Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the NIM, China, and the BIPM in low-energy x-rays

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Abstract A key comparison has been made between the air-kerma standards of the NIM and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement at the level of the combined standard uncertainty of 3.7 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison has been made between the air-kerma standards of the National Institute of Metrology (NIM), China, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. Two parallel-plate ionization chambers were used as transfer instruments. The measurements at the BIPM took place in April 2018 using the reference conditions recommended by the CCRI (CCEMRI 1972). Final results were received from the NIM in September 2018 and final information for the comparison report in February 2019.

2. Determination of the air-kerma rate

For a free-air ionization chamber standard with measuring volume *V*, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1 - g_{\mathrm{air}}} \prod_i k_i \tag{1}$$

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost through radiative processes in air, and $\Pi\, k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air}, the ionization current I must be corrected for humidity and for the difference between the density of the air of the measuring volume at the time of measurement and the value given in the table.[1]

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. The measuring volume *V* is defined by the diameter of the chamber aperture and the length of the collecting region. The BIPM air-kerma standard is described in Boutillon *et al* (1969) and the changes made to certain correction factors in October 2003 and September 2009 given in Burns (2004), Burns *et al* (2009) and the references therein. Details of the NIM standard are given in Wu Jinjie

[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction $k_{\mathrm{h}} = 0.9980$. At the BIPM, the factor 1.0002 is included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

et al. (2011). While the NIM has not previously taken part in the BIPM.RI(I)-K2 comparison series, the laboratory did participate in 2010 in the APMP.RI(I)-K2 comparison (Tanaka *et al.* 2014). The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2. Note that, as the comparison was carried out during 2018, changes to the standards made in 2019 as the result of the implementation of the recommendations of ICRU Report 90 (ICRU 2016) are not included.

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	u_i [a]
ρ_{air} [b]	1.2930 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0015

[a] u_i is the relative standard uncertainty.
[b] Density of dry air at T_0 = 273.15 K and P_0 = 101.325 kPa used at both laboratories.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	NIM
Aperture diameter / mm	9.941	10.022
Air path length / mm	100.0	100
Collecting length / mm	15.466	40.497
Electrode separation / mm	70	79
Collector width / mm	71	100
Measuring volume / mm^3	1200.4	3194.6
Polarizing voltage / V	1500	1600

4. The transfer instruments

4.1 Determination of the calibration coefficient for a transfer instrument

The air-kerma calibration coefficient N_K for a transfer instrument is given by the relation

$$N_K = \frac{\dot{K}}{I_{tr}} \tag{2}$$

where $\dot{K}$ is the air-kerma rate determined by the standard using (1) and I_{tr} is the ionization current measured by the transfer instrument and the associated current-measuring system. The current I_{tr} is corrected to the reference conditions of ambient air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101.325 kPa and h = 50 %).

To derive a comparison result from the calibration coefficients $N_{K,BIPM}$ and $N_{K,NMI}$ measured, respectively, at the BIPM and at a national measurement institute (NMI), differences in the radiation qualities must be taken into account. Normally, each quality used for the comparison has the same nominal generating potential at each institute, but the half-value layers (HVLs) might differ. A radiation quality correction factor $k_{Q,NMI}$ is derived for each comparison quality Q. This corrects the calibration coefficient $N_{K,NMI}$ determined at the NMI into one that applies at the ‘equivalent’ BIPM quality and is derived from a fit to the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

$$R_{K,\mathrm{NMI}} = \frac{k_{\mathrm{Q,NMI}} N_{K,\mathrm{NMI}}}{N_{K,\mathrm{BIPM}}} \tag{3}$$

In practice, the half-value layers normally differ by only a small amount and $k_{\mathrm{Q,NMI}}$ is close to unity.

4.2 Details of the transfer instruments

Two thin-window parallel-plate ionization chambers belonging to the NIM, type Radcal RC6M, were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The chambers were positioned with the entrance window centred on the beam axis and with the red line around the chamber casing positioned in the reference plane.

