APMP key comparison for the measurement of air kerma for ^{60}Co (APMP.RI(I)-K1.1)

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Abstract

The results are reported for an APMP.R(I)-K1.1 comparison that extends the regional comparison of standards for air kerma APMP.R(I)-K1 to several laboratories unable to participate earlier. The comparison was conducted with the goal of supporting the relevant calibration and measurement capabilities (CMCs) planned for publication by the participant laboratories.

The comparison was conducted by the pilot laboratory, the Australian Radiation Protection and Nuclear Safety (ARPANSA), Australia, supported by the Institute of Nuclear Energy Research (INER), Taiwan, in a modified ring-shaped arrangement from September 2009 to November 2010, in parallel with an APMP.R(I)-K4 comparison being piloted by the INER. The laboratories that took part in the comparison were the ARPANSA, the Centre of Technology of Radiation Safety and Metrology (PTKMR-BATAN), Indonesia, the Division of Radiation and Medical Devices (DMSC), Thailand, the INER, the National Centre for Radiation Science (NCRS), New Zealand, the National Institute for Standards (NIS), Egypt and the National Metrology Institute of Japan (NMIJ/AIST), Japan. The two primary laboratories, ARPANSA and NMIJ, were chosen as the linking laboratories.

Three ionization chambers were used as transfer instruments to be calibrated in terms of air kerma in ^{60}Co radiotherapy beams. The comparison result is based on the ratio between the air kerma calibration coefficients (N_K) determined by the participants and the mean of the results of the linking laboratories.

The mean comparison ratio was found to be within 0.5 % of the key comparison reference value KCRV. The largest deviation between any two comparison ratios for the three chambers in terms of air kerma was 2.0 %. An analysis of the participant uncertainty budgets enabled the calculation of degrees of equivalence (DoE) in terms of the deviations of the results and their associated uncertainties. As a result of this APMP comparison, the BIPM key comparison database (KCDB) should include three new entries since neither the PTKMR-BATAN nor the NCRS have yet been declared designated institutes and consequently their results cannot be entered.

1. Introduction

A regional comparison APMP.RI(I)-K1 of the standards for air kerma for ^{60}Co occurred in 2004-2005 [1]. Some countries in the region did not participate such as Indonesia, New Zealand and Thailand. Since these countries will be participating in the current APMP.RI(I)-K4 comparison piloted by the INER and the protocol for the APMP.RI(I)-K4 ^{60}Co absorbed dose comparison will incorporate air kerma measurements, it provides an opportunity to include the three mentioned countries (Indonesia, New Zealand, and Thailand) in a parallel multilateral comparison APMP.RI(I)-K1.1. The NIS (Egypt) had also requested to participate so the full list of participants is ARPANSA (Australia), BATAN (Indonesia), DMSC (Thailand), INER (Taiwan), NCRS (New Zealand), NIS (Egypt) and NMIJ/AIST (Japan).

The objective of this key comparison is to establish degrees of equivalence of national standards for air kerma as described by Allisy-Roberts *et al* [2] and to support the calibration and measurement capabilities (CMCs) of the participants for ionization chamber calibrations used in radiotherapy. The ARPANSA and the NMIJ maintain primary standards for air kerma and their participation in the comparison allow the results to be linked to the key comparison reference value KCRV. It is noted that the PTKMR-BATAN and the NCRS are yet to be declared as Designated Institutes and will be unable to enter their results in the KCDB. However the contribution of the PTKMR-BATAN and the NCRS to the stability and consistency measurements will still be included in this report so that the appropriate perspective of the conditions will not be lost.

As a result, an indirect comparison of the standards of air kerma has been undertaken using three ionization chambers as transfer instruments. These chambers are the same chambers that are used in the APMP.RI(I)-K4 comparison. The INER was responsible for managing the movement of equipment to and from the various institutions and collecting the data, but the air kerma results were provided to the ARPANSA for analysis and drawing up into a comparison report. The results of the APMP.R(I)-K1.1 comparison are given in terms of the ratio between the mean of the calibration coefficients of the transfer chambers determined by each participant and the mean of the results determined by the linking laboratories.

2. Procedure

2.1 Comparison methodology

The draft comparison protocol was sent to every participant for review and comments, and the revised protocol was submitted to the Section I of the Consultative Committee for Ionizing Radiation CCRI(I) for approval. In the joint K4/K1.1 comparison, there was to be a ring-shaped circulation of the transfer chambers among the participants, returning to the INER for stability checks at regular intervals. Each participant provided the calibration coefficients of the transfer chambers in terms of air kerma and of absorbed dose to water for ^{60}Co. A three-step process to secure the stability of the chambers during the circulation period was achieved by:

- checking the ratio of responses of the three chambers in terms of air kerma;
- checking the ratio of responses of the three chambers in terms of absorbed dose to water; and
- checking the calibration coefficients ratio of the absorbed dose to air kerma for each chamber.

These ratios of the transfer chamber calibration coefficients were reported to the INER after each participant completed the calibration. A "Consistency check" MS-Excel worksheet was provided by the INER to let the participants fill in the calibration coefficients of transfer chambers in terms of the absorbed dose to water and air kerma for ^{60}Co. If they were within a suitable range, the chambers could be sent directly to the next laboratory. If the ratios were beyond the range, the chambers were to be sent back to the INER and remeasured. No exceptions were found and only the scheduled INER measurements were made.

2.2 Reference conditions

The air kerma and absorbed dose to water for ^{60}Co is determined at the BIPM under reference conditions [3] defined by the CCRI(I) as:

The distance from the source to the reference plane (the centre of the detector) is 1 m;

The field size at the reference plane is 10 cm × 10 cm;

The reference depth for absorbed dose measurements is 5 g cm^{-2}.

