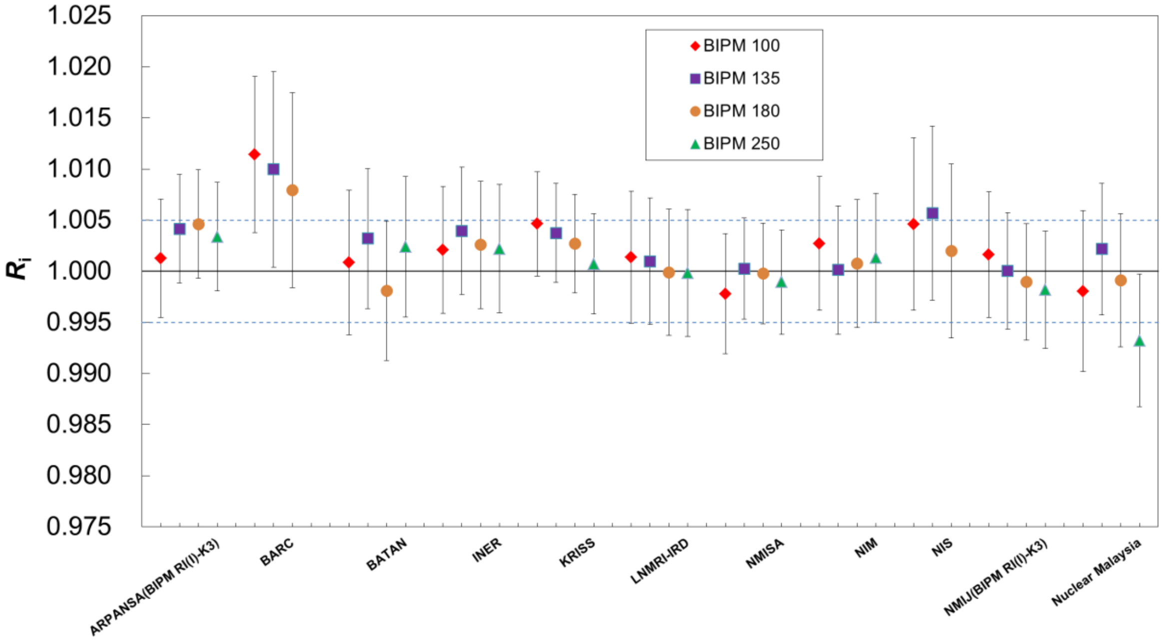

Figure 7. The results R_i for each participating laboratory for the APMP.RI(I)-K3.2013 comparison. Uncertainty bars show the combined standard uncertainty u_{Ri}. The two linking laboratories (each linked via the other linking laboratory and indicated with brackets) are included for completeness, as are the KRISS and the NIM who each have more recent BIPM.RI(I)-K3 results and hence will not update their degrees of equivalence.

The uncertainty in the ratio to the BIPM Key Comparison Reference Value has been calculated following [4] from the uncertainty budgets of the participants, that of the BIPM and those of the linking comparison ratios. The results are given in Tables 12-15. For this analysis we have used the uncertainty budgets which were submitted prior to the changes made following ICRU Report 90. As discussed in Section 5 later, this is acceptable because the changes are highly correlated and therefore do not alter the degrees of equivalence. Nevertheless, the uncertainty budgets in Appendix A have been adjusted for the increase in the W_{air} uncertainty to 0.35 % and the increased values used in Tables 8-11 and in Tables 12-15.

Table 12. Final result for BIPM-100: the ratio R_i and combined relative standard uncertainty u_{Ri} (Equation 2).

