Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the KRISS, Republic of Korea, 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 KRISS, Republic of Korea, and the BIPM in the low-energy x-ray range. The results show the standards to be agreement at the level of the standard uncertainty of the comparison of 2.2 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

A direct comparison has been made between the air-kerma standards of the Korea Research Institute of Standards and Science (KRISS), Republic of Korea, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. The comparison took place at the BIPM in February 2017 using the reference conditions recommended by the CCRI and described by Kessler and Burns (2018). Final results for the KRISS field-distortion correction were supplied in March 2022 following a determination of the electric-field distortion based on finite-element calculations and capacitance measurements. During this period, the recommendations of ICRU Report 90 (ICRU 2016) were implemented at both laboratories.

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 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]. The value used for W_{air}/e is that recommended in ICRU Report 90 (ICRU 2016), 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 L-01 is described in Boutillon *et al.* (1969) and the changes made to certain correction factors given in Burns (2004), Burns and Kessler (2009) and Burns *et al*. (2009). The changes made to the standard following the recommendations of ICRU Report 90 are given in Burns and

[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 the dry-air humidity correction $k_{\mathrm{h}} = 0.9980$.

Kessler (2018). Details of the KRISS standard L1, which has not previously been compared with the BIPM standard, are given in Yi *et al.* (2022). 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}[b] (KRISS)	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.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	KRISS L1
Aperture diameter / mm	9.941	10.0021
Air path length / mm	100.0	77.0
Collecting length / mm	15.466	15.800
Electrode separation / mm	70	69.5
Collector width / mm	71	70.0
Measuring volume / mm^3	1200.4	1241.5
Polarizing voltage / V	1500	2000

4. Comparison procedure

4.1 The BIPM irradiation facility and reference beam qualities

The comparison was carried out in the BIPM low-energy x-ray laboratory, which 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 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 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 3 in ascending HVL from left to right.

Table 3. 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
$(\mu/\rho)_{air}$[a] / cm^2 g^{-1}	14.83	3.662	2.604	0.754	0.379
$\dot{K}_{BIPM}$ / 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.

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; the KRISS standard does not contain an internal temperature sensor. Air pressure is measured by means of a calibrated barometer. The relative humidity is controlled within the range from 40 % to 55 %.

4.2 Correction factors

The correction factors applied to the ionization current measured at each radiation quality, together with their associated uncertainties, are given in Table 4 for the BIPM standard and in Table 5 for the KRISS standard.

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 corresponding correction factor k_a is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 3. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard. Ionization current measurements 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. At 10 kV, an additional correction factor of 1.0008 has been applied to the KRISS air-kerma rate determination because the mean mass attenuation coefficient for air over the 77 mm attenuation length of the KRISS standard is larger than the value given in Table 3, which was evaluated for an attenuation length of 100 mm corresponding to the BIPM standard.

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.

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 (see Table 4). Similarly, measurements using the KRISS standard were made using negative polarity and a correction factor of 1.0009 was applied (see Table 5). The relatively large field-distortion correction for the KRISS standard is discussed in Section 7.

All measured ionization currents are corrected for ion recombination. The measured values for the ion recombination correction k_s for the BIPM standard are given in Table 4. For the KRISS standard, the values for k_s given in Table 5 for the BIPM air-kerma rates are derived from measurements of the initial and volume recombination coefficients made at the KRISS. It is noted that the values for the KRISS standard are higher by 6 parts in 10^4, despite the fact that the standards have a similar dimensions and the KRISS polarizing voltage is higher (see Table 2).

Table 4. Correction factors for the BIPM standard L-01

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
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
Initial ionization k_{ii} Energy dependence of W_{air} k_W	0.9953	0.9968	0.9968	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.

4.3 Chamber positioning and measurement procedure

The KRISS chamber was positioned close to the BIPM chamber and both remained fixed throughout the comparison; the alternation of measurements between chambers was carried out by displacement of the radiation source. Lateral alignment on the beam axis was measured to around 0.1 mm and this position was reproducible to better than 0.01 mm. No correction is applied for the radial non-uniformity of the beam as the aperture diameters are very similar. The reference plane for each chamber was positioned at 500 mm from the exit window for all qualities. This distance was measured to 0.03 mm and was reproducible to 0.01 mm. The beam diameter in the reference plane is 45 mm for all qualities.

The KRISS chamber does not incorporate a sensor to measure the internal air temperature T_{KRISS}. Initially, a thermometer belonging to the BIPM was positioned in thermal contact with the side of the chamber, but this device was found to be unreliable. A series of temperature measurements inside the KRISS chamber were compared with the temperatures T_{BIPM} and T_{cap} measured inside the BIPM standard and in the nearby capacitor bank, respectively. These two temperatures were found to provide reasonable upper and lower limits, respectively, for T_{KRISS}. The result of this investigation was to adopt the value $T_{\mathrm{KRISS}} = T_{\mathrm{cap}} + 0.1$ °C. A corresponding standard uncertainty of 4 parts in 10^4 for the KRISS air-kerma rate determination is included in Table 6.