Table 3. Main characteristics of the transfer chambers

Chamber type	Radcal RC6M	Radcal RC6M
Serial number	10112	10167
Window material	metallized polyester	
Window thickness / mg cm^{-2}	0.7	
Nominal volume / cm^3	6	
Collector diameter / mm	30 [a]	
Cavity height / mm	8 [a]	
Polarizing potential [b] / V	300	300

[a] The Radcal RC6M cavity dimensions are not clearly stated by the manufacturer. From radiographic measurements, the collector diameter is known to be close to 30 mm, and ionometric measurements indicate a cavity volume of about 5.8 cm^3, consistent with the value 6 cm^3 stated by the manufacturer. From these, the cavity height is deduced to be around 8.2 mm, which would position the collector close to the red line around the chamber casing.

[b] At both laboratories, a positive polarizing potential was applied to the chamber window.

5. Calibration at the BIPM

5.1 The BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. A beryllium filter of thickness 2.16 mm is added (for all radiation qualities) so that the half-value layer (HVL) of the present 10 kV radiation quality matches that of the original BIPM x-ray tube when the same aluminium filter is used. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system of the BIPM. Rather than use a transmission monitor, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. The resulting BIPM air-kerma rate determination shows a long-term standard deviation of less than 3 parts in 10^4. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI (CCEMRI 1972) and are given in Table 4 in ascending HVL from left to right.

Note that the reference distance at the NIM is 1000 mm and so for the present comparison the BIPM measurements were also made at a distance of 1000 mm rather than at the usual reference distance of 500 mm.

The irradiation area is temperature controlled between 20 °C and 22 °C and is stable over the duration of a calibration to better than 0.1 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the BIPM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 40 % to 50 % and consequently no humidity correction is applied to the current measured using transfer instruments.

Table 4. Characteristics of the BIPM reference radiation qualities at 1000 mm

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.2082	0.3723	1.0082	3.989
Al HVL / mm (1000 mm)	0.045	0.195	0.265	1.04	2.27
$(\mu/\rho)_{\mathrm{air}}$[a] / cm^2 g^{-1} (1000 mm)	12.08	3.27	2.39	0.73	0.39
$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1} (1000 mm)	0.11	0.21	0.22	0.25	0.25

[a] Measured for an air-path length of 100 mm.

5.2 BIPM standard and correction factors

As noted above, for the present comparison the reference plane for the BIPM standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.03 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. Using an additional lead collimator positioned at the filter holder, the beam diameter in the reference plane was 88 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using positive polarity only. A correction factor of 1.0005 was applied to correct for the known polarity effect in the standard. The leakage current for the BIPM standard was measured to be less than 1 part in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the BIPM standard, together with their associated standard uncertainties, are given in Table 5.

The largest correction at low energies is that due to the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. The correction factor k_{a} is evaluated for the reference distance of 1000 mm using the measured mass attenuation coefficients $(\mu/\rho)_{\mathrm{air}}$ for 1000 mm given in Table 4. In practice, the values used for k_{a} take account of the temperature and pressure of the air in the standard at the time of the measurements. Ionization measurements (both for the standard and for transfer chambers) are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.03 mm. Each transfer chamber was aligned on the beam axis to an estimated uncertainty of 0.1 mm.

The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The leakage current for the Radcal transfer chambers was always less than 1 part in 10^4.

Table 5. Correction factors for the BIPM standard and their associated uncertainties

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	$u_{i\mathrm{A}}$ [a]	$u_{i\mathrm{B}}$ [a]
Air attenuation k_a [b] (1 m)	1.1566	1.0402	1.0292	1.0088	1.0047	0.0002	0.0001
Scattered radiation k_{sc}	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.0003
Fluorescence k_{fl}	0.9952	0.9971	0.9969	0.9980	0.9985	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Ion recombination k_s	1.0003	1.0004	1.0004	1.0004	1.0004	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	1.0005	1.0005	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia} [c]	0.9999	0.9995	0.9996	0.9989	0.9984	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] $u_{i\mathrm{A}}$ represents the relative standard uncertainty estimated by statistical methods, type A. $u_{i\mathrm{B}}$ represents the relative standard uncertainty estimated by other means, type B.
[b] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
[c] Correction factor k_{dia} for diaphragm transmission, scatter and fluorescence adopted September 2009, replacing the factor k_l for diaphragm transmission only. See Burns and Kessler (2009).

