Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the BFKH, Hungary, and the BIPM in medium-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 medium-energy x-ray range. The results show the standards to be in agreement at the level of the expanded uncertainty of the comparison of 6.2 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

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 100 kV to 250 kV. A cavity 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 April 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 $\Pi\, k_i$ 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 (1978) 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 (Burns

[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 $k_h = 0.9980$.

and Csete 2000, Burns *et al.* (2011). 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 M-01	BFKH XE-3
Aperture diameter / mm	9.939	9.8267
Air path length / mm	281.5	465
Collecting length / mm	60.004	99.75
Electrode separation / mm	180	320
Collector width / mm	200	320
Measuring volume / mm^3	4655.4	7565.2
Polarizing voltage / V	4000	6000

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

$$N_K = \frac{\dot{K}}{I_{\mathrm{tr}}} \quad (2)$$

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

$$R_K = \frac{k_Q N_{K,\mathrm{NMI}}}{N_{K,\mathrm{BIPM}}} \qquad (3)$$

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 spherical cavity ionization chamber with reference ND1001 belonging to the BFKH was used as transfer instrument for the comparison. The same chamber was used during the previous comparisons in 1998 and in 2010. Its main characteristics are given in Table 3. The chamber was oriented with the stem perpendicular to the beam direction and with the serial number facing the source.

Table 3. Main characteristics of the transfer chamber

Chamber type	ND1001
Serial number	7808
Geometry	spherical
External diameter / cm	3.8
Wall material	air-equivalent POM
Wall thickness / g cm^{-2}	0.28
Nominal volume / cm^3	20
Polarizing potential [a] / V	+250

[a] Potential applied to the outer electrode.

5. Calibration at the BIPM

5.1 The BIPM irradiation facility and reference radiation qualities

The BIPM medium-energy x-ray laboratory houses a high-stability generator and a tungsten-anode x-ray tube with a 3 mm beryllium window. In addition to the aluminium filter of thickness 1.203 mm used for the 100 kV radiation quality, an aluminium filter of thickness 2.228 mm is added for all radiation qualities to compensate for the decrease in filtration that occurred when the original BIPM x-ray tube (with an aluminium window of approximately 3 mm) was replaced in June 2004. Two voltage dividers monitor the tube voltage and a voltage-to-frequency converter combined with data transfer by optical fibre measures the anode current. No transmission monitor is used. 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 100 kV to 250 kV are those recommended by the CCRI and are given in Table 4.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to typically 0.2 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the BIPM standard (which is controlled at 25 °C). Air pressure is measured by means of a calibrated barometer.

Table 4. Characteristics of the BIPM reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.431	2.228	2.228	2.228
Additional Cu filtration / mm	-	0.232	0.485	1.570
Al HVL / mm	4.030	-	-	-
Cu HVL / mm	0.149	0.489	0.977	2.484
$(\mu/\rho)_{air}$ / cm^2 g^{-1}	0.290	0.190	0.162	0.137
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.50	0.50	0.50	0.50

5.2 The BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 1200 mm from the radiation source, 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 98 mm for all radiation qualities.

For the calibration of the transfer chamber, measurements using the BIPM standard are made using positive polarity only. A correction factor of 1.00015 was applied to correct for the known polarity effect in the standard. The leakage current for the BIPM standard, relative to the ionization current, was measured to be around 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 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 uncertainties for the BIPM M-01 standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0099	1.0065	1.0055	1.0047	0.0002	0.0001
Photon scatter k_{sc}	0.9952	0.9959	0.9964	0.9974	-	0.0003
Fluorescence k_{fl}	0.9985	0.9992	0.9994	0.9999	-	0.0003
Electron loss k_e	1.0000	1.0015	1.0047	1.0085	-	0.0005
Initial ionization k_{ii} [b] Energy dependence of W_{air} k_W [b]	0.9980	0.9980	0.9981	0.9986	-	0.0005
Ion recombination k_s	1.0010	1.0010	1.0010	1.0010	0.0002	0.0001
Polarity k_{pol}	1.0002	1.0002	1.0002	1.0002	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia}	0.9995	0.9993	0.9991	0.9980	-	0.0003
Wall transmission k_p	1.0000	1.0000	0.9999	0.9988	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$(1 - g_{air})^{-1}$	1.0001	1.0001	1.0002	1.0003	-	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 250 kV 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 3 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 The BFKH irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the BFKH comprises a high-stability generator and a tungsten-anode x-ray tube with an inherent filtration of 2.2 mm beryllium and 3 mm of aluminium. 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 monitor is around 2 parts in 10^4. The characteristics of the BFKH 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 0.1 °C. The air temperature is measured using a calibrated platinum (Pt 200) temperature probe positioned inside the primary standard and next to the transfer chamber, as appropriate. The air pressure is measured using a calibrated barometer.