The above BIPM reference distance and field size were not necessarily required at the participant's site. However, the actual conditions had to be specified if they were different from those of the BIPM. The calibration coefficients of the transfer chambers for air kerma are expressed in units of Gy C^{-1} and referred to standard conditions of 20 °C and 101.325 kPa.

2.3 Transfer chambers

The technical data for the three transfer chambers provided by the INER for this comparison are listed in Table 1. The chambers are representative of those commonly used in clinical radiotherapy dosimetry. The chambers were circulated without an electrometer and each participant used its own measuring system. The transfer ionization chambers were connected to the electrometer normally used in the particular laboratory. 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 water-proof envelope (engraved lines or serial numbers) facing the source. At each laboratory, a collecting voltage specified by the manufacturer was applied to each chamber at least 30 min before starting the measurement. Each chamber should be mounted with its own build-up cap for calibration in terms of air kerma. The pilot laboratory also provided the adaptors for switching the chamber BNT and TNC connectors as requested by some participants.

Table 1. Main technical data of the transfer chambers

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

* the central electrode is positive

2.4 Comparison schedule

The joint comparison began in March 2009 and was expected to be completed within 18 months. The laboratories involved in the K1.1 phase were included from February 2010. Any laboratory that was not able to perform the measurements according to the approved itinerary had to find another participant to exchange for their measurement time. In order to control the progress and time of the whole comparison, the INER took responsibility for the coordination and costs of transportation.

The chambers were continuously tested in the INER for at least 3 months before they were delivered to the first participants to ensure stable performance of the chambers. The total time period for chamber delivery and calibration measurements at any one institute was about one month. Each participant was expected to measure the transfer chambers for no longer than 15 days and the calibration coefficient ratios mentioned in Section 3.1 were to be reported to INER to determine if the chambers should be sent directly to the next laboratory. The schedule shown in Table 2 was generally followed, no laboratory having to return the chambers to INER outside the schedule.

Table 2: Schedule of APMP.RI(I)-K1.1 comparison

Participant	Date of chambers arriving at participant	Measurement duration at laboratory	Date of chambers leaving for the next participant
NMIJ	30-Sep-2009	01-Oct-2009 to 15-Oct-2009	16-Oct-2009
INER	30-Nov-2009 Chamber testing	01-Dec-2009 to 10-Jan-2010	11-Jan-2010
DMSC	28-Feb-2010	01-Mar-2010 to 15-Mar-2010	16-Mar-2010
BATAN	31-May-2010	01-Jun-2010 to 15-Jun-2010	16-Jun-2010
INER	30-Jun-2010 Chamber testing	16-Jul-2010 to 30-Jul-2010	31-Jul-2010
ARPANSA	15-Aug-2010	16-Aug-2010 to 30-Aug-2010	31-Aug-2010
NCRS	15-Sep-2010	16-Sep-2010 to 30-Sep-2010	01-Oct-2010
NIS	15-Oct-2010	16-Oct-2010 to 30-Oct-2010	31-Oct-2010
INER	15-Nov-2010 Chamber testing	16-Dec-2010	

2.5 Calibration results submission

All the participating laboratories submitted calibration results to the INER within 4 weeks after the measurements. Each submission included the calibration coefficients (Gy C^{-1}) of the transfer chambers, the air kerma rate of the radiation field (mGy s^{-1}), the calibration conditions, the standard traceability and the relative standard uncertainties of air kerma measurements and chamber calibrations. Furthermore, it was requested that the relative humidity conditions at the time of calibration be stated on 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 information about the national standards used by the participants and the calibration results could be completed.

2.6 Evaluation of measurement uncertainty

All the participating laboratories are 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) in 1995 [4]. The type A uncertainty is obtained by the statistical analysis of a series of observations; the Type B uncertainty is obtained by means other than a statistical analysis. In order to analyse the uncertainties and take correlations into account for degrees of equivalence entered in the BIPM KCDB, the CIPM requires that participating laboratories submit their detailed uncertainty budgets to the pilot laboratory (preferably with relative standard uncertainties, $k = 1$) together with the calibration results. Two MS-Excel worksheets "Primary/secondary standard uncertainty" and "Chamber calibration uncertainty" were provided in which the participants could detail the uncertainty. The participant could flexibly adjust the analysis items in the uncertainty evaluation worksheets, adding items where required but retaining the same terminology.

3. The comparison results

At the conclusion of the comparison measurements, the INER sent to the ARPANSA the MS-Excel worksheets from each participant containing the calibration coefficients and the uncertainty budgets, as well as the stability measurements. The INER also sent the stability data that it had accrued from March 2009 to December 2010. These are shown in Figure 1.

The calibration coefficients are shown in Table 3 where the uncertainties are regarded as global across the three chambers and no allowance has been made for correlations. The constituents of the uncertainty for each laboratory are given in Appendix B. An APMP reference value for each chamber has been established from the mean of the comparison measurements from the two linking laboratories. The APMP reference values for each chamber type are on average 0.55 % higher than the mean of all participants excluding the linking laboratories, although the PTW 30001 showed the largest discrepancy at 0.77 %.

