Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the PTB, Germany, and the BIPM in medium-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-92310 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 medium-energy x-ray range. The results show the standards to be in agreement at the limit 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 Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Two cavity 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

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

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

The free-air chamber standard M-01 of the BIPM is of the parallel-plate design, while the PTB FK (Faßkammer) standard has a cylindrical geometry in which the inner collector rod and the outer electrode are concentric, and the entrance aperture is displaced from the axis of cylindrical symmetry by 4.5 cm. For both chamber types the measuring volume V is defined by the diameter of the chamber aperture and the length of the collecting region. The BIPM air-kerma standard is

---

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

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 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 (Burns *et al*. 2002, 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] (BIPM)	1.2045 kg m^{-3}	0.0001
ρ_{air} [c] (PTB)	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 M-01	PTB FK
Aperture diameter / mm	9.939	20.009
Air path length / mm	281.5	481
Collecting length / mm	60.004	200.009
Electrode separation / mm	180	196.5 [a]
Collector width / mm	200	7.0 [b]
Measuring volume / mm^3	4655.4	62893
Polarizing voltage / V	4000	3000

[a] Difference in radius between the outer electrode (200 mm) and the collector rod.
[b] Diameter of the collector rod.

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 the 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 in the range from 30 % 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 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 $N_{K,\mathrm{NMI}}$ determined at the NMI into one that applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

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

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

4.2 Details of the transfer instruments

Two cavity ionization chambers belonging to the PTB, type Exradin A3, serial numbers XR230742 and XR230743, were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. Each chamber was positioned with the stem perpendicular to the beam direction and with the mark on the stem facing the source. The reference point for the chamber was taken to be at the centre of the sphere.

Table 3. Main characteristics of the transfer chambers

Chamber type	Exradin A3
Geometry	spherical
External diameter / mm	19.6
Wall material	C552
Nominal volume / cm^3	3.6
Polarizing potential / V	–300 [a]

[a] At both laboratories the stated potential was applied to the outer wall of the chamber.

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 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 0.1 °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
$(\mu/\rho)_{air}$ [a] / $cm^2\ g^{-1}$	0.290	0.190	0.162	0.137
$\dot{K}_{BIPM}$ / $mGy\ s^{-1}$	0.50	0.50	0.50	0.50

[a] Measured at the BIPM using an evacuated tube of length 280 mm.

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 is 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. 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 radiation source and the reference plane.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each 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 for each chamber was 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 transfer chamber and at each radiation quality, the relative standard uncertainty of the mean ionization current was typically below 1 part 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 3 parts in 10^4 is included (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	100 kV	135 kV	180 kV	250 kV	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
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
$1 - g_{air}$	0.9999	0.9999	0.9998	0.9997	-	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).

6. Calibration at the PTB

6.1 The PTB irradiation facility and reference radiation qualities

The medium-energy x-ray source used for the calibrations at the PTB is of type MGC41, manufactured by YXLON. The converter-type generators of type MGG46 and MGG47 operate at a frequency of 40 kHz and yield a constant potential. The bipolar x-ray tube Thales MB450-1H450 has a tungsten anode and an inherent filtration of 7 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 1 part in 10^3. The generating potential is measured invasively with a frequency compensated 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 0.1 °C. Three calibrated thermistors measure, respectively, the temperature of the air inside the standard and of the ambient air close to the monitor and transfer chamber. The air pressure is measured by means of a calibrated barometer.

Table 6. Characteristics of the PTB reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.511	2.312	2.303	2.311
Additional Cu filtration / mm	-	0.232	0.485	1.570
Al HVL [a] / mm	4.131	-	-	-
Cu HVL [a] / mm	0.157	0.483	0.995	2.460
$(\mu/\rho)_{air}$ [a] / cm^2 g^{-1}	0.287	0.197	0.168	0.143
$\dot{K}_{PTB}$ / mGy s^{-1}	0.72	0.73	0.73	0.67

[a] Calculated at the PTB using the photon-fluence spectra measured by means of a high-purity germanium detector.