Table 6. Characteristics of the BFKH reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	0.7	1.03	1.03	1.03
Additional Cu filtration / mm	-	0.20	0.47	1.60
Al HVL / mm	4.04	-	-	-
Cu HVL / mm	0.152	0.498	0.967	2.46
$(\mu/\rho)_{\text{air}}$ / cm^2 g^{-1}	0.292	0.206	0.171	0.133
$\dot{K}_{\text{BFKH}}$ / mGy s^{-1}	0.25	0.23	0.24	0.26

6.2 The BFKH standard and correction factors

The reference plane for the BFKH standard XE-3 was positioned at 1040 mm from the radiation 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 113 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 3 parts in 10^4 to take into account any small polarity effect in the standard. The leakage current was measured to be around 3 parts in 10^4.

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 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 at the reference distance, with a reproducibility of 0.1 mm. Lateral alignment on the beam axis was to an estimated uncertainty of 0.1 mm. The relative leakage current was below 1 part in 10^4.

Calibrations were made before and after the measurements at the BIPM. The uncertainty arising from these repeat measurements is discussed in Section 8.

Table 7. Correction factors and uncertainties for the BFKH XE-3 standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0165	1.0116	1.0096	1.0075	0.0005	0.0001
Photon scatter k_{sc}	0.9922	0.9934	0.9942	0.9957	-	0.0006
Fluorescence k_{fl}	0.9985	0.9992	0.9994	0.9998	-	0.0003
Electron loss k_e	1.0000	1.0000	1.0005	1.0020	-	0.0006
Initial ionization k_{ii} [b] / Energy dependence of W_{air} k_W [b]	0.9980	0.9980	0.9981	0.9986	-	0.0007
Ion recombination k_s	1.0010	1.0010	1.0010	1.0010	0.0004	0.0001
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0003	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0005
Diaphragm correction k_{dia} [c]	0.9995	0.9992	0.9990	0.9978	-	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0003	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$k_{br}\,(1 - g_{air})^{-1}$ [d]	1.00014	1.00014	1.00014	1.00021	-	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 $k_{ii}k_W$.
[c] The diaphragm correction factor is discussed in the report of the 2010 comparison (Burns *et al.* 2011).
[d] The BFKH correction for radiative loss includes the effect of bremsstrahlung reabsorption k_{br} (Burns 2001).

7. Additional considerations for transfer chamber calibrations

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

As can be seen from Tables 4 and 6, the air-kerma rates at the BIPM are twice those at the BFKH. The change in volume recombination is unknown but should be small; no recombination corrections have been applied but an uncertainty of 5 parts in 10^4 is included in Table 12. The transfer chamber was used with the same polarity at the two laboratories and so no corrections are applied for polarity effects in the transfer chamber.

No correction is applied at either laboratory for the radial non-uniformity of the radiation field. For the ND1001 chamber with external diameter 3.8 cm, the effect remains below 5 parts in 10^4 and should cancel to some extent at the two laboratories. A relative standard uncertainty of 3 parts in 10^4 is introduced in Table 12 for this effect.

The radiation field size at the BFKH of 113 mm in diameter is only marginally greater than the BIPM beam diameter of 98 mm. The effect of this difference on the transfer chamber calibration should be small and an uncertainty component of 3 parts in 10^4 in included in Table 12.

7.2 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities might require a correction factor k_Q. From Tables 4 and 6 it is evident that the radiation qualities at the BIPM and at the BFKH are well matched in terms of HVL; the k_Q values evaluated from a fit to the results obtained at the BIPM are typically within 1 part in 10^4 of unity. Consequently, no k_Q corrections have been applied but rather an uncertainty 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 a relative standard uncertainty s_{tr} representing the chamber stability[2]. The rms value for the four qualities, $s_{\mathrm{tr,comp}} = 0.0016$, is taken to represent the 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 $s_{\mathrm{tr,comp}}$.