Participant	R_i	u_i (%)	u_{BIPM} (%)	u_{corr}^* (%)	u_{tr} (%)	u_{LINK} (%)	**Combined $u_{R,i}$ (%)**
ARPANSA[a]	1.0013	0.49	0.37	0.49	0.22	0.16	0.45
BARC	1.0114	0.71	0.37	0.49	0.28	0.16	0.71
BATAN	1.0009	0.73	0.37	0.52	0.09	0.16	0.65
INER	1.0021	0.58	0.37	0.49	0.05	0.16	0.51
KRISS	1.0046	0.43	0.37	0.49	0.07	0.16	0.33
LNMRI-IRD	1.0014	0.58	0.37	0.52	0.12	0.16	0.49
NMISA	0.9978	0.53	0.37	0.52	0.20	0.16	0.46
NIM	1.0027	0.58	0.37	0.49	0.13	0.16	0.52
NIS	1.0046	0.86	0.37	0.52	0.08	0.16	0.80
NMIJ[a]	1.0016	0.52	0.37	0.49	0.22	0.16	0.48
Nuclear Malaysia	0.9981	0.56	0.37	0.52	0.40	0.16	0.60

[a] Link laboratories (see comment in Section 4.2)

*The combined correlated uncertainty component in Equation 2, to be subtracted in quadrature.

Table 13. Final result for BIPM-135: the ratio R_i and combined relative standard uncertainty u_{Ri} (Equation 2).

Participant	R_i	u_i (%)	u_{BIPM} (%)	u_{corr}^* (%)	u_{tr} (%)	u_{LINK} (%)	**Combined $u_{R,i}$ (%)**
ARPANSA[a]	1.0042	0.49	0.37	0.49	0.11	0.09	0.39
BARC	1.0100	0.71	0.37	0.49	0.46	0.09	0.78
BATAN	1.0032	0.73	0.37	0.52	0.03	0.09	0.64
INER	1.0040	0.58	0.37	0.49	0.13	0.09	0.50
KRISS	1.0037	0.43	0.37	0.49	0.06	0.09	0.30
LNMRI-IRD	1.0010	0.58	0.37	0.52	0.12	0.09	0.47
NMISA	1.0003	0.53	0.37	0.52	0.08	0.09	0.40
NIM	1.0001	0.58	0.37	0.49	0.08	0.09	0.49
NIS	1.0057	0.86	0.37	0.52	0.13	0.09	0.79
NMIJ[a]	1.0000	0.52	0.37	0.49	0.11	0.09	0.43
Nuclear Malaysia	1.0022	0.56	0.37	0.52	0.28	0.09	0.51

[a] Link laboratories (see comment in Section 4.2)

*The combined correlated uncertainty component in Equation 2, to be subtracted in quadrature.

Table 14. Final result for BIPM-180: the ratio R_i and combined relative standard uncertainty u_{Ri} (Equation 2).

Participant	R_i	u_i (%)	u_{BIPM} (%)	u_{corr}* (%)	u_{tr} (%)	u_{LINK} (%)	Combined $u_{R,i}$ (%)
ARPANSA[a]	1.0046	0.49	0.37	0.49	0.09	0.09	0.38
BARC	1.0079	0.71	0.37	0.49	0.35	0.09	0.73
BATAN	0.9981	0.73	0.37	0.52	0.03	0.09	0.64
INER	1.0026	0.58	0.37	0.49	0.04	0.09	0.49
KRISS	1.0027	0.43	0.37	0.49	0.05	0.09	0.29
LNMRI-IRD	0.9999	0.58	0.37	0.52	0.09	0.09	0.46
NMISA	0.9998	0.53	0.37	0.52	0.06	0.09	0.39
NIM	1.0008	0.58	0.37	0.49	0.08	0.09	0.49
NIS	1.0020	0.86	0.37	0.52	0.13	0.09	0.79
NMIJ[a]	0.9990	0.52	0.37	0.49	0.09	0.09	0.42
Nuclear Malaysia	0.9991	0.56	0.37	0.52	0.17	0.09	0.46

[a] Link laboratories (see comment in Section 4.2)

*The combined correlated uncertainty component in Equation 2, to be subtracted in quadrature.

Table 15. Final result for BIPM-250: the ratio R_i and combined relative standard uncertainty u_{Ri} (Equation 2).

