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

D T Burns[1], C Kessler[1] and S Pojtinger[2]

[1] Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres CEDEX
[2] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Abstract A key comparison has been made between the air-kerma standards of the PTB, Germany, 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 8.0 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 Physikalisch-Technische Bundesanstalt (PTB), Germany, 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 February 2024 using the reference conditions recommended by the CCRI as described in Kessler and Burns (2024). Final data from the PTB were received in May 2024.

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

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

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 $\Pi\, k_i$ 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 PTB standard is described in Büermann (2021), including changes made following ICRU Report 90 (ICRU 2016), and in the reports of the previous comparisons with the BIPM

[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 $k_h = 0.9980$.

(Burns *et al.* 2001, Burns *et al.* 2014). 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]	1.2045 kg m^{-3}	0.0001
ρ_{air} [c]	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 PTB.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	PTB PK100
Aperture diameter / mm	9.941	10.008
Air path length / mm	100.0	97.2
Collecting length / mm	15.466	20.021
Electrode separation / mm	70	234
Collector width / mm	71	240
Measuring volume / mm^3	1200.4	1574.8
Polarizing voltage / V	1500	6000

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 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 the PTB laboratory remained in the range from 30 % to 60 %.

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 metrology 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 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 $N_{K,NMI}$ 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

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

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 instruments

Two thin-window parallel-plate ionization chambers belonging to the PTB, type Radcal RC6M, serial numbers 10291 and 10292, were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. For positioning at the reference distance, the red line around the chamber casing (8.5 mm from the front of the casing) was positioned in the reference plane.

Table 3. Main characteristics of the transfer chambers

Chamber type	Radcal RC6M
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

[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 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 using 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. 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 0.1 °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.

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
Additional Al filtration / mm	0	0.208	0.372	1.008	3.989
Al HVL / mm	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{air}$ [a] / $cm^2\ g^{-1}$	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

[a] Measured for an equivalent air-path length of 100 mm using a variable-pressure tube.

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 were made using positive polarity only. A correction factor of 1.0005 is applied to correct for the known polarity effect in the standard (see Table 5). 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 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 corresponding correction factor k_a is evaluated using the measured mass attenuation coefficients for air $(\mu/\rho)_{air}$ 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.

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 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 for each chamber was less 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 of the transfer chambers at each radiation quality, the relative standard uncertainty of the mean ionization current was below 2 parts in 10^4. Based on the results of repeat calibrations including chamber repositioning and on long-term experience of calibrations in these beams, 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.

Table 5. Correction factors and uncertainties for the BIPM standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
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
$1 - g_{air}$	1.0000	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] The stated values are for the product $k_{ii}k_W$, as presented in Burns and Kessler (2018).

6. Calibration at the PTB

6.1 PTB irradiation facility and reference radiation qualities

The low-energy x-ray facility at the PTB uses a constant potential generator and a unipolar x-ray tube of type Y.TU 160-D02 (Comet Yxlon, Germany) with tungsten-anode and an inherent filtration of 0.8 mm beryllium. The x-ray output is monitored by means of a transmission monitor ionization chamber. The standard deviation of repeat calibrations of the transmission monitor over the period of a transfer chamber calibration is less than 5 parts in 10^3. The generating potential is measured invasively with a voltage divider manufactured and calibrated at the PTB. The characteristics of the PTB realization of the CCRI comparison qualities are given in Table 6.

The irradiation area is temperature controlled around 20 °C and is stable over the duration of a calibration to better than 0.5 °C. Two calibrated thermometers are used to measure air temperature, one positioned near the primary standard and near the transfer chamber during calibration, and the second near the transmission monitor. The air pressure is measured by means of a calibrated barometer.

6.2 PTB standard and correction factors

The reference plane for the PTB standard was positioned at 500 mm from the source, with an uncertainty of around 0.1 mm and a reproducibility of 0.05 mm. The standard was aligned laterally on the beam axis with a reproducibility of 0.05 mm. The beam diameter in the reference plane is

83 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the PTB standard were made using positive polarity only. No correction is applied but rather a standard uncertainty for the polarity effect as given in Table 7. The leakage current for the PTB standard was below 3.5 fA, corresponding to less than 1 part in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the PTB 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.

Table 6. Characteristics of the PTB 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	0.208	0.373	1.00	4.00
Al HVL / mm	0.032	0.139	0.230	1.178	2.353
$(\mu/\rho)_{air}$ [a] / $cm^2\ g^{-1}$	17.63	3.91	2.70	0.77	0.40
$\dot{K}_{PTB}$ / $mGy\ s^{-1}$	1.71	2.83	1.51	1.64	1.05

[a] Measured for an air path length of 98 mm.

