Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the BFKH, Hungary, 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 BFKH, Hungary, and the BIPM in the low-energy x-ray range. The results show the standards to agree at the level of the expanded uncertainty of the comparison of 6.8 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 Budapest Főváros Kormányhivatala (BFKH), Hungary, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. One parallel-plate ionization chamber was used as transfer instrument. The measurements at the BIPM took place in October 2021 using the reference conditions recommended by the CCRI as described in Kessler and Burns (2018). Final data were received from the BFKH in February 2023.

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 value used for ρ_{air} at each laboratory is given in Table 1. For use with this dry-air value, the ionization current measured for the standard 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]. The value used for W_{air}/e is that recommended in ICRU Report 90 (ICRU 2016) for dry air, also given in Table 1.

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. The BIPM air-kerma standard is described in Boutillon *et al.* (1969) and the changes made to certain correction factors are given in Burns (2004), Burns and Kessler (2009) and Burns *et al.* (2009). Implementation of the recommendations of ICRU Report 90 (ICRU 2016) is reported in Burns and Kessler (2018). The BFKH standard is described in the reports of previous comparisons with the BIPM standard

[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density for the standard involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction $k_{\mathrm{h}} = 0.9980$.

(Perroche and Jacab 1989, Burns and Csete 2002, Burns *et al.* 2012). Changes to the BFKH standard following the recommendations of ICRU Report 90 were made during the present comparison and are reported here. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

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

Constant	Value	u_i [a]
ρ_{air} [b] (BIPM)	1.2045 kg m^{-3}	0.0001
ρ_{air} [c] (BFKH)	1.2048 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0035

[a] u_i is the relative standard uncertainty.
[b] Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa adopted at the BIPM.
[c] Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa adopted at the BFKH.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	BFKH XE-1 [a]
Aperture diameter / mm	9.941	4.9995
Air path length / mm	100.0	63.7
Collecting length / mm	15.466	40.94
Electrode separation / mm	70	60.0
Collector width / mm	71	60.4
Measuring volume / mm^3	1200.4	803.69
Polarizing voltage / V	1500	1600

[a] In the previous comparisons this standard was labelled XE-3.

4. The transfer instrument

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 Equation (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 standard conditions of air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101.325 kPa, RH = 50 %). No humidity correction is applied to the current measured using transfer instruments, on the basis that the BIPM laboratory is maintained with a relative humidity in the range from 40 % to 55 % and variations in the BFKH laboratory are normally in the range from 20 % to 60 %.

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

$$R_K = \frac{k_Q N_{K,\mathrm{NMI}}}{N_{K,\mathrm{BIPM}}} \tag{3}$$

In practice, the half-value layers normally differ by only a small amount and k_Q is close to unity.

4.2 Details of the transfer instrument

A thin-window parallel-plate ionization chamber belonging to the BFKH, type Radcal 10X5-6M, was used as transfer instrument for the comparison. The same chamber was used for supporting measurements during the direct comparison carried out in 2011. Its main characteristics are given in Table 3. For positioning at the reference distance, the red line around the chamber casing (8.6 mm from the front of the casing) was positioned in the reference plane.

Table 3. Main characteristics of the transfer chamber

Chamber type	Radcal 10X5-6M [a]
Serial number	8626
Window material	metallized polyester
Window thickness / mg cm^{-2}	0.7
Nominal volume / cm^3	6
Collector diameter / mm	30
Cavity height / mm	8
Polarizing potential [b] / V	+250

[a] The Radcal 10X5-6M dimensions are not clearly stated by the manufacturer. From radiographic measurements, the collector diameter appears to be close to 30 mm. Ionometric measurements indicate a collecting volume around 5.8 cm^3, consistent with the value 6 cm^3 stated by the manufacturer. From these one can deduce a cavity height of around 8.2 mm.

[b] Potential 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 high-stability 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 to compensate for the decrease in filtration that occurred when the original BIPM x-ray tube (with a beryllium window of approximately 3 mm) was replaced in 2000; the added thickness was determined experimentally to give a half-value layer (HVL) at

10 kV matching that of the original x-ray tube. 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, which might introduce its own variability, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. For a given radiation quality, the standard deviation of repeat air-kerma rate determinations over many months is typically 3 parts in 10^4. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI and are given in Table 4 in ascending HVL from left to right.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.15 °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.