Participant	R_i	u_i (%)	u_{BIPM} (%)	u_{corr}* (%)	u_{tr} (%)	u_{LINK} (%)	Combined $u_{R,i}$ (%)
ARPANSA[a]	1.0034	0.49	0.37	0.49	0.08	0.12	0.39
BARC	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BATAN	1.0024	0.73	0.37	0.52	0.11	0.12	0.65
INER	1.0022	0.58	0.37	0.49	0.06	0.12	0.50
KRISS	1.0007	0.43	0.37	0.49	0.06	0.12	0.31
LNMRI-IRD	0.9998	0.58	0.37	0.52	0.07	0.12	0.47
NMISA	0.9989	0.53	0.37	0.52	0.07	0.12	0.40
NIM	1.0013	0.58	0.37	0.49	0.08	0.12	0.50
NIS	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NMIJ[a]	0.9982	0.52	0.37	0.49	0.08	0.12	0.43
Nuclear Malaysia	0.9932	0.56	0.37	0.52	0.12	0.12	0.45

[a] Link laboratories (see comment in Section 4.2)

*The combined correlated uncertainty component in Equation 2, to be subtracted in quadrature.

The degrees of equivalence were calculated for eligible laboratories (omitting the KRISS and the NIM for the reasons noted in Section 2.1 and discussed below) and they are presented in Table 16.

Table 16. Degrees of Equivalence for the APMP.R(I)-K3.2013 comparison.

Participant	BIPM-100		BIPM-135		BIPM-180		BIPM-250	
	D_i (mGy/Gy)	U_i (mGy/Gy)	D_i (mGy/Gy)	U_i (mGy/Gy)	D_i (mGy/Gy)	U_i (mGy/Gy)	D_i (mGy/Gy)	U_i (mGy/Gy)
BARC	11.4	14.1	10.0	15.7	7.9	14.5	N/A	N/A
BATAN	0.9	13.1	3.2	12.7	-1.9	12.7	2.4	13.0
INER	2.1	10.1	4.0	10.0	2.6	9.7	2.2	9.9
LNMRI-IRD	1.4	9.8	1.0	9.4	-0.1	9.3	-0.2	9.3
NMISA	-2.2	9.1	0.3	8.0	-0.2	7.9	-1.1	8.1
NIS	4.6	15.9	5.7	15.8	2.0	15.8	N/A	N/A
Nuclear Malaysia	-1.9	12.1	2.2	10.2	-0.9	9.2	-6.8	9.1

5. Discussion

5.1 Consistency

The ratio to the BIPM reference value for the non-linking participants range from 0.9932 to 1.0114, which is within two standard uncertainties of unity. Excluding the BARC, the results range from 0.9932 to 1.0057, which is within one standard uncertainty of unity. The laboratories showed reasonably good consistency across the energy range and there were few signs of any energy-dependent effects.

The consistency between the results for the different transfer chambers is, however, a different story, with some laboratories showing a larger variation between the three chambers than others. For several beam qualities the ratio $R_{i,j,k}$ to the BIPM reference value derived using different chambers j (for a given linking lab k) deviated for the BARC and Nuclear Malaysia by more than 1 %. The individual chamber results are given in Appendix B. From the results for the other participants, as well as from the chamber stability measurements, it can be deduced that this was not a result of transfer chamber instabilities.

The effect can be seen in the values of u_{tr} in Tables 12-15 which suggest that the BARC had somewhat higher inter-chamber variability for all four beams while Nuclear Malaysia showed a similar effect but decreasing as the beam quality increased. Although it is not possible to assign a cause, such behavior could possibly result from certain humidity effects, from a non-uniformity in the beam profile that was not corrected for, or from an extra-cameral signal (such as that which can arise when certain connectors are close enough to the x-ray beam to receive scattered radiation). Nevertheless, all laboratories were within the expanded uncertainty of the reference value.

