Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the GUM, Poland, 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 GUM, Poland, and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement at the level of the expanded uncertainty of the comparison of 5.8 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 Główny Urząd Miar, Poland, 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 November 2021 using the reference conditions recommended by the CCRI as described in Kessler and Burns (2018). Final information on the GUM uncertainties was received in March 2022.

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 GUM standard is described in the reports of previous comparisons with the BIPM (Boutillon

[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 $k_h = 0.9980$.

et al. 1996, Burns *et al.* 2012) and the changes made following ICRU Report 90 are reported in Knyziak (2019). 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
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.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	GUM
Aperture diameter / mm	9.941	9.995
Air path length / mm	100.0	102.2
Collecting length / mm	15.466	20.273
Electrode separation / mm	70	69.9
Collector width / mm	71	70.4
Measuring volume / mm^3	1200.4	1590.8
Polarizing voltage / V	1500	4000

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 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 GUM laboratory 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 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 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 by interpolation of the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

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

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 GUM, type Exradin A600 (Magna) and Radcal RC6M, were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. For positioning at the reference distance, the line inscribed around the Exradin A600 casing (4 mm from the front of the casing) and the red line around the Radcal casing (8.5 mm from the front of the casing) were each positioned in the reference plane.

Table 3. Main characteristics of the transfer chambers

Chamber type	Exradin A600 [a]	Radcal RC6M [b]
Serial number	M200571	10267
Window material	conductive Kapton film	metallized polyester
Window thickness / mg cm^{-2}	3.9	0.7
Nominal volume / cm^3	1.5	6
Collector diameter / mm	15	30
Cavity height / mm	8	8
Polarizing potential [c] / V	+300	+300

[a] There is some ambiguity over the dimensions of the Exradin A600. Its volume is given variously as 1 cm^3 or 1.5 cm^3; ionometric measurements indicate a value close to 1.5 cm^3. Assuming this value and the stated cavity height of 8 mm implies an 'effective' collector diameter of 15 mm (Exradin state 12.7 mm with a guard ring of 3.9 mm).

[b] The Radcal RC6M 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, which would position the collector close to the red line around the chamber casing.

[c] 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 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 the past few years is below 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	0.2082	0.3723	1.0082	3.989
Al HVL / mm	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{\mathrm{air}}$[a] / $\mathrm{cm^2\ g^{-1}}$	14.83	3.66	2.60	0.75	0.38
$\dot{K}_{\mathrm{BIPM}}$ / $\mathrm{mGy\ s^{-1}}$	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.

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 polarity effect in the standard measured previously (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 $(\mu/\rho)_{\mathrm{air}}$ 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. Ionization current 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 source and the reference plane.

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 $k_{\mathrm{ii}}k_W$ 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 for the BIPM 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]	1.1956	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).

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 leakage current for both chambers was less than 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 typically 1 part in 10^4. Repeat calibrations at all qualities (up to four times at 30 kV), including chamber repositioning, showed the Exradin to be reproducible at this level of 1 part in 10^4. However, repeat Radcal measurements showed a larger deviation, the mean value being determined to around 1 part in 10^3. As this instability was not evident in the results for the Exradin, the usual 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 (see the discussion on transfer chamber stability at the GUM in Section 6.3).

6. Calibration at the GUM

6.1 GUM irradiation facility and reference radiation qualities

The GUM low-energy x-ray facility is a PANTAK HF 160/50 industrial unit with a high-stability generator and a tungsten-anode x-ray tube model Varian OEG-50 NDT-2 with an inherent filtration of 1 mm beryllium. The generating potential is measured by means of a non-destructive spectrometric method (according to ISO 16526-3:2011). The short-term stability of the generating potential is 1 part in 10^4. The standard deviation of repeat air-kerma rate determinations over a period of many months is typically 2 parts in 10^3. No monitor chamber is used. The characteristics of the GUM realization of the CCRI comparison qualities are given in Table 6.