Table 3. The calibration coefficients (N_K) of the transfer chambers for the APMP.RI(I)-K1.1 key comparison

Participant	N_K (10^7 Gy C^{-1})			Relative standard uncertainty* $u_i(N_K)$ (%)
	NE-2571 (S/N 3025)	PTW-30001 (S/N 2340)	PTW-30013 (S/N 0348)	
DMSC	4.204	4.860	4.880	0.44
BATAN	4.218	4.876	4.880	0.75
INER	4.219	4.898	4.899	0.20
NCRS	4.214	4.865	4.892	0.54
NIS	4.175	4.817	4.845	1.13
NMIJ	4.217	4.902	4.893	0.37
ARPANSA	4.223	4.900	4.912	0.33
Mean Link value	4.220	4.901	4.903	

*The combined standard uncertainty in the mean taken in quadrature from the three chambers if the uncertainties differed.

As mentioned earlier, the consistency of the measurements has been checked in two ways. The first looked at the relative responses between the chambers. Figure 2 shows ratios of the two PTW chambers relative to the NE2571 chamber measured by each laboratory. Over the period from September 2009 to December 2010, the chamber ratios do not vary more that 0.8 %. This magnitude is not unexpected from secondary standards laboratories. Some of the variation may be due to the drift characteristics of both the PTW30013 and the PTW30001 chambers which show a 0.5 % drift in air kerma rate values when irradiated for about 20 hours. This behaviour in particular chamber types has been noted also by Takata and Morishita [5]. The ARPANSA results have been adjusted for an expected irradiation period of the order of 2-3 hours at other laboratories and a contribution of 0.03 % to the ARPANSA uncertainty allows for a reasonable match.

The second approach shown in Figure 3 considers the ratio of absorbed dose to water to air kerma calibration coefficients. The spread of values across the three chambers for each laboratory is consistent to within 0.5 %. The variation of up to 2 % between the laboratories reflects the realisation of the underlying standards in each laboratory.

Furthermore, when the calibration coefficients are normalised to the measured values from the linking laboratories, the NMIJ and the ARPANSA, to create the ratios $R_{\mathrm{i,APMP}}$, for each participant, the statistical standard deviation across the three chambers $u_{m,APMP}$ was small, as given in Table 4, the largest being 0.17 %. It is noted that the difference between those holding secondary standards is roughly ten times larger than for primary standards. This Type A measurement uncertainty has been added to the uncertainty budgets for each participant.

Table 4. Statistical variation between the normalized responses of the chambers, $R_{i,APMP}$, for each participant.

Participant	$R_{i,APMP}$ Mean	Measurement uncertainty $u_{m,APMP}$ (%)*	SEOM $u_{i,APMP}$ (%)
DMSC	0.9944	0.12	0.32
BATAN	0.9966	0.12	0.48
INER	0.9994	0.01	0.23
NCRS	0.9964	0.15	0.37
NIS	0.9868	0.17	0.68
ARPANSA	1.0008	0.05	0.28
NMIJ	0.9992	0.05	0.29

4. The linking of regional comparisons to international comparisons for eligible institutions

The ARPANSA was the initial linking laboratory to link the regional APMP/TCRI comparison with the BIPM reference value. At the December 2012 APMP/TCRI meeting in Wellington, New Zealand, the NMIJ (Japan) agreed to be a second linking institute to provide more robust linkage. The ARPANSA and the NMIJ had separately made bilateral comparisons of the standards for air kerma with the BIPM in 2010 [6] and 2012 [7] respectively. The key comparison results of the ARPANSA and the NMIJ for air kerma at ^{60}Co are given in Table 5.

Table 5. Key comparison ratios NMI/BIPM of air kerma at ^{60}Co for the ARPANSA [6] and the NMIJ [7]

Laboratory	Year of comparison	$R_{NMI,BIPM}$	Combined standard uncertainty u_{link}
ARPANSA	2010	1.0009	0.0031
NMIJ	2012	1.0012	0.0022
Mean $R_{link,BIPM}$		1.0011	0.0027

Then, through Equation 1, the measured calibration coefficients for each laboratory (i) are converted to ratios relative to the BIPM;

$$R_{i,\mathrm{BIPM}} = R_{\mathrm{i,APMP}} \times R_{\mathrm{link,BIPM}} \qquad (1)$$

In this equation,

$R_{\mathrm{i,APMP}}$ = the ratio of the air kerma calibration coefficient determinations from a participating NMI to that of the linking laboratories. In this case it is the mean of the values from the two linking laboratories and referred to as the APMP reference value.

$R_{\mathrm{link,BIPM}}$ = the mean of the comparison results of the two linking laboratories (ARPANSA [6] and NMIJ [7]) that took part in the BIPM key comparison for air kerma standards BIPM.RI(I)-K1.

$R_{\mathrm{i,BIPM}}$ = the derived ratio of the participating laboratory and the BIPM.

Using the key comparison results of the ARPANSA and the NMIJ in Equation 1, the measurement results for each participant could be linked to that of the BIPM as given in Table 6. As previously mentioned, at the time of the comparison two laboratories had not been designated by their national institutes as signatories of the CIPM MRA. The PTKMR-BATAN and the NCRS are still undesignated and their results in this linkage with the BIPM will not be included in this section.

Table 6. Comparison ratios between participants and the BIPM using the unweighted mean for the two linking laboratories (L), the ARPANSA and the NMIJ, from Table 4.

