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

D.T. Burns[1], C Kessler[1] and L Büermann[2]

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

Abstract A key comparison has been made between the air-kerma standards of the PTB, Germany and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement at the level of the standard uncertainty of the comparison of 2.1 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 Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. The comparison took place at the BIPM in March 2014 using the reference conditions recommended by the CCRI (CCEMRI 1972).

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

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

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 $\Pi\, k_{\text{i}}$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air}, 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].

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. 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 L-01 is described in Boutillon *et al* (1969) and the changes made to certain correction factors given in Burns (2004), Burns *et al* (2009) and the references therein. Details of the PTB standard PK100, which was compared with the BIPM standard in 1999, are given in Burns *et al* (2001). The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

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[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 a humidity correction $k_{\text{h}} = 0.9980$. At the BIPM, the factor 1.0002 is included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	u_i[a]
ρ_{air}[b] (BIPM)	1.2930 kg m^{-3}	0.0001
ρ_{air}[b] (PTB)	1.2048 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0015

[a] u_i is the relative standard uncertainty.

[b] The value used at the BIPM is for dry air at T_0 = 273.15 K and P_0 = 101 325 Pa, while at the PTB the value is for T_0 = 293.15 K and P_0 = 101 325 Pa.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	PTB PK100
Aperture diameter / mm	9.941	10.008
Air path length / mm	100.0	97.2
Collecting length / mm	15.466	20.021
Electrode separation / mm	70	234
Collector width / mm	71	240
Measuring volume / mm^3	1200.4	1575.0
Polarizing voltage / V	+1500	+6000

3. Comparison procedure

3.1 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) so that the half-value layer (HVL) of the present 10 kV radiation quality matches that of the original BIPM 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, the anode current is measured and the ionization chamber current normalized for any deviation from the reference anode current. The resulting variation in the BIPM free-air chamber current over the duration of a comparison is normally not more than 2 parts in 10^4 and the standard deviation of repeat air-kerma 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 (CCEMRI 1972) and are given in Table 3 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 thermistors, calibrated to a few mK, measure the temperature of the ambient air and the air inside the BIPM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range from 47% to 53%.

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
$(\mu/\rho)_{\text{air}}{}^{\text{a}}$ / cm^2 g^{-1}	14.84	3.661	2.604	0.753	0.378
$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	1.00	1.00	1.00	1.00	1.00

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

3.2 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 PTB standard.

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

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	$u_{i\text{A}}$	$u_{i\text{B}}$
Air attenuation $k_{\text{a}}{}^{\text{a}}$	1.1957	1.0451	1.0319	1.0091	1.0046	0.0002	0.0001
Scattered radiation $k_{\text{sc}}{}^{\text{b}}$	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.0003
Fluorescence $k_{\text{fl}}{}^{\text{b}}$	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
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
$1 - g_{\text{air}}$	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] Values for k_{sc} and k_{fl} adopted in October 2003, based on Monte Carlo calculations.

[c] Correction factor k_{dia} for diaphragm transmission, scatter and fluorescence adopted September 2009, replacing the factor k_{l}. See reference Burns and Kessler (2009).

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 correction factor k_{a} is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{\text{air}}$ 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 at the time of the measurements. Ionization measurements 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. The usual correction to k_a at 10 kV for standards with attenuation length not close to that for the BIPM standard has not been applied because of the similarity of the attenuation lengths.

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. Similarly, measurements using the PTB standard were made using positive polarity only; no polarity correction was applied, but rather an appropriate uncertainty was included (see Table 5).

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 PTB standard, the values for k_s given in Table 5 for the BIPM air-kerma rates are derived from measurements at the PTB.