For each of the transfer chambers and at each radiation quality, two sets of seven measurements were made, each measurement with integration time 40 s. The relative standard uncertainty of the mean ionization current for each set was typically below 1 part in 10^4. Repeat measurements for each chamber at several qualities showed a typical reproducibility of 2 parts in 10^4. Despite this good agreement, an additional relative standard uncertainty component of 5 parts in 10^4 is included (Table 11) to account for the typical reproducibility of calibrations in low-energy x-rays at the BIPM.

6. Calibration at the NIM

6.1 NIM irradiation facility and reference radiation qualities

The NIM low-energy x-ray facility consists of a constant-potential generator that can be operated from 7.5 kV to 160 kV and a tungsten-anode x-ray tube with an inherent filtration of 0.8 mm beryllium. A voltage divider is used to measure the generating potential. The characteristics of the NIM realization of the CCRI comparison qualities (CCEMRI 1972) are given in Table 6.

Table 6. Characteristics of the NIM reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.179	0.349	1.002	3.993
Al HVL / mm	0.046	0.170	0.245	1.012	2.241
$(\mu/\rho)_{\mathrm{air}}$ [a] / $\mathrm{cm}^2\ \mathrm{g}^{-1}$	13.45	3.764	2.626	0.742	0.370
$\dot{K}_{\mathrm{NIM}}$ / $\mathrm{mGy\ s}^{-1}$	0.60	1.03	1.02	1.04	0.60

[a] Values measured using an evacuation tube, except for the 10 kV quality which is measured using the two-distance method.

The irradiation area is temperature controlled between 16 °C and 22 °C and is stable over the duration of a calibration to better than 0.2 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the NIM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 35 % to 65 % and consequently no humidity correction is applied to the current measured using transfer instruments.

6.2 NIM standard and correction factors

The reference plane for the NIM standard was positioned at 1000 mm from the radiation source, with an estimated uncertainty of 0.4 mm corresponding to 8 parts in 10^4 in the air-kerma determination. The standard was aligned on the beam axis to an estimated uncertainty of 0.2 mm. The beam diameter in the reference plane is approximately 120 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the NIM standard were made using positive polarity only. No polarity correction factor was applied as the polarity effect in the standard is negligible at the level of the stated uncertainty of 5 parts in 10^4. The leakage current for the NIM standard was measured to be less than 1 part in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the NIM standard, together with their associated uncertainties, are given in Table 7.

The correction factors k_{a} are evaluated using the measured air-attenuation coefficients given in Table 6. In practice, the values used for k_{a} take account of the temperature and pressure of the air in the standard at the time of the measurements. Ionization measurements (standard and transfer chambers) are also corrected for variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

6.3 Transfer chamber positioning and calibration at the NIM

The reference point for each chamber was positioned in the reference plane with an estimated uncertainty of 0.5 mm corresponding to 1 part in 10^3 in the air-kerma determination. Alignment on the beam axis was to an estimated uncertainty of 0.5 mm.

The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current for the Radcal chambers was around 2 parts in 10^4.

For each transfer chamber and at each radiation quality, ten measurements were made, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each set was around 3 parts in 10^4.

Table 7. Correction factors for the NIM standard and their associated uncertainties

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a [a] (1 m)	1.1759	1.0464	1.0321	1.0090	1.0045	-	0.0020
Scattered radiation k_{sc} [b]	0.9915	0.9951	0.9959	0.9959	0.9970	-	0.0015
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0002
Ion recombination k_s	1.0012	1.0012	1.0012	1.0012	1.0012	0.0005	0.0002
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	0.0005
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0010
Diaphragm transmission k_t	1.0000	1.0000	1.0000	0.9999	0.9999	-	0.0001
Diaphragm scatter k_b [c]	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	0.0005
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

[b] Includes fluorescence.

[c] The NIM standard does not include a correction for fluorescence from the diaphragm, which is the largest diaphragm effect for the BIPM standard. See Burns and Kessler (2009).