5.2 Modifications following ICRU 90 Report

After the publication of ICRU Report 90 [9] the resulting changes to primary standards for dosimetry were agreed by the CCRI to be implemented by laboratories on 1 January 2018. The BIPM reference value changed on that date, and hence the results in this comparison, which refer to the previous reference value, need these changes to be considered, if the comparison is to support current laboratory capabilities.

A full re-analysis would have required all the laboratories to submit their changes and revised uncertainty budgets. However, in the case of medium-energy x-rays the situation is simplified because all of the results are traceable to free-air chambers. In this case the adoption of ICRU 90 data results in highly correlated changes across all of the participants and the BIPM. For example the introduction of $k_{ii}.k_W$ (the correction for initial ionization and the energy dependence of W) does not significantly change the ratios between the laboratories. The other significant change is the increase in the standard uncertainty of W_{air} from 0.15 % to 0.35 %. Likewise, this is fully correlated between all laboratories and the BIPM and so does not alter the linking uncertainties or the degrees of equivalence. It does, however, affect the laboratory uncertainty budgets and so the submitted uncertainty budgets have been modified to include it. For primary standards laboratories the uncertainty for W_{air} had been changed from 0.15 % to 0.35 % (k = 1). For the secondary standards laboratories we have included an additional 0.32 % which results from the removal of 0.15 % and inclusion of 0.35 %. With the updated uncertainty budgets, the comparison as presented can be used to support laboratories capabilities after the implementation of ICRU 90 data.

6. Conclusion

A regional key comparison has been carried out by the Asia Pacific Metrology Program for standards of air kerma for medium-energy x-rays following the original comparison published in 2008 [1]. Three ionization chambers, each a different type, were used as transfer standards and circulated among the 11 laboratories for calibration. Regular constancy tests at the pilot laboratory indicated that they were well-behaved throughout the comparison. Nearly all of the calibration coefficients fell within the stated standard uncertainty of the corresponding mean calibration coefficient as evaluated from the comparison results. All coefficients were within two standard uncertainties of the mean, indicating reasonable agreement between all 11 participants. The result for the NMIJ and the ARPANSA were used to link the results to the BIPM Key Comparison Reference Value for the 9 non-linking laboratories. Two laboratories, the KRISS and the NIM, have subsequently participated in the BIPM.RI(I)-K3 comparison and so their results are not used to evaluate degrees of equivalence. Thus, the degrees of equivalence were established for the remaining 7 laboratories. While the comparison took place before the adoption of ICRU Report 90 recommendations, the degrees of equivalence are essentially unchanged by these recommendations and hence the results support post-ICRU 90 measurement capabilities, when the adjustments to the submitted uncertainty budgets are taken into account.

Consequently, participants have been able to verify their measurement capabilities as well as strengthen technical cooperation and exchange ideas with other laboratories in the process of achieving a link to the BIPM.

References

[1] J. H. Lee, W. S. Hwang, L. H. Kotler, D. V. Webb, L. Büermann, D. T. Burns, M. Takeyeddin, V. V. Shaha, S. Srimanoroth, A. Meghzifene, S. H. Hah, K. J. Chun, T. B. Kadni, N. Takata and Z. Msimang, APMP/TCRI key comparison report of measurement of air kerma for medium-energy x-rays (APMP.RI(I)-K3), 2008, *Metrologia* **45** Tech. suppl., 06012

[2] M. Boutillon, Mesure de l'exposition au BIPM dans le domaine des rayons X de 100 à 250 kV, 1978, *Rapport BIPM*-78/3

[3] "Guide to the Expression of Uncertainty in Measurement," International Organization of Standards, Switzerland (1995)

[4] 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)

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

[6] D. T. Burns, "Degrees of equivalence for the key comparison BIPM.RI(I)-K3 between national primary standards for medium-energy x-rays", *Metrologia* **40**(1A) , Tech. Suppl.,

06036 (2003)

[7] D. T. Burns, J. E. Lye, P. Roger and D. J. Butler, "Key comparison BIPM/.RI(I)-K3 of the air-kerma standards of the ARPANSA, Australia and the BIPM in medium-energy x-rays", *Metrologia* **49**, Tech. Suppl., 06007 (2012)