Table 5. Correction factors for the PTB standard PK100 used at the BIPM

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.1897	1.0438	1.0310	1.0089	1.0044	0.0002[b]	0.0001[b]
Scattered radiation k_{sc} [c]	0.9856	0.9894	0.9902	0.9928	0.9939	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Ion recombination k_s	1.0019	1.0022	1.0022	1.0022	1.0022	0.0005	0.0005
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	0.0005	0.0005
Field distortion k_d [d]	0.9910	0.9910	0.9910	0.9910	0.9910	0.0010	-
Aperture edge k_l	0.9998	0.9997	0.9996	0.9991	0.9986	-	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0005	-
Guard strip attenuation k_{ap} [e]	1.0306	1.0086	1.0060	1.0020	1.0012	0.0005	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] Values for 293.15 K and 101.325 kPa, 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 PTB, the uncertainties are $u_{iA} = 0.0005$ and $u_{iB} = 0.0005$, except at 10 kV where $u_{iA} = 0.0010$.

[c] This includes the effect of fluorescence, treated separately for the BIPM standard as k_{fl}.

[d] This is the result of new measurements at the PTB, the value used for the 1999 comparison was 0.9920.

[e] The value for 10 kV was measured at the BIPM in 1999. The values for the other qualities were measured at the PTB.

3.3 Chamber positioning and measurement procedure

The PTB 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. 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 both standards were used with the same aperture diameter. The reference plane for each chamber was positioned at 500 mm from the radiation source 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 air temperature for the PTB chamber was measured using a BIPM platinum resistance thermometer positioned in the holder of the chamber, with a resolution of 0.01 K and calibrated to better than 0.1 K. 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 the BIPM chamber the leakage current, relative to the ionization current of around 45 pA, was less than 1 part in 10^4 and for the PTB chamber, with measured current around 60 pA, between 2 and 3 parts in 10^4.

For the PTB chamber, the standard uncertainty of the mean of a series of seven measurements, each with integration time 60 s, was less than 1 part in 10^4. Two series were made for each comparison. For the BIPM standard, a similar series was made for each comparison with a standard uncertainty around 1 part in 10^4. For the 10 kV, 30 kV and 25 kV radiation qualities the comparison was repeated on a subsequent day (the chambers remaining fixed in position) and the two comparison results for each quality agreed to 1 part in 10^4.

4. 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, with the measurement of the ionization current and with chamber positioning are those that apply to measurements at the BIPM.

The combined standard uncertainty u_c of the ratio $\dot{K}_{\text{PTB}}/\dot{K}_{\text{BIPM}}$ takes into account correlation in the type B uncertainties associated with the humidity correction and the physical constants. 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.

5. 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 2.1 parts in 10^3 given in Table 6. Also shown in Table 7 are the results of the previous comparison between the two standards, a direct comparison carried out in 1999 reported in Burns *et al* (2001) and updated in the BIPM key comparison database (KCDB 2014) for the changes made to the BIPM standard in the interim (Burns 2004, Burns *et al* 2009). The two sets of comparison results agree very closely at the three higher energies; the PTB standard has not changed appreciably over this period, a decrease of 0.1% in the field distortion correction k_d, an increase of around 0.1% in the guard strip correction at 30 kV and 25 kV and small changes to k_{sc} and k_l. At 10 kV the comparison result has decreased by 0.25%, largely a result of the combined decrease of 0.1% in k_d, 0.04% in k_{sc} and 0.02% in k_l.

Table 6. Uncertainties associated with the comparison results

Standard	BIPM		PTB	
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]
Positioning	0.0001	0.0001	0.0001[b]	0.0001[b]
Volume	0.0003	0.0005	0.0006	-
Correction factors (excl. k_h)	0.0003	0.0010	0.0014[c]	0.0011[c]
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}_{\mathrm{Standard}}$	0.0005	0.0019	0.0015	0.0019
	0.0020		0.0024[d]	
$\dot{K}_{\mathrm{PTB}}/\dot{K}_{\mathrm{BIPM}}$	u_c = 0.0021[e]			

[a] For measurements at the PTB, the uncertainty components for ionization current are $u_{i\mathrm{A}}$ = 0.0010 and $u_{i\mathrm{B}}$ = 0.0006.