6.2 The PTB standard and correction factors

The reference plane for the PTB standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.05 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is 80 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the PTB standard were made at a single polarity. No correction is applied but rather a standard uncertainty for the polarity effect as given in Table 7. The relative leakage current was measured to be less than 2 parts 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 calculated using the mean mass attenuation coefficients $(\mu/\rho)_{air}$ for air 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.

The PTB standard involves the correction factor k_{sh} for the shadow effect of the central electrode in the cylindrical free-air chamber design.

6.3 Transfer chamber positioning and calibration at the PTB

The reference point for each transfer chamber was positioned at the reference plane with a reproducibility of 0.05 mm. Alignment on the beam axis was to an estimated uncertainty of 0.1 mm. The leakage current was measured before and after each measurement series and a correction made using the mean value. The relative leakage current for each transfer chamber was less than 2 parts in 10^4. The relative standard uncertainty of the mean ionization current for each series was typically 3 parts in 10^4.

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.

Table 7. Correction factors and uncertainties for the PTB standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_{a} [a]	1.0168	1.0115	1.0098	1.0083	0.0005	0.0005
Scattered radiation k_{sc} [b]	0.9917	0.9935	0.9946	0.9958	-	0.0005
Electron loss k_{e}	1.0000	1.0000	1.0004	1.0018	-	0.0005
Initial ionization k_{ii} [c] Energy dependence of W_{air} k_W [c]	0.9980	0.9980	0.9981	0.9985	-	0.0011
Ion recombination k_{s}	1.0030	1.0030	1.0030	1.0028	-	0.0011
Shadow effect k_{sh}	1.0010	1.0020	1.0023	1.0031	-	0.0005
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0005	0.0005
Field distortion k_{d}	1.0000	1.0000	1.0000	1.0000	-	0.0010
Wall transmission k_{p}	1.0000	1.0000	1.0000	1.0000	0.0005	-
Aperture transmission k_{l}	1.0000	1.0000	0.9999	0.9994	-	0.0005
Humidity k_{h}	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{\mathrm{air}}$	1.0000	1.0000	1.0000	1.0000	-	0.0004

[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] This includes the effect of fluorescence, treated separately for the BIPM standard as k_{fl}.
[c] The stated values are for the product $k_{\mathrm{ii}}k_W$.

7. Additional corrections to 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 is about 1.4 times that of the BIPM. For the Exradin A3 chamber, the recombination effect was measured at the KRISS during a previous comparison with the BIPM (Burns *et al.* 2022). According to the equation obtained for k_{s}, it is dominated by the correction for initial recombination and consequently k_{s} largely cancels at the two laboratories. No corrections are applied for ion recombination but rather an uncertainty of 2 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 small chambers with cavity dimensions below around 2 cm, the effect should be small, and it is reasonable to assume some cancellation at the two laboratories. A corresponding uncertainty of 3 parts in 10^4 is introduced in Table 12 for this effect.

At the PTB the field size and the reference distance are smaller than those at the BIPM (80 mm at 1000 mm and 98 mm at 1200 mm, respectively). The effect of this difference was evaluated at the PTB during the previous comparison with the BIPM to be around 3 parts in 10^4 for the Exradin A3 chamber. A corresponding uncertainty of 3 parts in 10^4 is included in Table 12.

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. However, from Tables 4 and 6 it is evident that the radiation qualities at the BIPM and at the PTB are closely matched in terms of HVL. The k_Q values evaluated from a fit to the results obtained at the PTB 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 $N_{K,\mathrm{PTB}}$ 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].