[8] D. T. Burns, C. Kessler, T. Tanaka. T. Kurosawa and N Saito, "Key comparison BIPM/.RI(I)-K3 of the air-kerma standards of the NMIJ, Japan and the BIPM in medium-energy x-rays", *Metrologia* **53**, Tech. Suppl., 06002 (2016)

[9] 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

[10] C. Kessler and D.T. Burns, Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM, 2018, *Rapport BIPM-2018*/06

Appendix A

ARPANSA Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
dry air density		0.01
temperature		0.03
pressure		0.03
volume (5127.9 mm^3)		0.08
W_{air}/e		0.35
scattered radiation	0.04	
fluorescence	0.03	
electron loss	0.02	
ion recombination		0.01
polarity correction		0.01
air attenuation inside free air chamber		0.20
electric field distortion		0.05
transmission through edges of diaphragm	0.06	
scattering from diaphragm		
transmission through walls of standard		0.03
humidity		0.03
bremsstrahlung loss		0.03
Quadratic sum	0.09	0.43
Combined standard uncertainty	0.44	

Uncertainty associated with the calibration of the transfer standards

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
humidity [a]		0.03
current measurement	0.05	0.05
reproducibility	0.17	
air kerma (from above)	0.09	0.43
Quadratic sum	0.20	0.44
Combined standard uncertainty	0.49	

[a] Type B uncertainties in the temperature and pressure are correlated with that of the free air chamber. Temperature differences between the thermistors and the ionization chambers (free air chamber, monitor and transfer standard) result in an uncertainty which is included in the assessment of the reproducibility.

<u>BARC Uncertainty budget</u>

Uncertainty associated with the standard

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Physical constants		
dry air density		0.01
W_{air}/e		0.35
Correction factors		
scatter radiation		0.10
fluorescence		
electron loss		0.10
ion recombination	0.10	0.10
air attenuation		0.13
Volume and current		
temperature		0.04
pressure		0.04
volume		0.41
current measurement	0.06	0.10
position		0.17
Quadratic sum	0.12	0.62
Combined standard uncertainty	0.63	

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
temperature		0.04
pressure		0.04
current measurement	0.21	0.25
air kerma	0.12	0.62
Quadratic sum	0.24	0.67
Combined standard uncertainty	0.71	

BATAN Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Air kerma rate		
(IAEA calibration certificate)		0.58
increase in $u(W_{air})$ from 0.15 % to 0.35 %		0.32
Related to the instrument to be calibrated		
current measurement	0.01	0.06
reproducibility		0.01
change in beam quality		0.06
positioning in air at the calibration distance		0.06
temperature correction		0.28
air pressure correction		0.06
Quadratic sum	0.01	0.73
Combined standard uncertainty	0.73	

INER Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	**Type B**
Physical constants		
dry air density		0.01
W_{air}/e		0.35
Correction factors		
electron loss		0.07
photon scatter		0.07
air attenuation		0.07
shadow effect		0.07
wall attenuation	0.08	
ion recombination	0.09	
humidity		0.10
Measurement of air kerma		
temperature		0.02
pressure		0.04
volume		0.06
current	0.27	0.05
position		0.13
Quadratic sum	0.29	0.42
Combined standard uncertainty	0.51	

Uncertainty associated with the calibration of the transfer standards

Uncertainty component	Relative standard uncertainty (%)	
	Type A	**Type B**
air kerma	0.29	0.42
current measurement	0.24	0.05
pressure		0.04
temperature		0.02
humidity		0.10
Quadratic sum	0.38	0.44
Combined standard uncertainty	0.58	

KRISS Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		0.01
W_{air}/e		0.35
scattered radiation	0.00	0.03
fluorescence	0.00	0.03
electron loss	0.00	0.05
ion recombination	0.02	0.01
polarity	0.01	
air attenuation	0.02	0.02
field distortion		0.07
transmission through walls	0.01	
humidity		0.03
bremsstrahlung		0.01
diaphragm contribution		0.03
bremsstrahlung		0.01
initial ionization and energy dependence of W_{air}/e		0.05
volume	0.01	0.10
current measurement	0.07	0.04
Quadratic sum	0.08	0.39
Combined standard uncertainty	0.39	