Participant	$R_{\mathrm{i,BIPM}}$				Comb. Std Uncertainty $u_{\mathrm{i,BIPM}}$ (%)
	NE-2571	PTW-30001	PTW-30013	Mean	
DMSC	0.9972	0.9926	0.9966	**0.9955**	0.436
INER	1.0008	1.0005	1.0003	**1.0005**	0.356
NIS	0.9904	0.9839	0.9893	**0.9879**	0.753
ARPANSA (L)	1.0018	1.0008	1.0030	**1.0019**	0.390
NMIJ (L)	1.0003	1.0013	0.9991	**1.0002**	0.402
Mean (excl. links)	0.9961	0.9923	0.9954	**0.9946**	

The uncertainty in the mean ratio for a participant is given by:

$$u_{i,\mathrm{BIPM}} = \left[u_i^{\,2} + u_m^2 + u_{\mathrm{BIPM}}^2 - \sum_n f_n^{\,2}\left(u_{i,n}^2 + u_{\mathrm{BIPM},n}^2\right) + u_{\mathrm{link}}^2 + u_{\mathrm{stab}}^2 \right]^{1/2} \qquad (3)$$

In Equation 3, u_i is the standard uncertainty of the mean, u_m is the statistical measurement uncertainty (from Table 4) and the linking uncertainty u_{link} is the uncertainty of the linking measurements taken from each linking laboratory and applying the unweighted mean value to the other participants. The summation contains those components $f_n u_{i,n}$ and $f_n u_{\mathrm{BIPM},n}$ that are correlated between laboratory *i* and the BIPM, with correlation factor f_n. The components of u_{link} are detailed in [6] and [7] and are essentially those associated with transfer chamber positioning and ionization current measurements for the linking laboratory in both the APMP and BIPM comparisons. The mean value for u_{link} has been taken as 0.27 %. The uncertainty in the chamber stabilities u_{stab} has been estimated from Figure 1 obtained by the INER over the course of the comparison. The very similar behaviour for all three chambers reduces to the simple mean of the chamber ratios and a mean uncertainty in the stability $\bar{u}_{\mathrm{stab}}$ of 0.05 %.

5. Degrees of Equivalence

The analysis of the results of the BIPM comparisons in air kerma for ^{60}Co in terms of Degrees of Equivalence is described in [8]. Following a decision of the CCRI, the BIPM determination of the air kerma is taken as the key comparison reference value N_{KCRV}. It follows that for each laboratory *i* having a comparison result $R_{i,\mathrm{BIPM}}$ with a combined standard uncertainty $u_{i,\mathrm{BIPM}}$, (as given in Table 5), the degree of equivalence with respect to the reference value is

$$D_i = R_{i,\mathrm{BIPM}} - 1 \text{ and its expanded uncertainty is } U_i = 2u_{i,\mathrm{BIPM}}. \quad (4)$$

For the evaluation of the uncertainty, each laboratory submitted its uncertainty budget for u_i. These budgets are summarized in Appendix B. The uncertainty u_{BIPM} given by the BIPM is 0.17 %.

There are several correlated quantities to be taken into consideration in this comparison. Among the physical constants that enter into the determination of air kerma, the product of the graphite to air stopping power ratio and the energy to create an ion pair is important because all the NMIs with primary standards use the same value for this quantity. Therefore, this quantity is fully correlated (f_k = 1) and the contribution of the quantity to the uncertainty is 0.11 %. The quantities such as the air to graphite mass-energy absorption coefficient ratio and the loss of electron energy are also correlated. Unless the primary laboratory carried out the evaluation of these physical constants by itself, these values are taken from the CCRI agreed values and the uncertainties for these constants are 0.05 % and 0.02 % respectively.

The correction factor for the humidity and the value of the dry air density are also fully correlated because every laboratory has taken these values from the ICRU reference data [9]. The uncertainty for the humidity correction is 0.03 %, and 0.01 % for the air density.

The traceability of any participating secondary standard laboratory is also relevant. If a secondary standard laboratory taking part in this comparison is traceable to the BIPM, the uncertainty of the calibration coefficients obtained for the APMP comparison is fully correlated (f_k = 1) with the non-statistical component of the BIPM uncertainty u'_{BIPM} of 0.17 % [2].

$$u_i(D_i) = \left[u_i^2 + u_m^2 + +u_{\mathrm{link}}^2 + u_{\mathrm{stab}}^2 + u_{\mathrm{BIPM}}^2 - \sum_k f_k \cdot u_i^2(k) - u'^2_{\mathrm{BIPM}}(i) \right]^{1/2} \tag{5}$$

The summation over k refers to uncertainties for a laboratory traceable to the BIPM.

Other quantities such as the wall correction factor, the uniformity correction factor and the chamber volume are assumed to be obtained by their experimental or theoretical evaluations and are not correlated.

The results for D_i and U_i, including those of the present comparison, are shown in Figure 4 and in Table 7, expressed in mGy/Gy.

For those institutes that are NMIs or designated institutes signatories of the CIPM MRA either as Member States or Associates, the comparison results will be sent to the BIPM for inclusion in the KCDB.

Table 7. Degrees of Equivalence for eligible participating laboratories in the APMP.R(I)-K1.1 comparison. The table does not include the two linking laboratories.

Lab i	D_i / (mGy/Gy)	U_i
DMSC	-4.5	7.8
INER	0.5	6.9
NIS	-12.1	14.6

6. Conclusion

A comparison of air kerma standards has been carried out among seven laboratories. Three transfer chambers were circulated among the laboratories and each laboratory was asked to provide calibration coefficients and associated uncertainties. The ionization chambers were returned several times to the INER during the comparison and they showed satisfactory stability. The results showed the calibration capabilities of all participating laboratories to be in general agreement within the stated uncertainties. All three eligible secondary standard laboratories tended to have a negative value for the D_i ratio. Two laboratories were outside a deviation of one sigma but within two sigma deviation. As a result, each participating laboratory has not only verified its own measurement capabilities but also strengthened technical cooperation and the exchange of ideas with other laboratories in the process of achieving a comparison result linking it to the BIPM.