Table 4. Characteristics of the BIPM reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Al filtration / mm	0	0.2082	0.3723	1.0082	3.989
Al HVL / mm	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{air}$ / $cm^2\ g^{-1}$	14.83	3.66	2.60	0.75	0.38
$\dot{K}_{BIPM}$ / $mGy\ s^{-1}$	1.00	1.00	1.00	1.00	1.00

5.2 BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 500 mm from the exit window, with a reproducibility of 0.03 mm. The standard was aligned laterally on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is 84 mm for all radiation qualities.

For the calibration of transfer chambers, measurements using the BIPM standard are made using positive polarity only. A correction factor of 1.0005 is applied to correct for the known polarity effect in the standard. The leakage current 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 factor k_a corrects for the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. It is evaluated using the measured mass attenuation coefficients for air $(\mu/\rho)_{air}$ given in Table 4, taking into account the air temperature and pressure at the time of the measurements.

Two new correction factors, k_{ii} and k_W, are implemented following the recommendations of ICRU Report 90 (ICRU 2016) and presented as the product $k_{ii}k_W$ by Burns and Kessler (2018). Both correction factors are related to the mean energy expended in dry air per ion pair formed, W_{air}. The initial ionization correction factor k_{ii} accounts for the fact that the definition of W_{air} does not include the charge of the initial charged particle, while the correction factor k_W accounts for the rapid increase in the value of W_{air} at electron energies below around 10 keV.

Table 5. Correction factors and their uncertainties for the BIPM L-01 standard

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]	1.1956	1.0451	1.0319	1.0091	1.0046	0.0002	0.0001
Photon scatter 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
Initial ionization k_{ii} [b] / Energy dependence of W_{air} k_W [b]	0.9953	0.9968	0.9969	0.9977	0.9980	-	0.0012
Ion recombination k_s	1.0006	1.0007	1.0007	1.0007	1.0007	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}	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
$(1 - g_{air})^{-1}$	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 temperature and pressure measured at the time.
[b] The stated values are for the product $k_{ii}k_W$, as presented in Burns and Kessler (2018).

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for the transfer chamber was positioned in the reference plane with a reproducibility of 0.03 mm. The chamber was aligned laterally 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 relative leakage current was well below 1 part in 10^4.

The calibration procedure involves measurements with a transfer chamber and with the standard at a given radiation quality before proceeding to the next quality, with a period of typically 10 minutes following a change of quality to allow the generator and tube to stabilize (longer for the 50 kVa quality). For each radiation quality, the relative standard uncertainty of the mean ionization current was typically 1 part in 10^4. Based on the results of repeat calibrations including chamber repositioning, an uncertainty component of 5 parts in 10^4 is included in Table 11 for the short-term reproducibility of the calibration coefficients determined at the BIPM.

6. Calibration at the BFKH

6.1 BFKH irradiation facility and reference radiation qualities

The low-energy x-ray facility at the BFKH comprises a high-stability generator and a tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. The x-ray output is monitored by means of a transmission ionization chamber whose Mylar windows introduce a filtration of

3 mg cm^{-2}. For a given radiation quality, the short-term standard uncertainty of the distribution of repeat calibrations of the transmission monitor is around 2 parts in 10^4. The characteristics of the BFKH realization of the CCRI comparison qualities are given in Table 6. Note that no comparison was made for the 10 kV quality.

Table 6. Characteristics of the BFKH reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Al filtration / mm	0	0.235	0.455	1.13	4.24
Al HVL / mm	0.034	0.17	0.25	1.07	2.25
$(\mu/\rho)_{air}$ / cm^2 g^{-1}	12.62	3.08	2.02	0.69	0.39
$\dot{K}_{BFKH}$ / mGy s^{-1}	0.33	0.54	0.48	0.22	0.14

The irradiation area is temperature controlled around 20 °C and is stable over the duration of a calibration to better than 0.1 °C. The air temperature is measured for each current measurement using a platinum (Pt 200) temperature probe positioned next to the standard and to the transfer chamber, as appropriate. The air pressure is measured using a calibrated barometer.