Uncertainty associated with the calibration of the transfer standards

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
air kerma	0.08	0.39
current measurement	0.01	0.04
positioning		0.12
air attenuation	0.02	0.02
scatter contribution	0.01	0.10
chamber stability		0.10
Combined standard uncertainty	0.43	

LNMRI-IRD Uncertainty budget

Uncertainty associated with the calibration of the transfer standards

Uncertainty component	Relative standard uncertainty (%)	
	Type A	**Type B**
Air kerma rate	0.14	0.42
increase in $u(W_{air})$ from 0.15 % to 0.35 %		0.32
Related to the instrument to be calibrated		
temperature correction		0.06
air pressure correction		0.07
humidity		0.09
current measurement	0.14	
Quadratic sum	0.20	0.54
Combined standard uncertainty	0.58	

NMISA Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Air kerma		
calibration coefficient of secondary standard	0.05	0.19
increase in $u(W_{air})$ from 0.15 % to 0.35 %		0.316
pressure		0.003
temperature		0.028
positioning		0.231
drift of standard		0.289
electrometer		0.050
charge measurement	0.016	
Related to the instrument to be calibrated		
temperature correction		0.003
air pressure correction		0.028
Quadratic sum	0.052	0.526
Combined standard uncertainty	0.53	

NIM Uncertainty budget

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		0.01
W_{air}/e		0.35
scattered radiation fluorescence		0.05
electron loss		0.07
ion recombination	0.01	0.01
polarity	0.02	0.01
air attenuation at 293.15 K 101.325 kPa		0.05
field distortion		0.07
transmission through edges of diaphragm scattering from diaphragm		0.03
transmission through walls of standard	0.01	0.01
humidity		0.03
bremsstrahlung		0.01
Measurement of air kerma rate		
temperature	0.01	0.05
pressure	0.01	0.01
volume	-	0.04
current	0.02	0.01
position	0.01	0.06
Quadratic sum	0.04	0.38
Combined standard uncertainty	0.38	

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
temperature	0.01	0.12
pressure	0.01	0.01
humidity	-	0.02
current measurement	0.02	0.01
reproducibility		0.40
air kerma	0.04	0.38
position	0.01	0.11
Quadratic sum	0.05	0.57
Combined standard uncertainty	0.58	

NIS Uncertainty budget

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Air kerma rate	0.40	0.55
increase in $u(W_{air})$ from 0.15 % to 0.35 %		0.32
Related to the instrument to be calibrated		
temperature correction	0.10	0.10
air pressure correction	0.10	0.10
humidity		0.10
current measurement	0.30	0.20
Quadratic sum	0.52	0.69
Combined standard uncertainty	0.86	

<u>NMIJ Uncertainty budget</u>

Uncertainty associated with the standard

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
dry air density		0.01
W_{air}/e		0.35
scattered radiation fluorescence		0.14
electron loss		0.14
ion recombination		0.02
polarity		0.03
air attenuation at 293.15 K 101.325 kPa		0.10
field distortion		0.01
transmission through edges of diaphragm		0.06
scattering from diaphragm		0.14
transmission through walls of standard		0.02
humidity		0.02
bremsstrahlung		0.06
initial ionization and energy dependence of W_{air}		0.14
Measurement of air kerma		
temperature	-	0.02
pressure	-	0.05
volume	-	0.10
current measurement	0.05	0.06
position	-	0.12
Quadratic sum	0.05	0.49
Combined standard uncertainty	0.49	

Uncertainty associated with the calibration of the transfer standards

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
temperature		0.03
pressure		0.05
humidity		0.05
current measurement	0.05	0.06
HVL		0.05
scattering radiation		0.05
field homogeneity		0.06
position		0.06
air kerma	0.05	0.49
Quadratic sum	0.07	0.51
Combined standard uncertainty	0.52	