5. References

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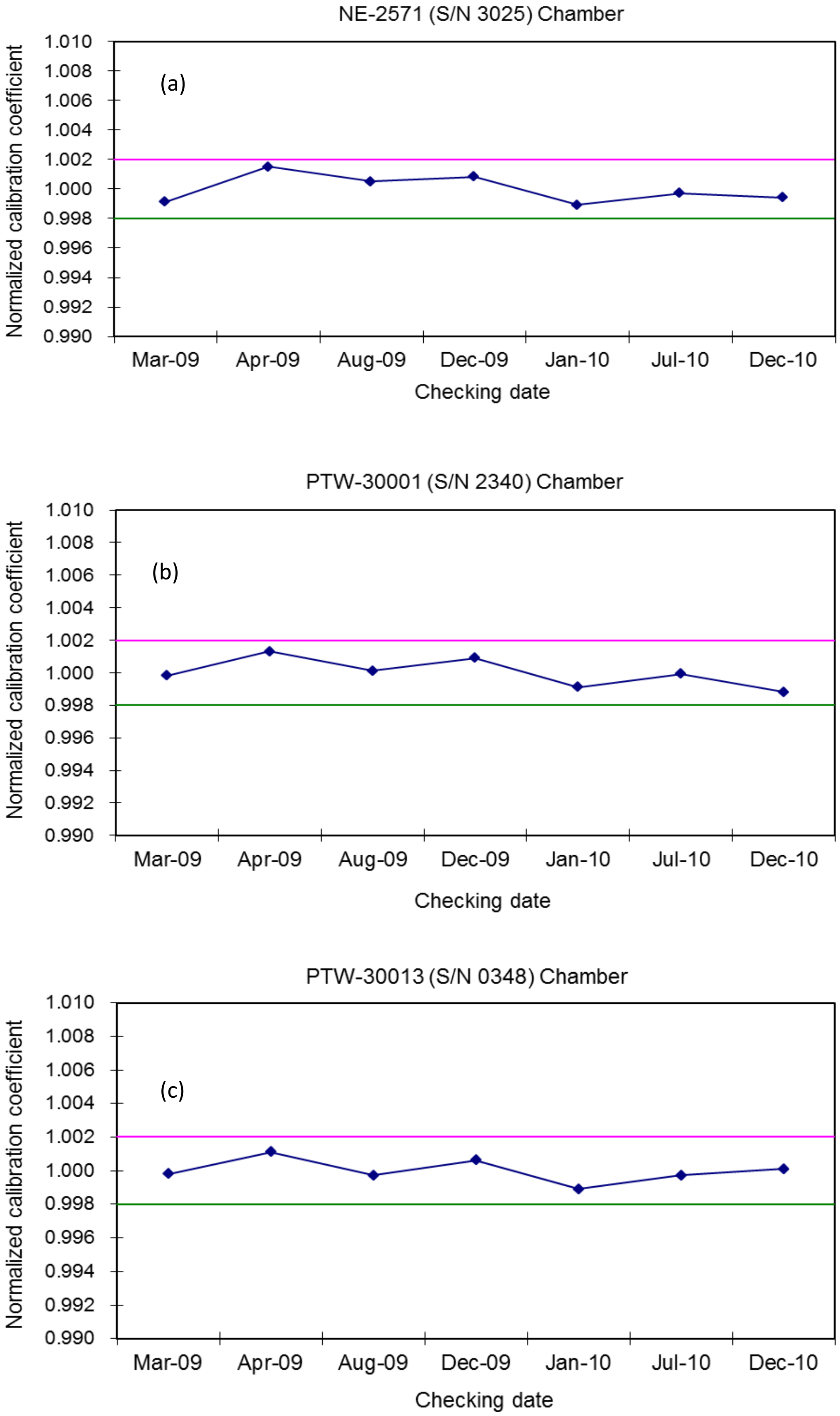


Figure 1. Stability tests of transfer chambers (all air kerma measurements made at the INER), (a) NE-2571 (s/n 3025); (b) PTW-30001 (s/n 2340); (a) PTW-30013 (s/n 0348).