The ionization current for both standards was measured using the BIPM current measurement system. The leakage current was measured before and after each series of ionization current measurements and a correction made based on the mean of these leakage measurements. For both standards the relative leakage current was well below 1 part in 10^4.

For the KRISS chamber, the standard uncertainty of the mean of a series of seven measurements, each with integration time 60 s, was around 1 part in 10^4. Two series were made for each radiation quality. For the BIPM standard, a similar series was made for each quality with a standard uncertainty also around 1 part in 10^4. A repeat comparison was made at 30 kV before removing and replacing the KRISS standard for a further series of measurements at each quality. The reproducibility of the repeat measurements was typically 2 parts in 10^4.

Table 5. Correction factors for the KRISS standard L1 used at the BIPM

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]	1.1473	1.0345	1.0245	1.0070	1.0035	0.0002 [b]	0.0001 [b]
Scattered radiation k_{sc}	0.9973	0.9980	0.9981	0.9984	0.9985	-	0.0003
Fluorescence k_{fl}	0.9960	0.9973	0.9975	0.9984	0.9988	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Initial ionization k_{ii} Energy dependence of W_{air} k_W	0.9950	0.9966	0.9969	0.9978	0.9981	-	0.0012
Ion recombination k_s	1.0013	1.0013	1.0013	1.0013	1.0013	0.0002	0.0001
Polarity k_{pol}	1.0009	1.0009	1.0009	1.0009	1.0009	0.0003	-
Field distortion k_d [c]	0.9894	0.9894	0.9894	0.9894	0.9894	-	0.0015
Aperture edge k_l	1.0000	0.9999	0.9999	0.9998	0.9997	-	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, determined using the BIPM values for the air-attenuation coefficient; each measurement is corrected using the air density measured at the time.
[b] For measurements at the KRISS, the uncertainties are $u_{i\mathrm{A}} = 0.0002$ and $u_{i\mathrm{B}} = 0.0002$.
[c] The field-distortion correction is discussed in Section 7.

5. Additional measurements

As an additional test of the measurement volumes, a third aperture belonging to the BIPM was used in both standards, for the 30 kV quality only. This aperture (of diameter 9.994 mm) is thinner than the usual BIPM aperture, allowing it to fit in the KRISS aperture holder. An aluminium adapter was fabricated to correctly position this aperture on axis in the KRISS standard. By comparing the two standards under these conditions, aperture effects are removed from the comparison. The result was within 5 parts in 10^4 of the 30 kV comparison result from the main comparison, which is consistent with the associated uncertainties and confirms that there is no significant difference in the standards arising from the determinations of aperture diameter.

A check measurement was also made at 25 kV of the KRISS polarity correction. The result was 1.0010, consistent with the value 1.0009 determined by the KRISS.

6. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 6. The uncertainties associated with air attenuation, measurement of the ionization current and chamber positioning are those that apply to measurements at the BIPM.

The combined standard uncertainty u_c of the comparison result $R_{K,\mathrm{KRISS}} = \dot{K}_{\mathrm{KRISS}} / \dot{K}_{\mathrm{BIPM}}$ 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_{sc} and k_{fl} is taken into account in an approximate way by assuming half of the uncertainty value for each factor at each laboratory, consistent with the analysis presented in Burns (2003).

Table 6. Uncertainties associated with the comparison results

Standard	BIPM L-01		KRISS L1	
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	0.0002[a]	0.0002[a]
Air temperature	-	-	-	0.0004[b]
Positioning	0.0001	0.0001	-	0.0001
Volume	0.0003	0.0005	0.0001	0.0005
Correction factors (excl. k_h)	0.0003	0.0015	0.0004	0.0020
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}_{\mathrm{std}}$	0.0005	0.0039	0.0005	0.0041
	0.0039		0.0041[c]	
$R_{K,\mathrm{KRISS}}$	$u_c = 0.0022$[d]			

[a] For measurements at the KRISS, the uncertainty components for ionization current are also $u_{i\mathrm{A}} = 0.0002$ and $u_{i\mathrm{B}} = 0.0002$.
[b] This additional component arises because the KRISS standard does not have an internal thermometer. See Section 4.3.
[c] The uncertainty of the air-kerma rate determination at the KRISS is also 0.0041 and appears as $u_{\mathrm{Lab}\,i}$ in the KCDB.
[d] Takes account of correlation in the type B uncertainties as described in Section 6.

7. Results and discussion

The comparison results are given in Table 7. Agreement at the level of 2 parts in 10^3 is observed, which is consistent with the standard uncertainty of the comparison of 2.2 parts in 10^3 given in Table 6. No significant trend with energy is observed in the comparison results.

In the interest of transparency, it is noted that at the time of the comparison in 2017 the preliminary results were not satisfactory. The two KRISS staff members present at the BIPM were made aware of this, but were not informed of the magnitude or sign of the discrepancy. Following discussions of correction factors, and noting that aperture effects had been eliminated (see Section 5), the KRISS decided to re-determine the effective collecting length for their standard. In March 2022, following finite-element electric-field calculations and capacitance measurements, the KRISS reported a field distortion correction factor of 0.9894 with an uncertainty of 1.5 parts in 10^3. This significant reduction in the KRISS air-kerma rate determination results in better agreement between the standards as presented in this report.