6.3 Transfer chamber positioning and calibration at the PTB

The reference point for each chamber was positioned in the reference plane with an uncertainty of around 0.1 mm and a reproducibility of 0.05 mm. Each transfer chamber was aligned laterally on the beam axis to an estimated uncertainty of 0.1 mm. The leakage current was measured for each measurement series and a correction applied. The leakage current was typically below 1 fA, corresponding to less than 2 parts in 10^5.

For each transfer chamber at each radiation quality, a calibration was made before the measurements at the BIPM and following the return of the chambers to the PTB. The uncertainty arising from these repeat measurements is discussed in Section 8.

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 PTB and BIPM air-kerma rates differ; for the PTB air-kerma rate for the 30 kV quality is almost three times that of the BIPM. The effect of such increase has been measured at the BIPM for the Radcal RC6M chamber type to be not more than 2 parts in 10^4 and a corresponding uncertainty for ion recombination is included in Table 12. Each 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 diameter 30 mm, the correction for the BIPM reference fields at 500 mm is about 2 parts in 10^3. It is reasonable to assume some cancellation at the two laboratories. A corresponding uncertainty of 5 parts in 10^4 is included in Table 12.

As the reference distance is the same at both laboratories (500 mm) and the field diameters are similar (84 mm at the BIPM and 83 mm at the PTB) no corresponding correction factors are applied.

Table 7. Correction factors and uncertainties for the PTB standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.2294	1.0468	1.0321	1.0090	1.0047	0.0020	0.0005
Scattered radiation k_{sc} [b]	0.9852	0.9889	0.9900	0.9929	0.9939	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Initial ionization k_{ii} [c] / Energy dependence of W_{air} k_W [c]	0.9953	0.9964	0.9967	0.9977	0.9980	-	0.0011
Ion recombination k_s	1.0027	1.0049	1.0029	1.0032	1.0022	-	0.0011
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	0.0005	0.0005
Field distortion k_d	0.9910	0.9910	0.9910	0.9910	0.9910	-	0.0010
Guard strip attenuation k_{ap}	1.0341	1.0084	1.0059	1.0014	1.0007	0.0020	0.0005
Aperture transmission k_l	0.9999	0.9993	0.9990	0.9974	0.9964	0.0005	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	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] This includes the effect of fluorescence, treated separately for the BIPM standard as k_{fl}.
[c] The stated values are for the product $k_{ii}k_W$.

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 PTB and the BIPM might require a correction factor k_Q. The values for k_Q given in Table 8 are evaluated and applied to the comparison results for each chamber according to Equation (3). The same set of values is used for each chamber. The uncertainty of these corrections estimated to be 3 parts in 10^4 is included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{PTB}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8. For each chamber at each radiation quality, the values $N_{K,\mathrm{PTB}}$ provided 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_{stab} representing the chamber stability[2].

[2] Because of the very small sample size, the modified standard uncertainty including the appropriate *t*-factor is used, which for n = 2 gives $s_{\mathrm{stab}} = 1.8\, s_{\mathrm{dev.s}}/\sqrt{2}$. Likewise for s_{tr}. See Burns (2024).

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Radcal RC6M-10291					
$N_{K,\mathrm{PTB}}$ (pre-BIPM) / Gy μC^{-1}	4.840	4.765	4.761	4.779	4.804
$N_{K,\mathrm{PTB}}$ (post-BIPM) / Gy μC^{-1}	4.828	4.762	4.756	4.779	4.805
$s_{\mathrm{stab},1}$	0.0023	0.0006	0.0010	0.0000	0.0002
k_Q for $N_{K,\mathrm{PTB}}$	0.9979	0.9993	0.9999	0.9991	0.9997
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	4.822	4.772	4.761	4.779	4.828
Radcal RC6M-10292					
$N_{K,\mathrm{PTB}}$ (pre-BIPM) / Gy μC^{-1}	4.867	4.791	4.788	4.804	4.830
$N_{K,\mathrm{PTB}}$ (post-BIPM) / Gy μC^{-1}	4.855	4.787	4.782	4.803	4.829
$s_{\mathrm{stab},2}$	0.0023	0.0008	0.0012	0.0002	0.0002
k_Q for $N_{K,\mathrm{PTB}}$	0.9979	0.9993	0.9999	0.9991	0.9997
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	4.851	4.801	4.792	4.807	4.855