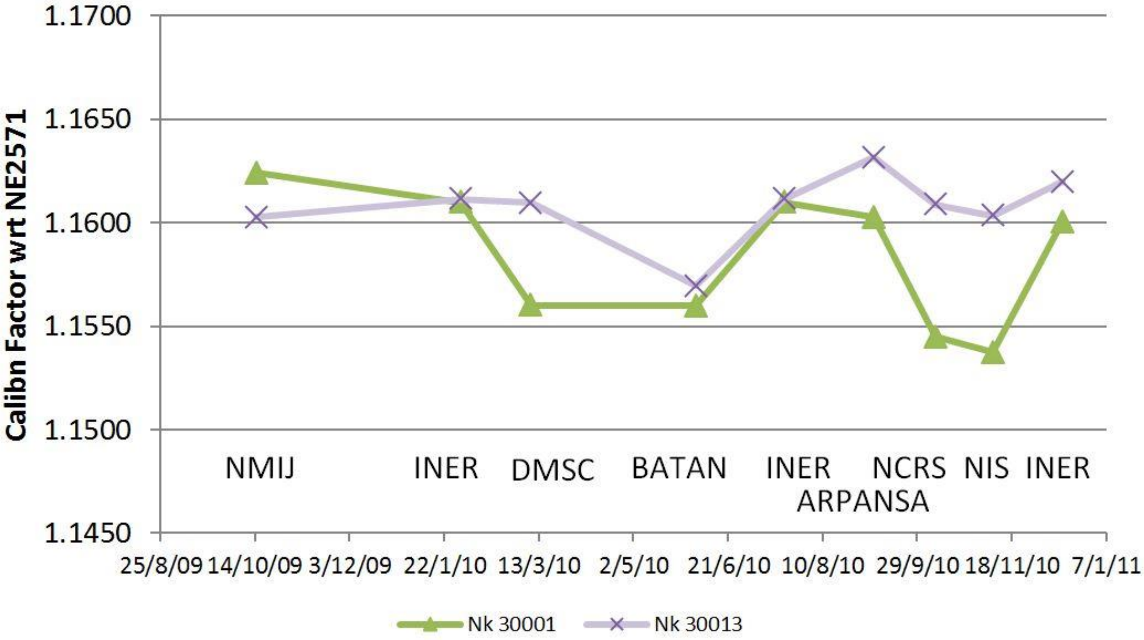


Figure 2. Relative air kerma response of PTW chambers 30001 (▲) and 30013 (✕) with respect to the NE 2571 chamber

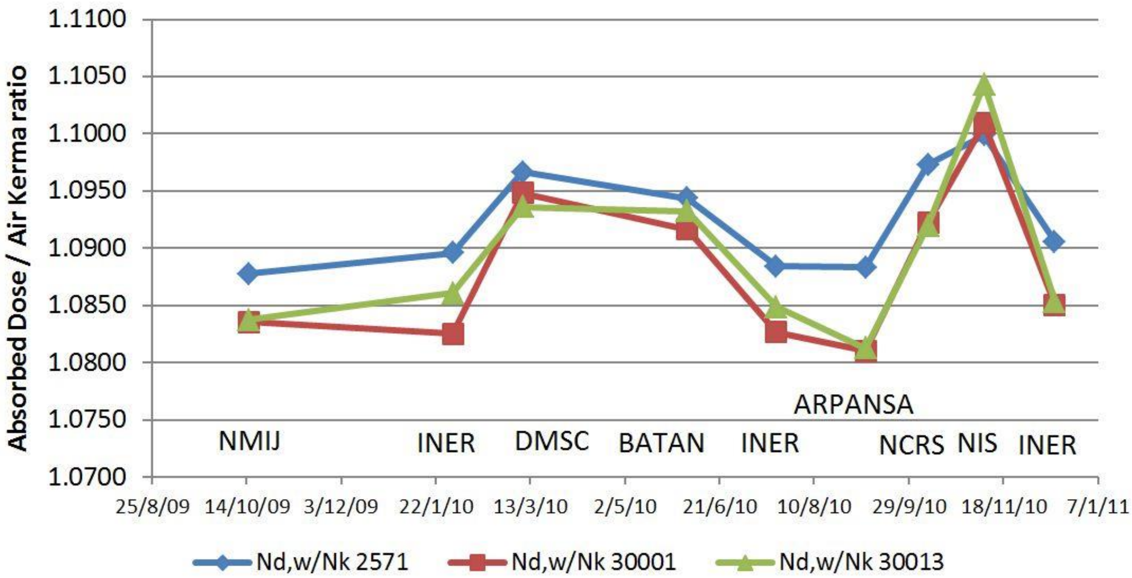
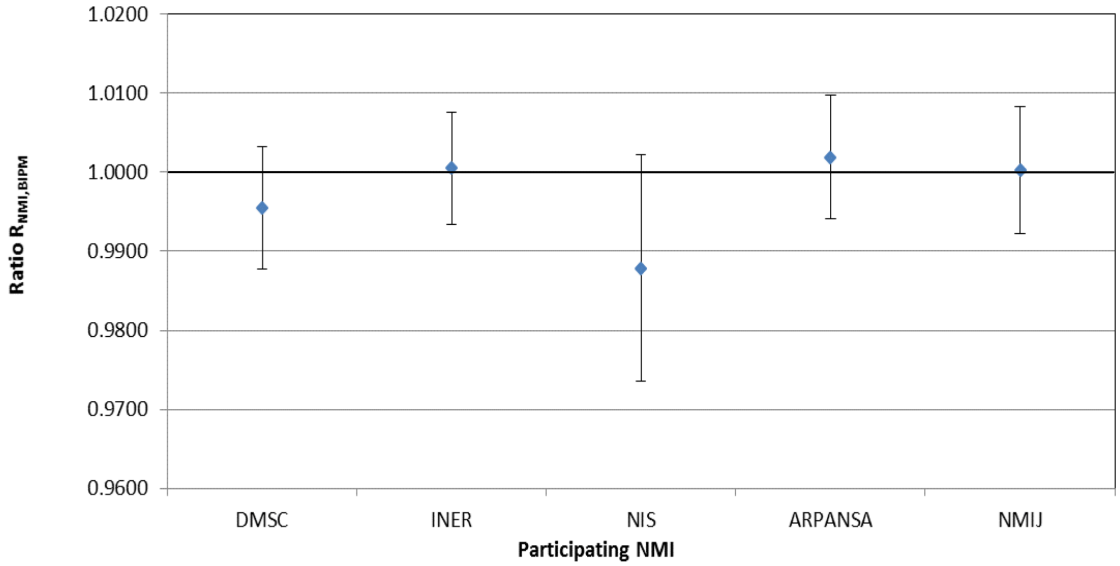


Figure 3. Ratio of absorbed dose to water $N_{d,w}$ to air kerma N_k calibration coefficients for NE2571 (◆), PTW 30001 (■) and PTW 30013 (▲) chambers.