Table 7. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$\boldsymbol{R_{K,\mathrm{KRISS}}}$	**0.9984**	**0.9976**	**0.9984**	**0.9982**	**0.9981**

8. 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 8 and in Figure 1. 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).

9. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the KRISS and the BIPM to be in agreement at the level of the standard uncertainty for the comparison of 2.2 parts in 10^3. A table and graph of degrees of equivalence, including those for the KRISS, are presented for entry in the BIPM key comparison database.

Table 8. 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 D_i /(mGy/Gy)	10 kV U_i /(mGy/Gy)	30 kV D_i /(mGy/Gy)	30 kV U_i /(mGy/Gy)	25 kV D_i /(mGy/Gy)	25 kV U_i /(mGy/Gy)	50 kVb D_i /(mGy/Gy)	50 kVb U_i /(mGy/Gy)	50 kVa D_i /(mGy/Gy)	50 kVa U_i /(mGy/Gy)
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
GUM	-5.1	6.4	-3.7	6.4	-0.1	6.4	-2.8	6.4	0.5	6.4
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
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

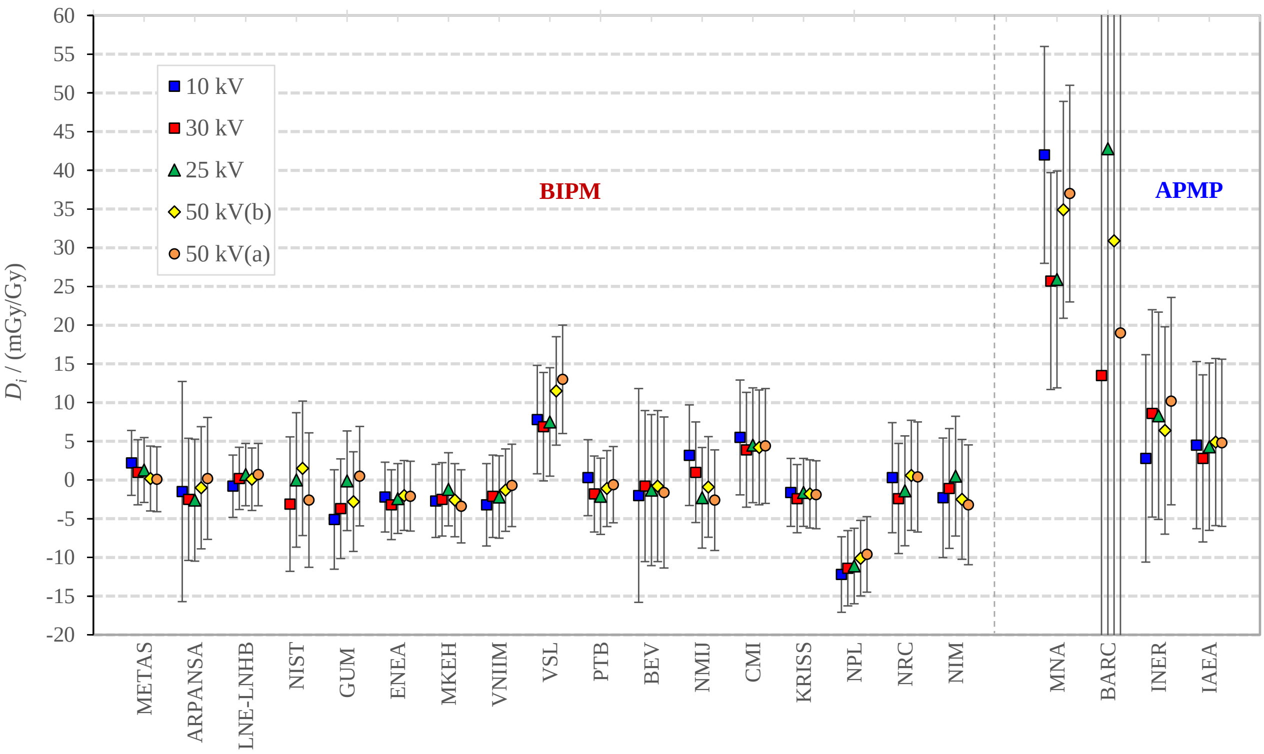

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K2 and those to the right are for the regional comparison APMP.RI(I)-K2 conducted between 2008 and 2010. The large uncertainty bars for the BARC are not shown (±100 mGy/Gy, see Table 8).

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

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** *Technical Supplement* 06031

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

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

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

KCDB 2022 The BIPM key comparison database is available online at http://kcdb.bipm.org/

Kessler C, Burns D T 2018 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport* BIPM-18/06

Yi C-Y, Kim Y H, Jeong D Y 2022 Effective volume of the Korea Research Institute of Standards and Science free air chamber L1 for low-energy x-ray measurement *Prog. Med. Phys.* **33(1)**