Table 6. Characteristics of the GUM 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	0.019	0.240	0.404	1.042	3.934
Al HVL / mm	0.038	0.168	0.247	1.018	2.262
$(\mu/\rho)_{air}$[a] / cm^2 g^{-1}	15.35	3.70	2.53	0.68	0.37
$\dot{K}_{GUM}$ / mGy s^{-1}	1.3	4.4	1.4	1.9	0.42

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

The irradiation area is temperature controlled around 23 °C and is stable over the duration of a calibration to better than 0.1 °C. Two calibrated PT-401 thermistors measure the temperature of the ambient air and the air inside the GUM standard. The air pressure is measured by means of a calibrated Vaisala PTB-220 barometer.

6.2 GUM standard and correction factors

The reference plane for the GUM standard was positioned at 500 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 0.1 mm. The beam diameter in the reference plane is 85 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the GUM standard were made using positive polarity only. A correction factor was applied to correct for the polarity effect in the standard measured previously for each quality (see Table 7). The leakage current for the GUM standard was measured to be not more than 7 parts in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the GUM 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 current measurements (standard and transfer chambers) are also corrected for variations in the temperature and pressure of the ambient air between the source and the reference plane.

6.3 Transfer chamber positioning and calibration at the GUM

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.1 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 leakage current for the Exradin was not more than 7 parts in 10^4 and for the Radcal was not more than 3 parts in 10^4.

For each transfer chamber at each radiation quality, a single calibration consists of a set of 10 measurements, each measurement with integration time 60 s. To determine the reproducibility of the calibration coefficients, 6 such calibrations were made over several months before sending the chambers to BIPM and 3 calibrations were made over one month following the return of the chambers. The standard uncertainty of the mean ionization current for each set was around 4 parts in 10^4. However, repeat calibrations for both transfer chambers showed a significantly higher standard deviation of around 2 parts in 10^3. This is included as the GUM uncertainty for short-term reproducibility in Table 11.

Table 7. Correction factors for the GUM 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]	1.2079	1.0466	1.0316	1.0084	1.0046	0.0005	0.0002
Scattered radiation k_{sc} [b]	0.9910	0.9933	0.9939	0.9950	0.9959	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Initial ionization k_{ii} [c] / Energy dependence of W_{air} k_W [c]	0.9953	0.9968	0.9969	0.9977	0.9980	-	0.0012
Ion recombination k_s	1.0006	1.0005	1.0005	1.0004	1.0004	0.0002	0.0002
Polarity k_{pol}	0.9994	0.9988	0.9984	0.9986	0.9993	0.0002	0.0002
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Diaphragm transmission k_l	1.0000	0.9997	0.9997	0.9994	0.9990	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h [d]	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 stated values are for the product $k_{ii}k_W$.
[d] Each measurement is corrected using the relative partial vapour pressure calculated at the time of measurement, according to ICRU Report 31 (ICRU 1979).

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 GUM are higher than at the BIPM by a factor of up to 4 (except for 50 kVa where the GUM value is around half). From previous measurements at the BIPM with the Radcal chamber type, the effect of a four-fold increase in current is around 8 parts in 10^4. No correction is applied, rather a corresponding uncertainty of 5 parts in 10^4 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 a chamber with collector radius 15 mm (Radcal) and 7.5 mm (Exradin), the correction for the BIPM reference fields at 500 mm is 1.0022 and 1.0003, respectively. It is reasonable to assume some cancellation at the two laboratories. A relative standard uncertainty of 5 parts in 10^4 is introduced in Table 12.

As the reference distance is the same at both laboratories (500 mm) and the field diameters are almost the same (84 mm at the BIPM and 85 mm at the GUM) no correction factors are applied.