Figure 4. Degrees of Equivalence in terms of the ratio $R_{i,BIPM}$ and the expanded uncertainty U_i. The two linking laboratories are included for the sake of reference.

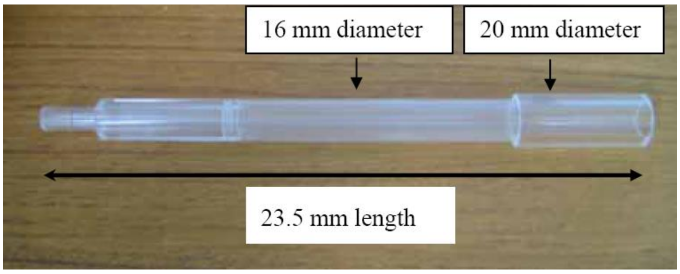


APPENDIX A: Pictures of the transfer chambers

NE 2571 chamber
(S/N 3025, non-waterproof)

PTW 30001 chamber
(S/N 2340 non-waterproof)

PTW 30013 chamber
(S/N 0348, waterproof)



PMMA sleeve made by INER

APPENDIX B: Uncertainty budgets

ARPANSA (Australia) uncertainty budget

Uncertainty associated with the primary standard air kerma rate

Symbol	Parameter/unit	Value	$100s_i$ (Type A)	$100u_i$ (Type B)
Physical constants				
ρ_a	Dry air density (0°C, 101.325 kPa)/kg m^{-3}	1.2047		0.01
$(\mu_{en}/\rho)_{a,c}$	Ratio of mass energy-absorption coefficients	0.9995	0.03	0.04
$s_{c,a}$	Ratio of mass stopping powers	1.002	0.01[a]	0.12[a]
W/e	Mean energy per charge/ J C^{-1}	33.97		
g_a	Fraction of energy lost in radiative processes	0.0024	0.04	0.02
Correction factors				
k_g	Re-absorption of radiative loss			0.04
k_h	Humidity	0.9971		0.04
k_s	Saturation	1.0012		0.03
k_{st}	Stem scattering	0.9986		0.09
k_{wall}	Wall attenuation and scattering	1.0009	0.02	0.03
k_{an}	Axial non-uniformity	1.0028	0.04	0.06
k_{rn}	Radial non-uniformity	0.999		0.1
Measurement of I/v				
I	Ionization current (0°C, 101.325 kPa)		0.05	
ν	Effective volume/cm^3			0.15
Quadratic summation			0.08	0.26
Combined relative standard uncertainty			0.27	

[a] Uncertainty in the product $s_{c,a}$. W/e

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.08	0.26
Ionization current of the transfer chambers	0.07	
Repeatability of measurement		
Distance and orientation		0.10
TPH correction		0.05
Decay correction		0.01
Leakage current		0.12
Radial non-uniformity		0.05
Recombination		
Quadratic summation	0.11	0.31
Combined relative standard uncertainty	0.33	

INER (Taiwan) uncertainty budget

Uncertainty associated with the primary standard air kerma rate

Symbol	Parameter/unit	Value	$100s_i$ (Type A)	$100u_i$ (Type B)
Physical constants				
ρ_a	Dry air density (0°C, 101.325 kPa)/kg m^{-3}			0.01
$(\mu_{en}/\rho)_{a,c}$	Ratio of mass energy-absorption coefficients			0.05
$s_{c,a}$	Ratio of mass stopping powers			0.11 [a]
W/e	Mean energy per charge/ J C^{-1}			
g_a	Fraction of energy lost in radiative processes			0.02
Correction factors				
k_g	Re-absorption of radiative loss			
k_h	Humidity			0.03
k_s	Saturation		0.01	0.02
k_{st}	Stem scattering			0.04
k_{wall}	Wall attenuation and scattering		0.04	0.04
k_{an}	Axial non-uniformity			0.07
k_{rn}	Radial non-uniformity			0.04
Measurement of I/v				
I	Ionization current (0°C, 101.325 kPa)		0.05	
v	Effective volume/cm^3			0.15
Quadratic summation			0.08	0.16
Combined relative standard uncertainty			0.18	

[a] Uncertainty in the product $s_{c,a}$. W/e

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.08	0.16
Ionization current of the transfer chambers	0.06	
Repeatability of measurement		
Distance and orientation	0.05	
TPH correction		0.02
Decay correction		
Leakage current		
Radial non-uniformity		0.01
Recombination		
Quadratic summation	0.11	0.16
Combined relative standard uncertainty	0.20	

NMIJ (Japan) uncertainty budget

Uncertainty associated with the primary standard air kerma rate

Symbol	Parameter/unit	Value	$100s_i$ (Type A)	$100u_i$ (Type B)
Physical constants				
ρ_a	Dry air density (0°C, 101.325 kPa)/kg m^{-3}			0.01
$(\mu_{en}/\rho)_{a,c}$	Ratio of mass energy-absorption coefficients			0.05
$s_{c,a}$	Ratio of mass stopping powers			0.11 [a]
W/e	Mean energy per charge/ J C^{-1}			
g_a	Fraction of energy lost in radiative processes			0.02
Correction factors				
k_g	Scattering photon effect (re-absorption of radiative loss)			0.26
k_h	Humidity			0.03
k_s	Saturation(recombination)			0.01
k_{st}	Stem scattering		0.01	0.1
k_{wall}	Wall attenuation and scattering (incl electron production)		0.05	0.1
k_{an}, k_{rn}	Axial and radial non-uniformity		0.11	0.05
K_{tp}	Temperature and pressure			0.03
Measurement of I/v				
I	Ionization current (0°C, 101.325 kPa)		0.01	0.05
v	Effective volume/cm^3		0.01	0.05
	Position of the primary chamber			0.04
Quadratic summation			0.12	0.34
Combined relative standard uncertainty			0.36	