Nuclear Malaysia Uncertainty budget

Uncertainty associated with the calibration of the transfer standards

Uncertainty component	**Relative standard uncertainty (%)**	
	Type A	**Type B**
Air kerma		
calibration coefficient of air kerma	0.403	
increase in $u(W_{air})$ from 0.15 % to 0.35 %		0.316
pressure		0.014
temperature		0.144
positioning		0.058
current measurement	0.016	
Related to the instrument to be calibrated		
temperature		0.144
pressure		0.014
current measurement	0.012	
position		0.058
Quadratic sum	0.403	0.385
Combined standard uncertainty	0.56	

Appendix B: Results for each chamber NE 2571 SN 3716 (j=1), PTW 30001 S/N 2340 (j=2) and EXRADIN A3 S/N XR143432 (j=3) for each laboratory, i, linked through two link laboratories ARPANSA and NMIJ.

Laboratory, i	Beam quality	**RATIO TO BIPM VIA LINK1 (ARPANSA)**					**RATIO TO BIPM VIA LINK2 (NMIJ)**				
		$R_{i,\text{LINK1}}$			**Mean**	u_{tr}	$R_{i,\text{LINK2}}$			**Mean**	u_{tr}
		j=1	j=2	j=3	$\boldsymbol{R_{i,\text{LINK1}}}$	%	j=1	j=2	j=3	$\boldsymbol{R_{i,\text{LINK2}}}$	%
ARPANSA	BIPM-100						0.9975	1.0041	1.0021	**1.0013**	0.22
BARC	BIPM-100	1.0119	1.0183	1.0078	**1.0126**	0.34	1.0057	1.0188	1.0062	**1.0102**	0.48
BATAN	BIPM-100	1.0051	1.0011	1.0000	**1.0021**	0.17	0.9990	1.0016	0.9984	**0.9997**	0.11
INER	BIPM-100	1.0063	1.0013	1.0023	**1.0033**	0.17	1.0002	1.0018	1.0007	**1.0009**	0.05
KRISS	BIPM-100	1.0086	1.0028	1.0062	**1.0059**	0.19	1.0024	1.0033	1.0046	**1.0034**	0.07
LNMRI-IRD	BIPM-100	1.0003	1.0041	1.0033	**1.0026**	0.13	0.9942	1.0046	1.0017	**1.0002**	0.35
NMISA	BIPM-100	1.0032	1.0000	0.9938	**0.9990**	0.31	0.9970	1.0005	0.9922	**0.9966**	0.27
NIM	BIPM-100	1.0066	1.0043	1.0009	**1.0039**	0.18	1.0004	1.0048	0.9993	**1.0015**	0.19
NIS	BIPM-100	1.0066	1.0043	1.0066	**1.0058**	0.08	1.0004	1.0048	1.0050	**1.0034**	0.17
NMIJ	BIPM-100	1.0054	0.9988	1.0008	**1.0016**	0.22					
Nuclear Malaysia	BIPM-100	0.9907	1.0013	1.0057	**0.9993**	0.50	0.9846	1.0018	1.0041	**0.9968**	0.69
ARPANSA	BIPM-135						1.0025	1.0059	1.0041	**1.0042**	0.11
BARC	BIPM-135	1.0179	1.0150	0.9992	**1.0107**	0.65	1.0148	1.0153	0.9977	**1.0092**	0.64
BATAN	BIPM-135	1.0054	1.0028	1.0036	**1.0039**	0.08	1.0022	1.0031	1.0021	**1.0025**	0.03
INER	BIPM-135	1.0039	1.0024	1.0077	**1.0047**	0.18	1.0008	1.0027	1.0063	**1.0032**	0.18
KRISS	BIPM-135	1.0052	1.0026	1.0057	**1.0045**	0.11	1.0020	1.0028	1.0042	**1.0030**	0.07
LNMRI-IRD	BIPM-135	0.9993	1.0035	1.0023	**1.0017**	0.14	0.9962	1.0037	1.0009	**1.0003**	0.25
NMISA	BIPM-135	1.0015	1.0022	0.9993	**1.0010**	0.10	0.9984	1.0024	0.9978	**0.9995**	0.16
NIM	BIPM-135	1.0017	1.0018	0.9990	**1.0008**	0.10	0.9986	1.0020	0.9976	**0.9994**	0.15
NIS	BIPM-135	1.0037	1.0075	1.0080	**1.0064**	0.15	1.0005	1.0078	1.0065	**1.0050**	0.25
NMIJ	BIPM-135	1.0017	0.9983	1.0000	**1.0000**	0.11					
Nuclear Malaysia	BIPM-135	0.9967	1.0065	1.0056	**1.0029**	0.35	0.9935	1.0067	1.0041	**1.0015**	0.45