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 GUM 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 2 parts in 10^4 of unity and so no corrections are applied, except for the Exradin chamber at 10 kV where the factor 1.0006 is applied. An uncertainty component of 2 parts in 10^4 is included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\text{GUM}}$ and $N_{K,\text{BIPM}}$ for the transfer chambers are presented in Table 8. The values $N_{K,\text{GUM}}$ measured before and after the measurements at the BIPM give rise to relative standard uncertainties $s_{\text{tr},1}$ and $s_{\text{tr},2}$ for the two chambers, which represent the uncertainty in $N_{K,\text{GUM}}$ arising from transfer chamber stability.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Exradin A600-M200571					
$N_{K,\text{GUM}}$ (pre-BIPM)	20.12	19.66	19.51	19.19	19.18
$N_{K,\text{GUM}}$ (post-BIPM)	20.08	19.66	19.48	19.17	19.11
$s_{\text{tr},1}$ (relative)	0.0010	0.0000	0.0008	0.0005	0.0018
$N_{K,\text{BIPM}}$	20.194	19.546	19.442	19.106	19.101
Radcal RC6M-10267					
$N_{K,\text{GUM}}$ (pre-BIPM)	4.691	4.708	4.683	4.739	4.807
$N_{K,\text{GUM}}$ (post-BIPM)	4.703	4.718	4.691	4.745	4.822
$s_{\text{tr},2}$ (relative)	0.0013	0.0011	0.0009	0.0006	0.0016
$N_{K,\text{BIPM}}$	4.731	4.692	4.682	4.731	4.808

[a] As noted in Section 7.2, the $N_{K,\text{GUM}}$ values for the Exradin chamber at 10 kV as given here have been multiplied by the factor $k_{Q,\text{GUM}} = 1.0006$.

For each chamber at each radiation quality, the mean of the GUM results before and after the BIPM measurements is used to evaluate the results $N_{K,\mathrm{GUM}}$ / $N_{K,\mathrm{BIPM}}$ given in Table 9. The final comparison results $R_{K,\mathrm{GUM}}$ in Table 9 are evaluated as the mean for the two transfer chambers. For each quality, the corresponding uncertainty s_{tr} is the standard uncertainty of this mean, or taken as

$$s_{\mathrm{tr}} = \frac{\sqrt{s_{\mathrm{tr},1}^2 + s_{\mathrm{tr},2}^2}}{2} \qquad (4)$$

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 $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ from Table 8). The root mean square value of s_{tr} for the four qualities, $s_{\mathrm{tr,comp}} = 0.0009$, is a global representation of the comparison uncertainty arising from the stability of the transfer chambers and is included in Table 12.

Also given in the last two rows of Table 9 are the results for the GUM in the previous comparisons in 2010 and in 1995, revised for the changes made to the standards in the interim period.

Table 9. Combined comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$R_{K,\mathrm{GUM}}$ using Exradin	0.9953	1.0058	1.0027	1.0039	1.0023
$R_{K,\mathrm{GUM}}$ using Radcal	0.9928	1.0045	1.0011	1.0023	1.0014
s_{tr}	0.0012	0.0008	0.0008	0.0008	0.0008
Final $R_{K,\mathrm{GUM}}$	**0.9941**	**1.0052**	**1.0019**	**1.0031**	**1.0019**
Updated results of 2010	0.9966	0.9963	0.9997	0.9964	1.0006
Updated results of 1995	0.9979	0.9985	-	0.9974	0.9995

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 $R_{K,\mathrm{GUM}}$ 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 $k_{\mathrm{ii}}k_W$. Correlation in the values for k_{e}, 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).

10. Discussion

The comparison results $R_{\mathrm{K,GUM}}$ show the GUM and BIPM standards to agree at the level of the expanded uncertainty of the comparison of 5.8 parts in 10^3. Although the results for the different qualities vary by over 1 part in 10^2, no clear trend with energy is evident. The results for the three highest qualities are now self-consistent at the level of 1 part in 10^3, which was not the case for the two previous comparisons. However, the difference of more than 1 part in 10^2 between the present results for 10 kV and 30 kV was not observed previously. This appears to be the combined effect of a low result at 10 kV, perhaps related to the attenuation correction which is very large for this quality, and a high result at 30 kV which might be related, at least in part, to the high air-kerma rate at the GUM for this quality (as noted in Section 7.1, no corrections were applied for ion recombination in the transfer chambers).