An important change in procedure is noted here. The calibration coefficients $N_{K,\mathrm{BFKH}}$ (post-BIPM) given in Table 8 were provided to the BIPM in April 2023; original post-BIPM values provided in February 2023 were found to be too low by 0.7 % because a metal rod used to position the chamber was malfunctioning. This discovery was made at the Draft B stage, after the BIPM results $N_{K,\mathrm{BIPM}}$ had been disclosed, and for this reason the April revision could not be accepted. Because the erroneous results provided in February do not reflect the quantity disseminated by the BFKH, the decision was taken to evaluate the final comparison results R_K using only the values $N_{K,\mathrm{BFKH}}$ (pre-BIPM). As noted in the preceding paragraph, the April values $N_{K,\mathrm{BFKH}}$ (post-BIPM) given in Table 8 *have* nevertheless been used in the evaluation of $s_{\mathrm{tr,comp}}$ because they provide the best available estimate of the stability of the transfer chamber over the course of the comparison.

Table 8. Calibration coefficients for the transfer chamber ND1001-7808

Radiation quality	100 kV	135 kV	180 kV	250 kV
$N_{K,\mathrm{BFKH}}$ (pre-BIPM) / Gy μC^{-1}	1.479	1.477	1.480	1.487
$N_{K,\mathrm{BFKH}}$ (post-BIPM) / Gy μC^{-1} [a]	*1.481*	*1.477*	*1.479*	*1.480*
s_{tr}	0.0009	0.0000	0.0004	0.0030
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	1.487	1.478	1.481	1.488

[a] The post-BIPM calibration coefficients have not been used for the evaluation of R_K; see text.

The comparison results R_K are presented in Table 9, evaluated according to Equation (3) with k_Q equal to unity. Also given in Table 9 are the results of the previous comparison of the BFKH and BIPM standards (Burns *et al.* 2011), updated for the changes made to the standards in the interim period (see Section 10).

Table 9. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$\boldsymbol{R_K}$	**0.9946**	**0.9993**	**0.9993**	**0.9993**
Updated results of 2010 comparison	*0.9996*	*1.0009*	*1.0004*	*1.0004*

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

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 medium-energy x-rays described in Burns (2003).

Table 10. Uncertainties associated with the standards

Standard	BIPM		BFKH	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0005	0.0010
Positioning	0.0001	0.0001	-	0.0010
Volume	0.0001	0.0005	0.0005	0.0005
Correction factors (excl. k_h)	0.0003	0.0011	0.0008	0.0014
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}$	0.0004	0.0037	0.0011	0.0041

Table 11. Uncertainties associated with transfer chamber calibrations

Laboratory	BIPM		BFKH	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}$	0.0004	0.0037	0.0011	0.0041
I_{tr}	0.0002	0.0002	0.0007	0.0003
Positioning of transfer chamber	0.0001	-	-	0.0010
Reproducibility	0.0003	-	- [a]	-
$N_{K,lab}$	0.0005	0.0037	0.0013	0.0042

[a] See Section 8 and Table 12.

10. Discussion

The comparison results presented in Table 9 show the BFKH and the BIPM standards to be in agreement at the level of the expanded uncertainty of the comparison of 6.2 parts in 10^3. No particular trend with energy is observed although the result at 100 kV is lower by almost 5 parts in 10^3.

The final row of Table 9 shows the results of the previous comparison in 2010; no update to these results is necessary because no changes have been made to either standard other than the adoption of the k_{ii} and k_W correction factors, which are the same for both standards. The new results are in good agreement with those of 2010 with the exception of the 100 kV quality as noted above.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{BFKH}}$ / $N_{K,\mathrm{BIPM}}$	0.0014	0.0022 [a]
Ion recombination	-	0.0005
Beam non-uniformity	-	0.0003
Field size	-	0.0003
k_Q	-	0.0001
Transfer chamber stability $s_{\mathrm{tr,\ comp}}$	0.0016	-
R_K	0.0021	0.0023
	u_{c} = 0.0031	

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

11. Degrees of Equivalence

The analysis of the results of BIPM comparisons in medium-energy x-rays in terms of degrees of equivalence is described in Burns (2003). Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the key comparison reference value, for each of the CCRI radiation qualities. It follows that for each laboratory i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_{\mathrm{i}} - 1$ 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)-K3 for the determination of air kerma in medium-energy x-rays shows the standards of the BFKH and the BIPM to be in agreement at the level of the expanded uncertainty of the comparison of 6.2 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 BIPM 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)-K3 and green in SIM.RI(I)-K3.