The comparison results R_K are presented in Table 9, evaluated according to Equation (3). For each radiation quality the final comparison result is evaluated as the mean for the two transfer chambers. The uncertainty s_{tr} is the standard uncertainty of this mean, or taken as

$$s_{\mathrm{tr}} = \frac{\sqrt{s_{\mathrm{stab},1}^2 + s_{\mathrm{stab},2}^2}}{2} \tag{4}$$

if this is larger (on the basis that the agreement between the comparison results for different transfer chambers should not, on average, be better than their combined stability estimated using $s_{\mathrm{stab},1}$ and $s_{\mathrm{stab},2}$ from Table 8). The rms value of s_{tr} for the five qualities, $s_{\mathrm{tr,comp}} = 0.0009$, is taken to represent the uncertainty arising from the transfer chambers and is included in Table 12.

Table 9. Combined comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
R_K using Radcal RC6M-10291	1.0004	0.9975	0.9994	0.9991	0.9948
R_K using Radcal RC6M-10292	1.0000	0.9968	0.9984	0.9984	0.9944
s_{tr}	0.0016	0.0006	0.0009	0.0006	0.0004
Final R_K	**1.0002**	**0.9972**	**0.9989**	**0.9988**	**0.9946**
Updated results of 2014	1.0038	0.9972	0.9970	0.9966	0.9967

Also given in the final row of Table 9 are the results for the PTB from the previous comparison in 2014, revised for the changes made to the standards in the interim period (k_{ap}, k_l and $k_{ii}k_W$).

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 factor $k_{ii}k_W$. Correlation in the values for k_e, k_l, k_{sc} and k_{fl}, 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 in terms of degrees of equivalence described in Burns (2003).

Table 10. Uncertainties associated with the standards

Standard	BIPM L-01		PTB PK100	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0003	-
Positioning	0.0001	0.0001	-	0.0001
Volume	0.0003	0.0005	-	0.0006
Correction factors (excl. k_h)	0.0003	0.0015	0.0030	0.0022
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}$	0.0005	0.0039	0.0030	0.0042

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

Institute	BIPM		PTB	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}$	0.0005	0.0039	0.0030	0.0042
I_{tr}	0.0002	0.0002	0.0003	-
Monitor ionization current I_{mon}	-	-	0.0003	-
Air density correction k_{rho}	-	-	-	0.0007
Positioning of transfer chamber	0.0001	-	-	0.0001
Reproducibility	0.0005	-	- [a]	-
N_K	0.0007	0.0039	0.0030	0.0043

[a] The reproducibility of the PTB transfer chambers calibrations over the duration of comparison is implicitly included in s_{tr} in Table 9 and consequently in $s_{tr,comp}$ in Table 12.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$	0.0031	0.0022 [a]
Ion recombination	-	0.0002
Radial non-uniformity	-	0.0005
k_Q	-	0.0003
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0009	-
R_K	0.0032	0.0023 [a]
	u_c = 0.0040 [a]	

[a] Takes account of correlation in type B uncertainties.

10. Discussion

The comparison results R_K show the PTB and BIPM standards to agree at the level of the expanded uncertainty of the comparison of 8.0 parts in 10^3.

The results agree with the results of the direct comparison carried out in 2014 at the level of the standard uncertainty of the comparisons. The differences for all radiation qualities except for 10 kV are typically below 2 parts in 10^3, while the new 10 kV result is lower than that of 2014 by 3.6 parts in 10^3.

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 PTB and the BIPM to agree at the level of the standard uncertainty of the comparison of 4 parts in 10^3.

Tables and a graph of degrees of equivalence, including those for the PTB, 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. In accordance with the validity rules for comparison data agreed by the CCRI(I), results older than 15 years are considered no longer valid and have been removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database (KCDB 2024).

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
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	9.2			-5.4	9.2	-4.8	9.2
PTB	2024	0.2	8.0	-2.8	8.0	-1.1	8.0	-1.2	8.0	-5.4	8.0
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