7. Additional considerations for transfer chamber calibrations

7.1 Ion recombination, polarity, radial non-uniformity, field diameter and distance

As can be seen from Tables 4 and 6, the air-kerma rates at the NIM are higher than at the BIPM by a factor of 2 to 5, depending on beam quality. From previous measurements at the BIPM with this chamber type, the effect of this difference is in the range from 4 to 10 parts in 10^4. A corresponding uncertainty of 8 parts in 10^4 is included in Table 12.

Each transfer chamber was used with the same polarity at each institute and so no corrections are applied for polarity effects in the transfer chambers.

No correction is applied at either laboratory for the radial non-uniformity of the radiation field. For a chamber with collector radius 15 mm (Radcal type), the correction for the BIPM reference fields at 1000 mm is around 1.0010. Data supplied by the NIM show the effect at the NIM to be 1.0005 to 1.0015, depending on beam quality. Given this similarity, the effect of non-uniformity will largely cancel and a relative standard uncertainty of 5 parts in 10^4 is introduced in Table 12.

The field diameter of 120 mm at the NIM is significantly larger than the BIPM field size of 88 mm. From previous BIPM measurements with different field sizes, the effect of this difference on the Radcal chamber type is known to be around 4 parts in 10^4. A corresponding uncertainty in included in Table 12. No additional uncertainty is introduced for distance as both laboratories set a reference distance of 1000 mm for the comparison measurements.

7.2 Radiation quality correction factors $k_{Q,\mathrm{NMI}}$

As noted in Section 4.1, slight differences in the realizations of the CCRI radiation qualities at the NIM and the BIPM might require a correction factor $k_{\mathrm{Q,NMI}}$. Using the HVL values determined at each laboratory as given in Tables 4 and 6, interpolation of the N_K values as described in Section 4.1 results in the $k_{Q,\mathrm{NIM}}$ factors given in Table 8. The uncertainty of these values is taken to be 3 parts in 10^4 and is included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{NIM}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8 along with the correction factors $k_{Q,\mathrm{NIM}}$ evaluated as described in Section 7.2. Note that because of temperature instability problems at the NIM during the post-comparison (summer) period, the $N_{K,\mathrm{NIM}}$ values supplied after the comparison (shown in italic in the table) are *not* used for the final comparison results. Nevertheless, they are used to provide an estimate of the stability of the transfer chambers, which might be considered an upper estimate. These stability estimates $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ for the two chambers are evaluated at each quality as the relative change in $N_{K,\mathrm{NIM}}$ before and after the comparison. The best estimates, $\bar{s}_{\mathrm{tr},1}$ and $\bar{s}_{\mathrm{tr},2}$, are then evaluated for each chamber as the mean for the five qualities, as given in the final column of the table.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	
Radcal 10112						
$N_{K,\mathrm{NIM}}$ (pre-BIPM)	4.813	4.772	4.761	4.775	4.814	
$N_{K,\mathrm{NIM}}$ (post-BIPM) [a]	*4.815*	*4.776*	*4.759*	*4.788*	*4.818*	$\bar{s}_{\mathrm{tr},1}$
$s_{\mathrm{tr},1}$ (relative)	0.0004	0.0008	0.0004	0.0027	0.0008	0.0010
$N_{K,\mathrm{BIPM}}$	4.829	4.773	4.754	4.784	4.834	
$k_{Q,\mathrm{NIM}}$	1.0002	0.9994	0.9998	1.0002	1.0003	
Radcal 10167						
$N_{K,\mathrm{NIM}}$ (pre-BIPM)	4.852	4.761	4.745	4.753	4.796	
$N_{K,\mathrm{NIM}}$ (post-BIPM) [a]	*4.849*	*4.773*	*4.748*	*4.775*	*4.812*	$\bar{s}_{\mathrm{tr},2}$
$s_{\mathrm{tr},2}$ (relative)	0.0006	0.0025	0.0006	0.0046	0.0033	0.0023
$N_{K,\mathrm{BIPM}}$	4.861	4.764	4.745	4.769	4.810	
$k_{Q,\mathrm{NIM}}$	1.0005	0.9991	0.9997	1.0002	1.0003	

[a] As noted in the text, the $N_{K,\mathrm{NIM}}$ values supplied after the comparison (shown in italic) are *not* used for the final comparison results, but rather in the evaluation of the uncertainty estimates $s_{\mathrm{tr},i}$.