6.2 BFKH standard and correction factors

The BFKH XE-1 standard used for the present comparison is the same chamber used for the comparisons made in 1988, 2001 and 2011 (previously labelled XE-3). The reference plane for the standard was positioned at 595 mm from the source, with a reproducibility of 0.1 mm. The standard was aligned laterally on the beam axis to an estimated uncertainty of 0.3 mm. The beam diameter in the reference plane is 110 mm for all radiation qualities.

During the calibration of the transfer chamber, measurements using the BFKH standard were made using positive polarity only. A correction factor of unity is applied with a standard uncertainty of 2 parts in 10^4 to take into account any small polarity effect in the standard. The leakage current was measured to be around 1 part in 10^3.

The correction factors applied to the ionization current measured at each radiation quality using the BFKH standard, together with their associated uncertainties, are given in Table 7. The correction factors k_a are evaluated using the measured mass attenuation coefficients for air $(\mu/\rho)_{air}$ given in Table 6, taking into account the air temperature and pressure at the time of the measurements.

As for the BIPM standard, two new correction factors k_{ii} and k_W, implemented as the product $k_{ii}k_W$, were adopted for the present comparison.

6.3 Transfer chamber positioning and calibration at the BFKH

The reference point for the transfer chamber was positioned in the reference plane with a reproducibility of 0.1 mm. The chamber was aligned laterally on the beam axis to an estimated uncertainty of 0.1 mm. The relative leakage current was typically 1 part in 10^4.

Calibrations were made before and after the measurements at the BIPM. The uncertainty of 1.9 parts in 10^3 arising from these repeat measurements is discussed in Section 8.

Table 7. Correction factors and uncertainties for the BFKH XE-1 standard

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]	1.1017	1.0239	1.0156	1.0053	1.0030	0.0005	0.0010
Scattered radiation k_{sc}	0.9970	0.9979	0.9980	0.9983	0.9985	-	0.0006
Fluorescence k_{fl}	0.9951	0.9968	0.9970	0.9980	0.9985	-	0.0007
Electron loss k_e	1.0000	1.0000	1.0000	1.0001	1.0003	-	0.0002
Initial ionization k_{ii} [b] Energy dependence of W_{air} k_W [b]	0.9953	0.9968	0.9969	0.9977	0.9980	-	0.0010
Ion recombination k_s	1.0012	1.0012	1.0012	1.0012	1.0012	0.0004	0.0001
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	0.0002	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Diaphragm effects k_{dia}	1.0000	1.0000	1.0000	0.9985	0.9981	-	0.0006
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	0.0001
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$k_{br}\,(1 - g_{air})^{-1}$ [c]	1.00001	1.00004	1.00004	1.00010	1.00015	-	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air temperature and pressure measured at the time. The uncertainty values for the 10 kV quality are larger ($u_{i\mathrm{A}}$ = 0.0020, $u_{i\mathrm{B}}$, = 0.0020) but this quality was not used for the comparison.

[b] The stated values are for the product $k_{ii}k_W$.

[c] The bremsstrahlung reabsorption correction factor k_{br} is defined in Burns (2001).

7. Additional considerations for transfer chamber calibrations

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

As can be seen from Tables 4 and 6, the air-kerma rates at the BFKH are lower than at the BIPM. From previous measurements at the BIPM with the Radcal chamber type, the effect of an increase in the air-kerma rate from 1 mGy s^{-1} to 4 mGy s^{-1} is around 8 parts in 10^4, from which we can deduce that the volume recombination effect for the BIPM reference condition of 1 mGy s^{-1} is not more than 3 parts in 10^4 and could be as low as 1 part in 10^4 at the BFKH. No correction is applied, rather a corresponding uncertainty of 2 parts in 10^4 is included in Table 12. The transfer chamber was used with the same polarity at each laboratory 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 the Radcal chamber type with collector radius 15 mm, the correction for the BIPM reference fields at 500 mm is 1.0022. It is reasonable to assume some cancellation at the two laboratories. A relative standard uncertainty of 5 parts in 10^4 is included in Table 12.