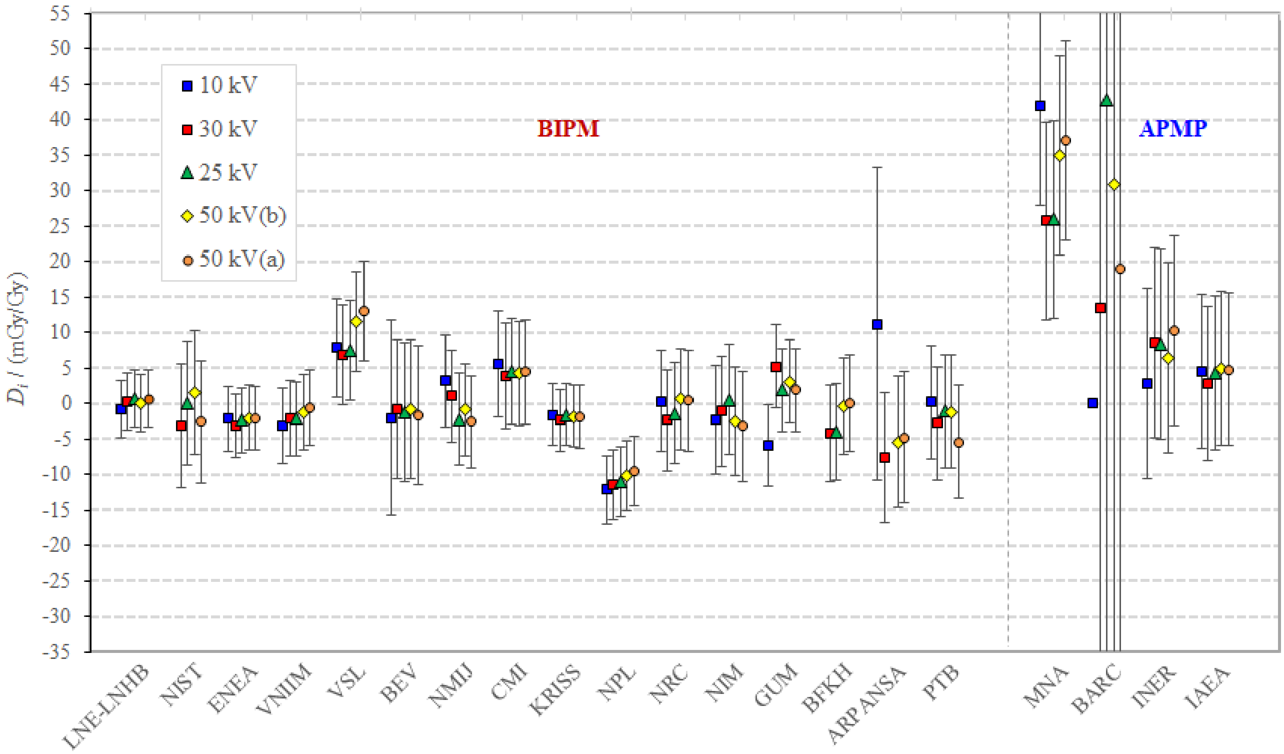

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K2 and those to the right for the regional comparison APMP.RI(I)-K2 conducted between 2008 and 2010. The large uncertainty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

References

Boutillon M, Henry W H, Lamperti P J 1969 Comparison of exposure standards in the 10-50 kV x-ray region *Metrologia* **5** 1–11

Büermann L 2021 The PTB free-air ionization chambers PTB Open Access Repository

Burns D T 2003 Degrees of equivalence for the key comparison BIPM.RI(I)-K2 between national primary standards for low-energy x-rays *Metrologia* **40** 06031

Burns D T 2004 Changes to the BIPM primary air-kerma standards for x-rays *Metrologia* **41** L3

Burns D T 2024 Unbiased estimation of uncertainty for small sample sizes (to be published)

Burns D T, Büermann L, Kramer H-M, Lange B 2001 Comparison of the air-kerma standards of the PTB and the BIPM in the low-energy x-ray range *Rapport* BIPM-01/08

Burns D T, Kessler C 2009 Diaphragm correction factors for free-air chamber standards for air kerma in x-rays *Phys Med Biol* **54** 2737–45

Burns D T, Kessler C 2018 Re-evaluation of the BIPM international dosimetry standards on adoption of the recommendations of ICRU Report 90 *Metrologia* **55** R21

Burns D T, Kessler C, Allisy P J 2009 Re-evaluation of the BIPM international standards for air kerma in x-rays *Metrologia* **46** L21–23

Burns D T, Kessler C, Büermann L 2014 Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the PTB, Germany and the BIPM in low-energy x-rays *Metrologia* **51** 06011

ICRU 2016 Key data for ionizing-radiation dosimetry: Measurement standards and applications *J. ICRU* **14** Report 90 (International Commission on Radiation Units and Measurements: Oxford University Press)

KCDB 2024 Up-to-date results for comparison BIPM.RI(I)-K2 are available in the BIPM key comparison database at BIPM.RI(I)-K2

Kessler C, Burns D T 2024 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport* BIPM-2024/04