For each chamber at each radiation quality, the NIM result before the BIPM measurements and the corresponding value for $k_{Q,\mathrm{NIM}}$ are combined with $N_{K,\mathrm{BIPM}}$ to evaluate the comparison result $R_{K,\mathrm{NIM}}$ according to Equation (3). The results are given in Table 9. For each quality, the final result in bold in Table 9 is evaluated as the mean for the two transfer chambers. The corresponding uncertainty s_{tr} is the standard uncertainty of this mean[2], or taken as

$$s_{\mathrm{tr}} = \sqrt{\left(\bar{s}_{\mathrm{tr},1}^2 + \bar{s}_{\mathrm{tr},2}^2\right)/2} = 0.0013 \qquad (4)$$

if this is larger (on the basis that the agreement between transfer chambers should, on average, not be better than their combined stability estimated using $\bar{s}_{\mathrm{tr},1}$ and $\bar{s}_{\mathrm{tr},2}$ from Table 8). For the present comparison, it is the evaluation using Equation (4) that dominates, presumably because of the temperature difficulties experienced post-comparison at the NIM. The mean value of s_{tr} for the five qualities, $s_{\mathrm{tr,comp}} = 0.0013$, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 12.

Also given in the final row of Table 9 are the results for the NIM in the APMP.RI(I)-K2 comparison (Tanaka *et al.* 2014, KCDB 2019), the NIM measurements dating from 2010.

Table 9. Combined comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$R_{K,\mathrm{NIM}}$ using Radcal 10112	0.9969	0.9992	1.0013	0.9983	0.9962
$R_{K,\mathrm{NIM}}$ using Radcal 10167	0.9986	0.9985	0.9997	0.9968	0.9974
s_{tr}	0.0013	0.0013	0.0013	0.0013	0.0013
Final $R_{K,\mathrm{NIM}}$	**0.9977**	**0.9989**	**1.0005**	**0.9975**	**0.9968**
Results of APMP comparison	*1.0147*	*1.0117*	*1.0107*	*1.0078*	*1.0061*

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 10, and those for the transfer chamber calibrations in Table 11. The combined uncertainty for the comparison results $R_{K,\mathrm{NIM}}$ is presented in Table 12. This combined uncertainty takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction. In the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described in Burns *et al* (2003), correlation in the values for the correction factors k_{e}, k_{sc} and k_{fl} are taken into account if the NMI has used values derived from Monte Carlo calculations. This is the case for the NIM standard and consequently this correlation has been assumed.

[2] The standard uncertainty is evaluated as the standard deviation of the population divided by (n–1.4), found empirically to be a better choice than (n–1) to estimate the standard uncertainty for low values of n.

Table 10. Uncertainties associated with the standards

Standard	BIPM		NIM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0002	0.0004
Positioning	0.0001	0.0001	-	0.0008
Volume	0.0003	0.0005	0.0001	0.0001
Correction factors (excl. k_h)	0.0003	0.0010	0.0005	0.0028
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0005	0.0033

Table 11. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		NIM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}$	0.0005	0.0019	0.0005	0.0033
I_{tr}	0.0002	0.0002	0.0002	0.0004
Positioning of transfer chamber	0.0001	-	0.0001	0.0010
Short-term reproducibility	0.0005	-	-	0.0008
N_K	0.0007	0.0019	0.0005	0.0036

10. Discussion

The comparison results $R_{K,NIM}$ show the NIM and BIPM standards to agree at the level of the standard uncertainty of the comparison of 3.7 parts in 10^3. Although the results for the different qualities vary by over 3 parts in 10^3, no clear trend with energy is evident.