The reference distance of 595 mm at the BFKH is greater than the 500 mm at the BIPM. From previous measurements at the BIPM, the effect on the Radcal chamber type of an increase in the calibration distance from 500 mm to 1000 mm (for a similar field size) is to decrease N_K by around

2 parts in 10^3 (largely independent of radiation quality), from which we can deduce that the effect for 595 mm might be 4 parts in 10^4. This component is included in Table 12.

The reference field size of 110 mm at the BFKH is larger than the 84 mm at the BIPM. From previous measurements at the BIPM, the effect on the Radcal chamber type of field sizes from 50 mm to 120 mm (for the same distance) has been determined; between 84 mm and 110 mm the effect is to decrease N_K by around 5 parts in 10^4 (not strongly dependent on radiation quality over this limited range). This component is included in Table 12. Note that the effects of larger distance and larger field size act in the same direction.

7.2 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in the realizations of the CCRI radiation qualities at the BFKH and the BIPM might require a correction factor k_Q. 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 k_Q factors within 1 part in 10^4 of unity, with the exception of the 50 kVb quality where the factor 0.9995 has been applied. An uncertainty component of 1 part in 10^4 is included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{BFKH}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chamber are presented in Table 8. For each radiation quality the values $N_{K,\mathrm{BFKH}}$ measured before and after the measurements at the BIPM give rise to the mean value used for the final comparison result and a relative standard uncertainty s_{tr} representing the chamber stability[2]. The rms value of s_{tr} for the four qualities, $s_{\mathrm{tr,comp}} = 0.0019$, is taken to represent the comparison uncertainty arising from the transfer chamber and is included in Table 12, replacing the BFKH reproducibility component of 1 part in 10^3 (Table 11) because the latter is necessarily included in $s_{\mathrm{tr,comp}}$.

Table 8. Calibration coefficients for the transfer chamber Radcal 10X5-6M-8626

Radiation quality	30 kV	25 kV	50 kVb	50 kVa
$N_{K,\mathrm{BFKH}}$ (pre-BIPM) / Gy μC^{-1}	4.796	4.789	4.827	4.864
$N_{K,\mathrm{BFKH}}$ (post-BIPM) / Gy μC^{-1}	4.785	4.775	4.820	4.885
s_{tr}	0.0015	0.0019	0.0009	0.0028
$N_{K,\mathrm{BIPM}}$	4.811	4.801	4.823	4.874

The comparison results R_K are presented in Table 9, evaluated according to Equation (3) with k_Q equal to unity (k_Q = 0.9995 at 50 kVb). Also given in the final two rows of Table 9 are the results for the BFKH in the previous comparison in 2011. At that time a direct comparison was made using the BFKH standard transported to the BIPM as well as an indirect comparison using the same Radcal transfer chamber. These results are discussed in Section 10.

[2] For n = 2, the modified standard uncertainty $s_{\mathrm{tr}} = s_{\mathrm{dev,pop}}/\sqrt{n-1.4}$ is used, following Burns (2023).

Table 9. Combined comparison results

Radiation quality	30 kV	25 kV	50 kVb	50 kVa
$\boldsymbol{R_K}$	0.9957	0.9960	0.9996	1.0001
Direct results of 2011	0.9975	0.9988	0.9974	0.9966
Indirect results of 2011	0.9984	0.9982	1.0008	1.0020

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 standard uncertainty u_c for the comparison results R_K is presented in Table 12. This uncertainty takes into account correlation in the type B uncertainties associated with the physical constants, the humidity correction and the product $k_{ii}k_W$. Correlation in the values for k_{sc}, k_{fl}, k_e and k_{dia}, derived from Monte Carlo calculations in each laboratory, are taken into account in an approximate way by assuming half of the uncertainty value for each factor at each laboratory. This is consistent with the analysis of the results of BIPM comparisons in low-energy x-rays described in Burns (2003).