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Exradin A3-XR230742				
$N_{K,\mathrm{PTB}}$ (pre-BIPM) / Gy μC^{-1}	7.662	7.685	7.708	7.723
$N_{K,\mathrm{PTB}}$ (post-BIPM) / Gy μC^{-1}	7.644	7.666	7.693	7.711
$s_{\mathrm{stab},1}$	0.0022	0.0023	0.0018	0.0014
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	7.615	7.637	7.662	7.689
Exradin A3-XR230743				
$N_{K,\mathrm{PTB}}$ (pre-BIPM) / Gy μC^{-1}	7.692	7.711	7.730	7.741
$N_{K,\mathrm{PTB}}$ (post-BIPM) / Gy μC^{-1}	7.680	7.701	7.722	7.731
$s_{\mathrm{stab},2}$	0.0014	0.0012	0.0010	0.0012
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	7.645	7.662	7.682	7.705

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

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

[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).

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 four qualities, $s_{\mathrm{tr,comp}}$ = 0.0011, is taken to represent the uncertainty arising from the transfer chambers and is included in Table 12.

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 ($k_{\mathrm{ii}}k_W$)[3].

Table 9. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
R_K using Exradin A3-XR230742	1.0050	1.0050	1.0050	1.0036
R_K using Exradin A3-XR230743	1.0054	1.0057	1.0057	1.0040
s_{tr}	0.0013	0.0013	0.0010	0.0009
Final R_K	**1.0052**	**1.0054**	**1.0054**	**1.0038**
Updated results of 2014	*1.0027*	*1.0045*	*1.0049*	*1.0054*

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 $R_{K,\mathrm{PTB}}$ is presented in Table 12. This combined 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 medium-energy x-rays in terms of degrees of equivalence described in Burns (2003).

10. Discussion

The comparison results presented in Table 9 show the PTB and BIPM standards to agree at the level of the expanded uncertainty of the comparison of 5.8 parts in 10^3. No significant trend with radiation quality is observed.

The results agree with the results of the comparison carried out in 2014 at the level of the standard uncertainty of the comparisons. The differences for 135 kV and 180 kV are less than 1 part in 10^3, while the new 100 kV result is higher than that of 2014 by 2.5 parts in 10^3 and 250 kV result is lower by 1.6 part in 10^3.

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

[3] During the previous comparison a different configuration of the PTB primary standard FK was used, so only the change in $k_{\mathrm{ii}}k_W$ (which is independent of the free-air chamber configuration) is included in the revision.

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 10. Uncertainties associated with the standards

Standard	BIPM		PTB FK	
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	0.0006	-
Positioning	0.0001	0.0001	-	0.0001
Volume	0.0001	0.0005		0.0006
Correction factors (excl. k_h)	0.0003	0.0011	0.0009	0.0023
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035		0.0035
$\dot{K}$	0.0004	0.0037	0.0011	0.0042

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

Institute	BIPM		PTB FK	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}_\mathrm{std}$	0.0004	0.0037	0.0011	0.0042
I_tr	0.0002	0.0002	0.0005	
Monitor ionization current I_mon	-	-	0.0005	-
Air density correction k_rho	-	-	-	0.0007
Positioning of transfer chamber	0.0001	-	-	0.0001
Short-term reproducibility	0.0003	-	- [a]	-
N_K	0.0005	0.0037	0.0013	0.0043

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

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$	0.0014	0.0022 [a]
Ion recombination	-	0.0002
Radial non-uniformity	-	0.0003
Field size and distance	-	0.0003
k_Q	-	0.0001
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0011	-
R_K	0.0018	0.0023 [a]
	u_c = 0.0029 [a]	

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

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 PTB and the BIPM to agree 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 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 BIPM.RI(I)-K3 and green in SIM.RI(I)-K3.

Lab i	Year	100 kV D_i /(mGy/Gy)	100 kV U_i /(mGy/Gy)	135 kV D_i /(mGy/Gy)	135 kV U_i /(mGy/Gy)	180 kV D_i /(mGy/Gy)	180 kV U_i /(mGy/Gy)	250 kV D_i /(mGy/Gy)	250 kV U_i /(mGy/Gy)
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
PTB	2024	5.2	5.8	5.4	5.8	5.4	5.8	3.8	5.8
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