[a] Uncertainty in the product $s_{c,a}$. W/e

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.12	0.34
Ionization current of the transfer chambers	0.03	0.05
Repeatability of measurement		
Positioning (distance and orientation)		0.05
TP correction		0.06
Humidity correction		0.05
Leakage current		
Radial non-uniformity		
Recombination		
Quadratic summation	0.12	0.36
Combined relative standard uncertainty	0.37	

BATAN (Indonesia) uncertainty budget

Uncertainty associated with the secondary standard air kerma rate

	Parameter/unit	$100s_i$ (Type A)	$100u_i$ (Type B)
Air Kerma rate determination			
	Calibration coefficient of reference chamber		
	--Uncertainty of calibration at ARPANSA		0.50
	--Stability of the reference instrument		0.06
	Correction for change in source position		0.22
	Raw reading of the reference instrument	0.04*	
	Temperature during ref. measurement		
	--Thermometer calibration		0.26
	--Resolution of thermometer		0.30
	Pressure during reference measurement		
	--Barometer calibration		0.07
	--Resolution of barometer		0.08
	Deviation in reference chamber depth		
Quadratic summation		0.04	0.69
Combined relative standard uncertainty		0.690	

* Averaged in quadrature over reference chamber values during measurement of the transfer chambers

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.04	0.69
Ionization current of the transfer chambers	0.02*	0.06
Repeatability of measurement		
Positioning (distance and orientation)		0.05
Temperature correction		0.26
Pressure correction		0.07
Humidity correction		
Leakage current		
Radial non-uniformity		
Recombination		
Quadratic summation	0.05	0.74
Combined relative standard uncertainty	0.75	

* Averaged in quadrature over values given for individual transfer chambers

DMSC (Thailand) uncertainty budget

Uncertainty associated with the secondary standard air kerma rate

	Parameter/unit	$100s_i$ (Type A)	$100u_i$ (Type B)
Air Kerma rate determination			
	N_K of secondary standard		0.42
	Ionization current of the secondary standard	0.01*	
	Repeatability of reference measurement		0.09
	Correction for change in source position		0.01
	Deviation in reference chamber distance		
	Temperature correction		0.04
	Pressure correction		0.01
	Leakage current		
	Recombination correction		0.04
Quadratic summation		0.01	0.43
Combined relative standard uncertainty		0.43	

* Averaged in quadrature over reference chamber values during measurement of the transfer chambers

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.01	0.43
Ionization current of the transfer chambers	0.01*	
Repeatability of measurement		
Positioning (distance and orientation)		0.01
Temperature correction		0.04
Pressure correction		0.01
Humidity correction		
Leakage current		
Radial non-uniformity		
Recombination		0.028**
Quadratic summation	0.02	0.43
Combined relative standard uncertainty	0.44	

* Maximum value of the individual transfer chambers
**Averaged in quadrature over the individual transfer chambers

NIS (Egypt) uncertainty budget

Uncertainty associated with the secondary standard air kerma rate

	Parameter/unit	$100s_i$ (Type A)	$100u_i$ (Type B)
Air Kerma rate determination			
	N_K of secondary standard		0.17
	Ionization current of the secondary standard		0.01
	Repeatability of reference measurement	0.35	
	Temperature, Pressure and Humidity correction	0.35	0.18
	Leakage current	0.10	0.10
	Radial non-uniformity	0.20	0.20
	Recombination correction	0.10	0.10
	Distance		0.50
Quadratic summation		0.55	0.61
Combined relative standard uncertainty		0.82	

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.55	0.61
Ionization current of the transfer chambers		0.01
Repeatability of measurement	0.26*	
Positioning (distance and orientation)	0.20	0.40
Temperature, pressure and humidity correction	0.35	0.18
Decay correction		
Leakage current	0.14	0.25
Radial non-uniformity	0.20	0.20
Recombination	0.10	0.10
Quadratic summation	0.78	0.82
Combined relative standard uncertainty	1.13	

* Averaged in quadrature over values given for individual transfer chambers

NCRS (New Zealand) uncertainty budget

Uncertainty associated with the secondary standard air kerma rate

	Parameter/unit	$100s_i$ (Type A)	$100u_i$ (Type B)
Air Kerma rate determination			
	N_K of secondary standard		0.50
	Ionization current of the secondary standard	0.10	0.15
	Repeatability of measurement	0.05	
	Temperature, Pressure and Humidity corrections		0.05
	Leakage current		0.02
	Radial non-uniformity		
	Recombination		0.03
	Chamber positioning		0.1
Quadratic summation		0.11	0.54
Combined relative standard uncertainty		0.55	

Uncertainty associated with the calibration of the transfer chambers

	s_i (Type A)	u_i (Type B)
Air kerma rate	0.11	0.52*
Ionization current of the transfer chambers		0.10
Repeatability of measurement	0.01	
Distance and orientation		0.10
Temperature, Pressure and Humidity correction		0.05
Decay correction		
Leakage current		0.02
Radial non-uniformity		
Recombination		0.03
Quadratic summation	0.11	0.54
Combined relative standard uncertainty	0.55	

*Corrected for Type B uncertainties in electrometer calibration for a ratiometric method

APPENDIX C: complete addresses of the participants

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