10. Discussion

The comparison results show the BFKH and the BIPM standards to agree at the level of the expanded uncertainty of the comparison of 6.8 parts in 10^3. The results for the four qualities show the same energy dependence of 4 parts in 10^3 observed during the indirect comparison in 2011, the new values being 1 to 3 parts in 10^3 lower than those obtained indirectly in 2011. This energy dependence is not evident in the direct comparison results of 2011 and therefore probably arises from the use of a transfer instrument, which appears to increase the comparison results for the two 50 kV qualities.

Table 10. Uncertainties associated with the standards

Standard	BIPM L-01		BFKH XE-1	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0007	0.0002
Positioning	0.0001	0.0001	-	0.0010
Volume	0.0003	0.0005	0.0010	0.0005
Correction factors (excl. k_h)	0.0003	0.0015	0.0007	0.0019
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}$	0.0005	0.0039	0.0014	0.0042

Table 11. Uncertainties associated with transfer chamber calibrations

Institute	BIPM		BFKH	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}$	0.0005	0.0039	0.0014	0.0042
I_{tr}	0.0002	0.0002	0.0008	0.0003
Positioning of transfer chamber	0.0001	-		0.0005
Reproducibility	0.0005	-	- [a]	-
N_K	0.0007	0.0039	0.0016	0.0042

[a] See Section 8 and Table 12.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{BFKH}}$ / $N_{K,\mathrm{BIPM}}$	0.0018	0.0020 [a]
Ion recombination	-	0.0002
Radial non-uniformity	-	0.0005
Distance	-	0.0004
Field size	-	0.0005
k_Q	-	0.0001
Transfer chamber $s_{\mathrm{tr,comp}}$	0.0019	-
R_K	0.0026	0.0022
	u_{c} = 0.0034	

[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 $D_i = (\dot{K}_i - \dot{K}_{\mathrm{BIPM},i}) / \dot{K}_{\mathrm{BIPM},i} = x_i - 1$ 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.

12. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the BFKH and the BIPM to agree at the level of the expanded uncertainty of the comparison of 6.8 parts in 10^3.

Tables and a graph of degrees of equivalence, including those for the BFKH, are presented for entry in the BIPM key comparison database. Note that these data, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. In addition, revised validity rules for comparison data have been agreed by the CCRI(I) so that results older than 15 years are no longer considered valid and do not appear in the key comparison database (KCDB). The formal results under the CIPM MRA are those available in the KCDB (KCDB 2023).

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. Laboratory names in red indicate participation in comparison BIPM.RI(I)-K2 and blue in APMP.RI(I)-K2.

		10 kV		30 kV		25 kV		50 kVb		50 kVa	
Lab *i*	Year	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
LNE-LNHB	2009	-0.8	4.0	0.2	4.0	0.7	4.0	0.1	4.0	0.7	4.0
NIST	2010			-3.1	8.7	0.0	8.7	1.5	8.7	-2.6	8.7
ENEA	2011	-2.2	4.5	-3.2	4.5	-2.4	4.5	-2.0	4.5	-2.1	4.5
VNIIM	2011	-3.2	5.3	-2.1	5.3	-2.2	5.3	-1.3	5.3	-0.7	5.3
VSL	2012	7.8	7.0	6.9	7.0	7.5	7.0	11.5	7.0	13.0	7.0
PTB	2014	0.3	4.9	-1.8	4.9	-2.1	4.9	-1.1	4.9	-0.6	4.9
BEV	2014	-2.0	14	-0.8	9.8	-1.3	9.8	-0.8	9.8	-1.6	9.8
NMIJ	2014	3.2	6.5	1.0	6.5	-2.3	6.5	-0.9	6.5	-2.6	6.5
CMI	2015	5.5	7.4	3.9	7.4	4.5	7.4	4.2	7.4	4.4	7.4
KRISS	2017	-1.6	4.4	-2.4	4.4	-1.6	4.4	-1.8	4.4	-1.9	4.4
NPL	2017	-12.2	4.9	-11.4	4.9	-11.1	4.9	-10.1	4.9	-9.6	4.9
NRC	2018	0.3	7.1	-2.4	7.1	-1.4	7.1	0.6	7.1	0.4	7.1
NIM	2018	-2.3	7.7	-1.1	7.7	0.5	7.7	-2.5	7.7	-3.2	7.7
GUM	2021	-5.9	5.8	5.2	5.8	1.9	5.8	3.1	5.8	1.9	5.8
BFKH	2021			-4.3	6.8	-4.0	6.8	-0.4	6.8	0.1	6.8
ARPANSA	2022	11.2	22	-7.6	9.1			-5.4	9.1	-4.8	9.1
MNA	2008	42.0	14	25.7	14	25.9	14	34.9	14	37.0	14
BARC	2009			13.5	100	42.8	100	30.9	100	19.0	100
INER	2009	2.8	13	8.6	13	8.3	13	6.4	13	10.2	13
IAEA	2010	4.5	11	2.8	11	4.3	11	4.9	11	4.8	11