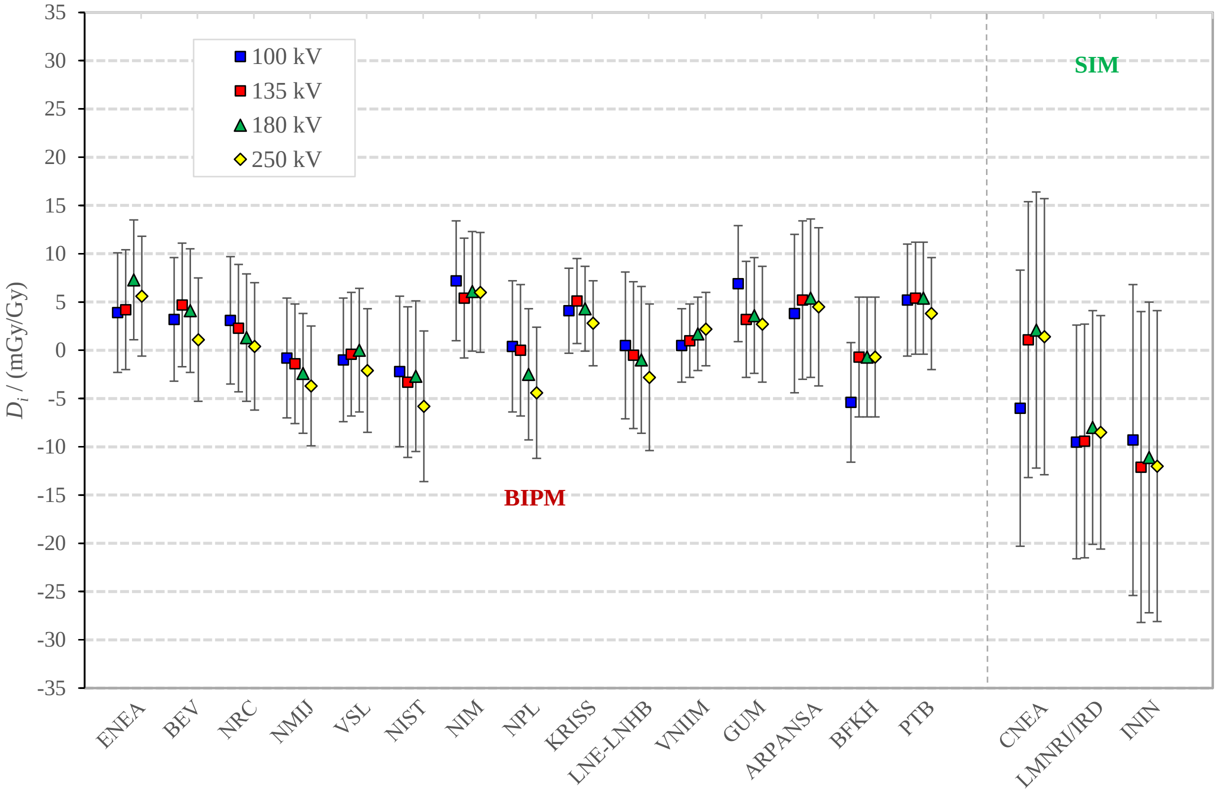

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K3 and those to the right are for the regional comparison SIM.RI(I)-K3.

References

Boutillon M 1978 Mesure de l'exposition au BIPM dans le domaine des rayons X de 100 à 250 kV *Rapport BIPM*-78/3

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)-K3 between national primary standards for medium-energy x-rays *Metrologia* **40** 06036

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 2002 Comparison of the air-kerma standards of the PTB and the BIPM in the medium-energy x-ray range *Rapport* BIPM-02/07

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)-K3 of the air-kerma standards of the PTB, Germany and the BIPM in medium-energy x-rays *Metrologia* **51** 06016

Burns D T, Kessler C, Chul-Young Yi, Yun Ho Kim 2022 Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the KRISS, Republic of Korea, and the BIPM in medium-energy x-rays *Metrologia* **59** 06009

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)-K3 are available in the BIPM key comparison database at BIPM.RI(I)-K3

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