		100 kV		135 kV		180 kV		250 kV	
Lab *i*	Lab *i*	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i
PTB	2014	2.7	5.2	4.5	5.2	4.9	5.2	5.5	5.2
ENEA	2014	3.9	6.2	4.2	6.2	7.3	6.2	5.6	6.2
BEV	2014	3.2	6.4	4.7	6.4	4.1	6.4	1.1	6.4
NRC	2014	3.1	6.6	2.3	6.6	1.3	6.6	0.4	6.6
NMIJ	2015	-0.8	6.2	-1.4	6.2	-2.4	6.2	-3.7	6.2
VSL	2016	-1.0	6.4	-0.4	6.4	0.0	6.4	-2.1	6.4
NIST	2016	-2.2	7.8	-3.3	7.8	-2.7	7.8	-5.8	7.8
NIM	2017	7.2	6.2	5.4	6.2	6.1	6.2	6.0	6.2
NPL	2017	0.4	6.8	0.0	6.8	-2.5	6.8	-4.4	6.8
KRISS	2017	4.1	4.4	5.1	4.4	4.3	4.4	2.8	4.4
LNE-LNHB	2018	0.5	7.6	-0.5	7.6	-1.0	7.6	-2.8	7.6
VNIIM	2020	0.5	3.8	1.0	3.8	1.7	3.8	2.2	3.8
GUM	2020	6.9	6.0	3.2	6.0	3.6	6.0	2.7	6.0
ARPANSA	2020	3.8	8.2	5.2	8.2	5.4	8.2	4.5	8.2
BFKH	2021	-5.4	6.2	-0.7	6.2	-0.7	6.2	-0.7	6.2
CNEA	2008	-6.0	14	1.1	14	2.1	14	1.4	14
LMNRI/IRD	2008	-9.5	12	-9.4	12	-8.0	12	-8.5	12
ININ	2008	-9.3	16	-12.1	16	-11.1	16	-12.0	16

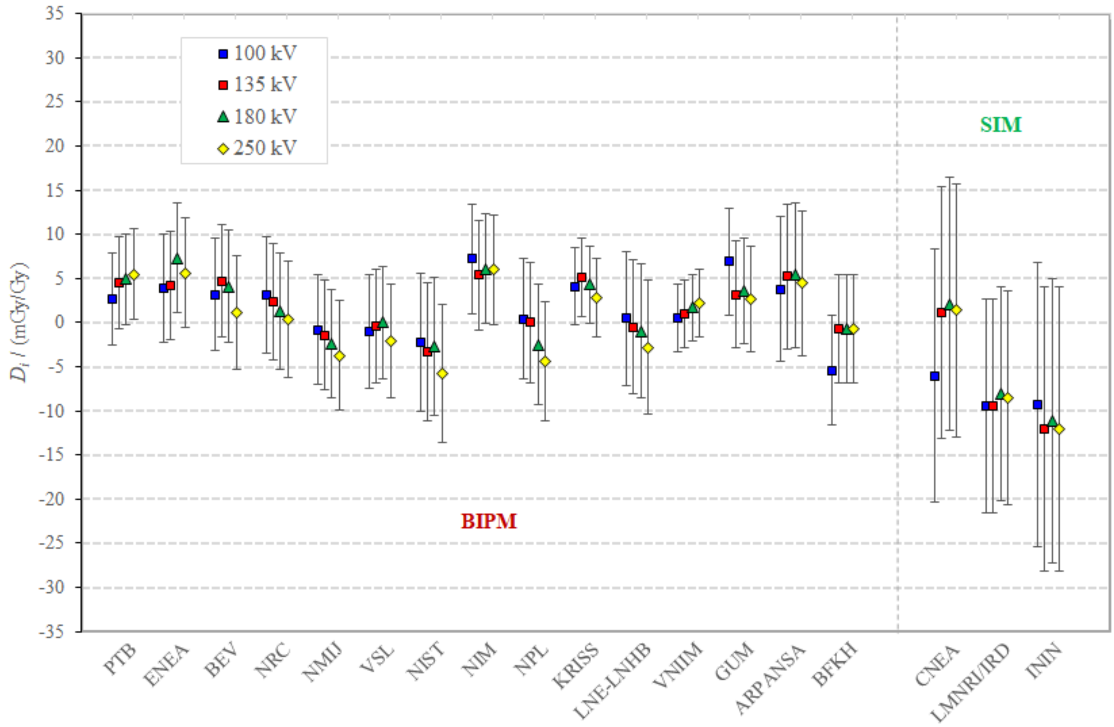

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K3 and those to the right for the regional comparison SIM.RI(I)-K3.

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