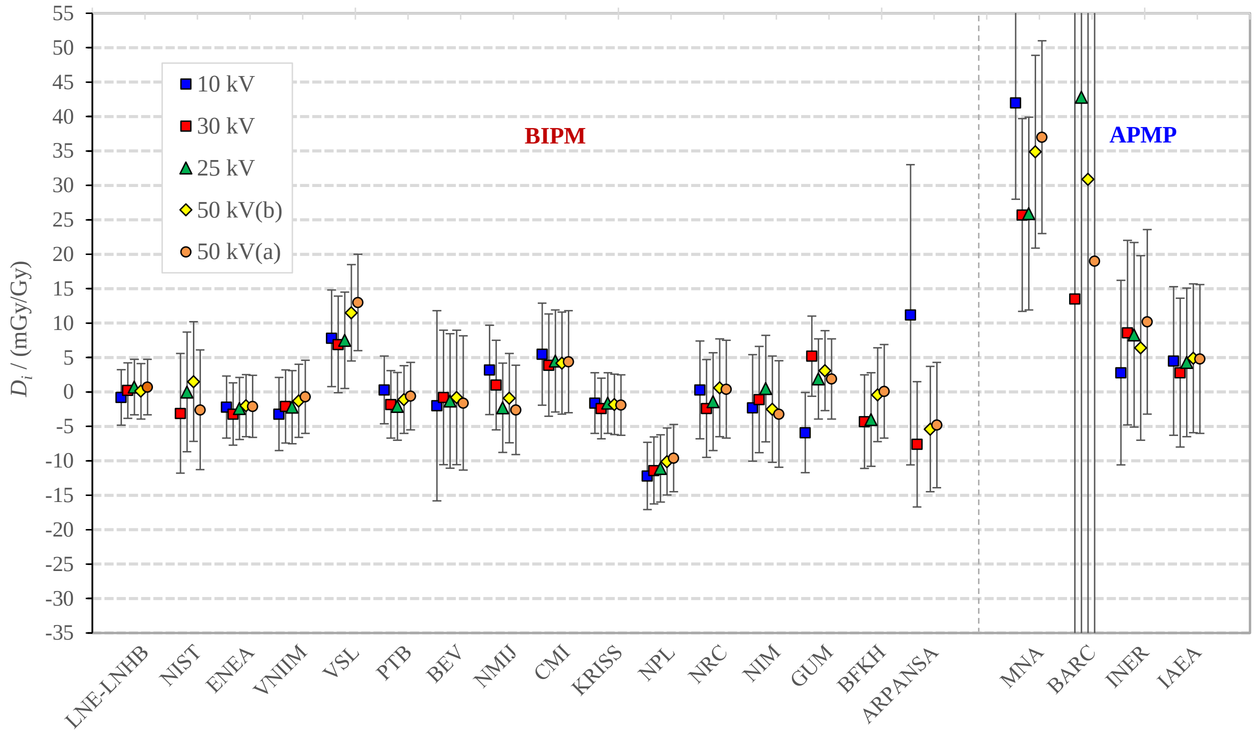

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K2 and those to the right are for the regional comparison APMP.RI(I)-K2 conducted between 2008 and 2010. The large uncertainty bars for the BARC are not shown (±100 mGy/Gy, see Table 13).

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