As can be deduced from the final row of Table 9, the present results differ by up to 1.7 parts in 10^2 from those obtained by the NIM in the APMP.RI(I)-K2 comparison carried out over the period 2008 to 2010, as documented in Tanaka *et al.* (2014) and in the BIPM key comparison database (KCDB 2019). Moreover, the clear trend with energy noted at that time is not evident in the present results. In the intervening period, changes were made to the NIM correction factors for air attenuation, photon scatter and ion recombination, based on new measurements and calculations. However, the combined changes result in a reduction in the NIM air-kerma determination of only around 2 parts in 10^3, with no significant impact on the trend with energy. In 2015 the NIM x-ray facility was upgraded, with changes to filtration, instrument positioning, the current measurement system and data acquisition software, which might offer an underlying reason for the discrepancy between the present results and those of the APMP comparison.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{NIM}}$ / $N_{K,\mathrm{BIPM}}$	0.0009	0.0032[a]
Ion recombination	-	0.0008
Radial non-uniformity	-	0.0005
Field size	-	0.0004
$k_{Q,\mathrm{NIM}}$	-	0.0003
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0013	-
$R_{K,\mathrm{NIM}}$	0.0016	0.0034
	u_{c} = 0.0037	

a Takes account of correlation in type B uncertainties.

11. Degrees of Equivalence

The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described in Burns (2003). Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the key comparison reference value, for each of the CCRI radiation qualities. It follows that for each laboratory i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$. The results for D_i and U_i, expressed in mGy/Gy and including those of the present comparison, are shown in Table 13 and in Figure 1, which include the linked results of the corresponding regional key comparison APMP.RI(I)-K2 (Tanaka *et al* 2014).

When required, the degree of equivalence between two laboratories i and j can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j (Burns 2003).

12. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the NIM and BIPM standards to be in agreement at the level of the standard uncertainty of the comparison of 3.7 parts in 10^3. Degrees of equivalence, including those for the NIM, are presented for entry in the BIPM key comparison database. Note that the data presented in the tables, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

Table 13. Degrees of equivalence. For each laboratory i, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i.
The results in red are for comparison BIPM.RI(I)-K2 and those in blue for APMP.RI(I)-K2.

	10 kV		30 kV		25 kV		50 kVb		50 kVa	
Lab i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i
METAS	2.2	3.4	1.0	3.4	1.3	3.4	0.2	3.4	0.1	3.4
ARPANSA	-1.5	14.0	-2.5	7.5	-2.6	7.5	-1.0	7.5	0.2	7.5
LNE-LNHB	-0.8	3.2	0.2	3.2	0.7	3.2	0.1	3.2	0.7	3.2
NIST			-3.1	8.4	0.0	8.4	1.5	8.4	-2.6	8.4
GUM	-5.1	6.0	-3.7	6.0	-0.1	6.0	-2.8	6.0	0.5	6.0
ENEA	-2.2	3.8	-3.2	3.8	-2.4	3.8	-2.0	3.8	-2.1	3.8
MKEH	-2.7	4.1	-2.5	4.1	-1.2	4.1	-2.6	4.1	-3.4	4.1
VNIIM	-3.2	4.7	-2.1	4.7	-2.2	4.7	-1.3	4.7	-0.7	4.7
VSL	7.8	6.6	6.9	6.6	7.5	6.6	11.5	6.6	13.0	6.6
PTB	0.3	4.3	-1.8	4.3	-2.1	4.3	-1.1	4.3	-0.6	4.3
BEV	-2.0	13.6	-0.8	9.5	-1.3	9.5	-0.8	9.5	-1.6	9.5
NMIJ	3.2	6.0	1.0	6.0	-2.3	6.0	-0.9	6.0	-2.6	6.0
CMI	5.5	7.0	3.9	7.0	4.5	7.0	4.2	7.0	4.4	7.0
NPL	-12.2	4.2	-11.4	4.2	-11.1	4.2	-10.1	4.2	-9.6	4.2
NRC	0.3	6.7	-2.4	6.7	-1.4	6.7	0.6	6.7	0.4	6.7
NIM	-2.3	7.4	-1.1	7.4	0.5	7.4	-2.5	7.4	-3.2	7.4
Nuc. Malaysia	42.0	14.0	25.7	14.0	25.9	14.0	34.9	14.0	37.0	14.0
BARC			13.5	100.0	42.8	100.0	30.9	100.0	19.0	100.0
INER	2.8	13.4	8.6	13.4	8.3	13.4	6.4	13.4	10.2	13.4
IAEA	4.5	10.8	2.8	10.8	4.3	10.8	4.9	10.8	4.8	10.8