ARPANSA	BIPM-180						1.0032	1.0061	1.0046	**1.0046**	0.09
BARC	BIPM-180	1.0113	1.0145	1.0001	**1.0086**	0.49	1.0085	1.0146	0.9987	**1.0073**	0.52
BATAN	BIPM-180	0.9982	0.9990	0.9991	**0.9988**	0.03	0.9954	0.9991	0.9977	**0.9974**	0.12
INER	BIPM-180	1.0036	1.0024	1.0039	**1.0033**	0.05	1.0007	1.0025	1.0025	**1.0019**	0.06
KRISS	BIPM-180	1.0043	1.0016	1.0043	**1.0034**	0.10	1.0015	1.0016	1.0029	**1.0020**	0.05
LNMRI-IRD	BIPM-180	0.9990	1.0020	1.0008	**1.0006**	0.10	0.9961	1.0021	0.9995	**0.9992**	0.19
NMISA	BIPM-180	1.0009	1.0013	0.9992	**1.0005**	0.07	0.9981	1.0014	0.9979	**0.9991**	0.13
NIM	BIPM-180	1.0026	1.0022	0.9996	**1.0015**	0.11	0.9998	1.0023	0.9982	**1.0001**	0.13
NIS	BIPM-180	0.9999	1.0041	1.0040	**1.0027**	0.15	0.9971	1.0042	1.0026	**1.0013**	0.24
NMIJ	BIPM-180	1.0004	0.9975	0.9990	**0.9990**	0.09					
Nuclear Malaysia	BIPM-180	0.9960	1.0018	1.0016	**0.9998**	0.21	0.9932	1.0018	1.0002	**0.9984**	0.30
ARPANSA	BIPM-250						1.0021	1.0045	1.0036	**1.0034**	0.08
BARC	BIPM-250										
BATAN	BIPM-250	1.0019	1.0057	1.0024	**1.0033**	0.13	0.9987	1.0049	1.0007	**1.0014**	0.20
INER	BIPM-250	1.0033	1.0017	1.0044	**1.0032**	0.09	1.0002	1.0009	1.0027	**1.0013**	0.08
KRISS	BIPM-250	1.0037	0.9995	1.0018	**1.0017**	0.14	1.0005	0.9987	1.0001	**0.9998**	0.06
LNMRI-IRD	BIPM-250	1.0009	1.0019	0.9995	**1.0008**	0.08	0.9978	1.0011	0.9978	**0.9989**	0.12
NMISA	BIPM-250	0.9992	1.0013	0.9991	**0.9999**	0.08	0.9961	1.0005	0.9974	**0.9980**	0.15
NIM	BIPM-250	1.0033	1.0032	1.0003	**1.0023**	0.11	1.0002	1.0024	0.9986	**1.0004**	0.12
NIS	BIPM-250										
NMIJ	BIPM-250	0.9994	0.9971	0.9980	**0.9982**	0.08					
Nuclear Malaysia	BIPM-250	0.9919	0.9942	0.9965	**0.9942**	0.15	0.9888	0.9934	0.9948	**0.9923**	0.20