Table 10. Uncertainties associated with the standards

Standard	BIPM L-01		GUM	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Ionization current	0.0002	0.0002	0.0004	0.0002
Positioning	0.0001	0.0001	0.0001	0.0001
Volume	0.0003	0.0005	0.0001	0.0005
Correction factors (excl. k_h)	0.0003	0.0010	0.0006	0.0015
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}$	0.0005	0.0039	0.0007	0.0039

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

Institute	BIPM		GUM	
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	0.0007	0.0039
I_tr	0.0002	0.0002	0.0004	0.0002
Positioning of transfer chamber	0.0001	-	0.0001	0.0001
Short-term reproducibility	0.0005	-	0.0020	-
N_K	0.0007	0.0039	0.0022	0.0039

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.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$
$N_{K,\text{GUM}}$ / $N_{K,\text{BIPM}}$	0.0023	0.0014 [a]
Ion recombination	-	0.0005
Radial non-uniformity	-	0.0005
$k_{Q,\text{GUM}}$	-	0.0002
Transfer chambers $s_{\text{tr,comp}}$	0.0009	-
$R_{K,\text{GUM}}$	0.0025	0.0016
	u_c = 0.0029	

a Takes account of correlation in type B uncertainties.

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 BIPM.RI(I)-K2 and blue in APMP.RI(I)-K2.

Lab *i*	10 kV		30 kV		25 kV		50 kVb		50 kVa	
	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	4.2	1.0	4.2	1.3	4.2	0.2	4.2	0.1	4.2
ARPANSA	-1.5	14.2	-2.5	7.9	-2.6	7.9	-1.0	7.9	0.2	7.9
LNE-LNHB	-0.8	4.0	0.2	4.0	0.7	4.0	0.1	4.0	0.7	4.0
NIST			-3.1	8.7	0.0	8.7	1.5	8.7	-2.6	8.7
ENEA	-2.2	4.5	-3.2	4.5	-2.4	4.5	-2.0	4.5	-2.1	4.5
MKEH	-2.7	4.7	-2.5	4.7	-1.2	4.7	-2.6	4.7	-3.4	4.7
VNIIM	-3.2	5.3	-2.1	5.3	-2.2	5.3	-1.3	5.3	-0.7	5.3
VSL	7.8	7.0	6.9	7.0	7.5	7.0	11.5	7.0	13.0	7.0
PTB	0.3	4.9	-1.8	4.9	-2.1	4.9	-1.1	4.9	-0.6	4.9
BEV	-2.0	13.8	-0.8	9.8	-1.3	9.8	-0.8	9.8	-1.6	9.8
NMIJ	3.2	6.5	1.0	6.5	-2.3	6.5	-0.9	6.5	-2.6	6.5
CMI	5.5	7.4	3.9	7.4	4.5	7.4	4.2	7.4	4.4	7.4
KRISS	-1.6	4.4	-2.4	4.4	-1.6	4.4	-1.8	4.4	-1.9	4.4
NPL	-12.2	4.9	-11.4	4.9	-11.1	4.9	-10.1	4.9	-9.6	4.9
NRC	0.3	7.1	-2.4	7.1	-1.4	7.1	0.6	7.1	0.4	7.1
NIM	-2.3	7.7	-1.1	7.7	0.5	7.7	-2.5	7.7	-3.2	7.7
GUM	-5.9	5.8	5.2	5.8	1.9	5.8	3.1	5.8	1.9	5.8
MNA	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

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 GUM and the BIPM to be in agreement at the level of the expanded uncertainty of the comparison of 5.8 parts in 10^3.