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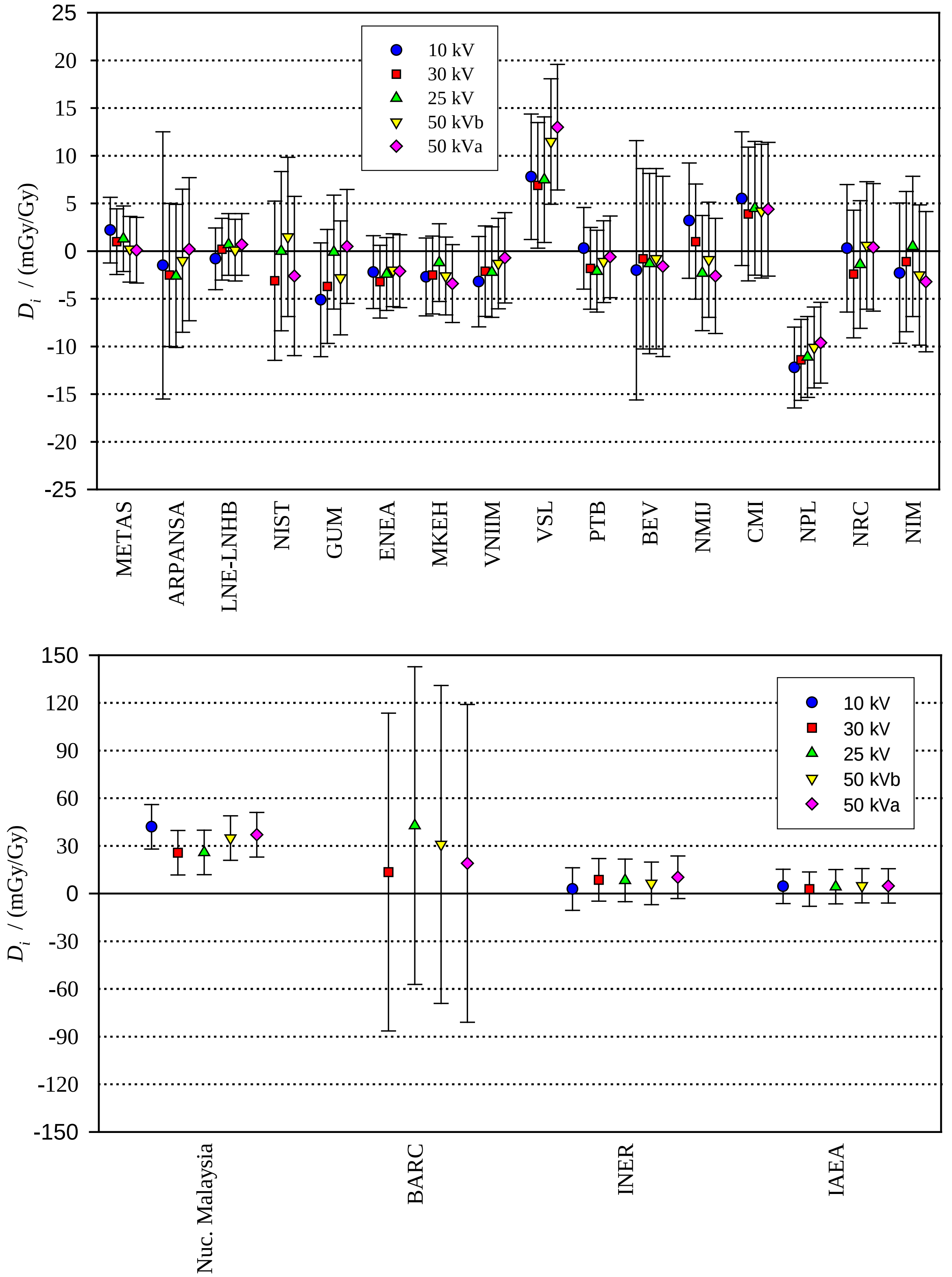

Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value. The top graph shows the results for the comparison BIPM.RI(I)-K2 and the bottom graph those for the regional comparison APMP.RI(I)-K2 (note the expanded ordinate axis for the latter).