Tables and a graph of degrees of equivalence, including those for the GUM, 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. The formal results under the CIPM MRA are those available in the key comparison database (KCDB 2022).

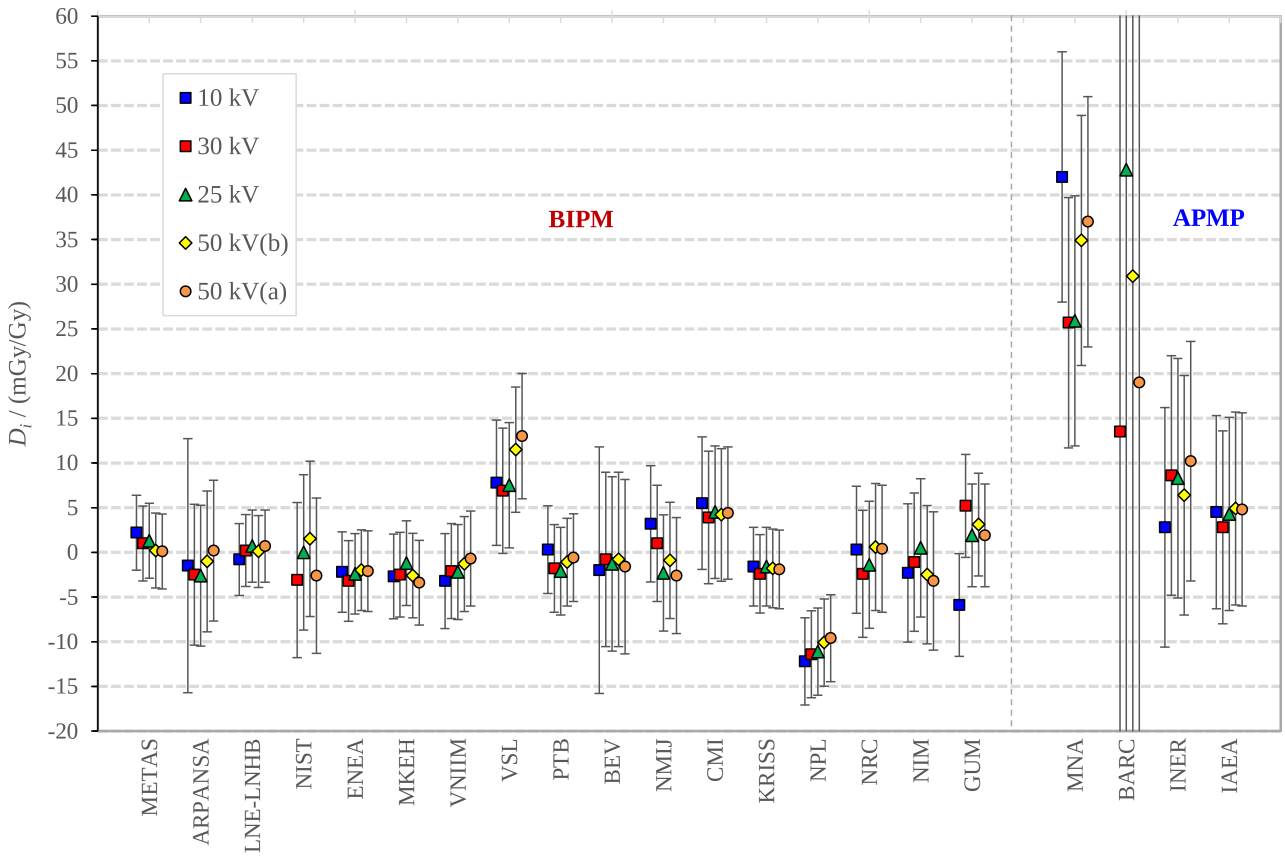

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K2 and those to the right are for the regional comparison APMP.RI(I)-K2 conducted between 2008 and 2010. The large uncertainty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

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