[b] At the PTB, the uncertainty for positioning is $u_{i\mathrm{A}}$ = 0.0004 (with no component $u_{i\mathrm{B}}$).

[c] At the PTB, the higher uncertainty for the attenuation correction (noted in the footnote to Table 5) results in correction factors with combined uncertainty $u_{i\mathrm{A}}$ = 0.0015 and $u_{i\mathrm{B}}$ = 0.0012 (except at 10 kV where $u_{i\mathrm{A}}$ = 0.0017).

[d] The uncertainty of the air-kerma determination at the PTB is 0.0028 (0.0029 at 10 kV), rather than the value 0.0024 tabulated here. It is the higher value that appears as $u_{\mathrm{Lab}i}$ in the KCDB.

[e] Takes account of correlation in the type B uncertainties as described in Section 4.

Table 7. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$\dot{K}_{\mathrm{PTB}}/\dot{K}_{\mathrm{BIPM}}$	**1.0003**	**0.9982**	**0.9979**	**0.9989**	**0.9994**
Results of 1999 comparison	1.0028	0.9969	0.9982	0.9987	0.9998

6. 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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ 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 2014).

7. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the PTB and the BIPM to be in agreement at the level of the standard uncertainty for the comparison of 2.1 parts in 10^3. A table and graph of degrees of equivalence, including those for the PTB, 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 .

- **Tables formatted as they appear in the BIPM key comparison database.**

10 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	1.1	4.8
METAS	2.2	3.4
BEV	-1.2	4.8
NMIJ	0.9	3.5
NRC	0.3	5.5
ARPANSA	-1.5	14.0
LNE-LNHB	-0.8	3.2
NIST		
GUM	-5.1	5.9
ENEA	-2.2	3.8
MKEH	-2.7	4.1
VNIIM	-3.2	4.7
VSL	7.8	6.6
PTB	0.3	4.3

30 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	-0.3	4.8
METAS	1.0	3.4
BEV	-2.4	4.8
NMIJ	1.0	3.5
NRC	1.3	5.5
ARPANSA	-2.5	7.5
LNE-LNHB	0.2	3.2
NIST	-3.1	8.3
GUM	-3.7	5.9
ENEA	-3.2	3.8
MKEH	-2.5	4.1
VNIIM	-2.1	4.7
VSL	6.9	6.6
PTB	-1.8	4.3

25 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	1.4	4.8
METAS	1.3	3.4
BEV	-1.2	4.8
NMIJ	3.2	3.5
NRC	0.7	5.5
ARPANSA	-2.6	7.5
LNE-LNHB	0.7	3.2
NIST	0.0	8.3
GUM	-0.1	5.9
ENEA	-2.4	3.8
MKEH	-1.2	4.1
VNIIM	-2.2	4.7
VSL	7.5	6.6
PTB	-2.1	4.3

50 kVb

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL		
METAS	0.2	3.4
BEV	-1.0	4.8
NMIJ	4.6	3.5
NRC	4.3	5.5
ARPANSA	-1.0	7.5
LNE-LNHB	0.1	3.2
NIST	1.5	8.3
GUM	-2.8	5.9
ENEA	-2.0	3.8
MKEH	-2.6	4.1
VNIIM	-1.3	4.7
VSL	11.5	6.6
PTB	-1.1	4.3

50 kVa

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	-0.7	4.8
METAS	0.1	3.4
BEV	-1.0	4.8
NMIJ	5.4	3.5
NRC	3.3	5.5
ARPANSA	0.2	7.5
LNE-LNHB	0.7	3.2
NIST	-2.6	8.3
GUM	0.5	5.9
ENEA	-2.1	3.8
MKEH	-3.4	4.1
VNIIM	-0.7	4.7
VSL	13.0	6.6
PTB	-0.6	4.3

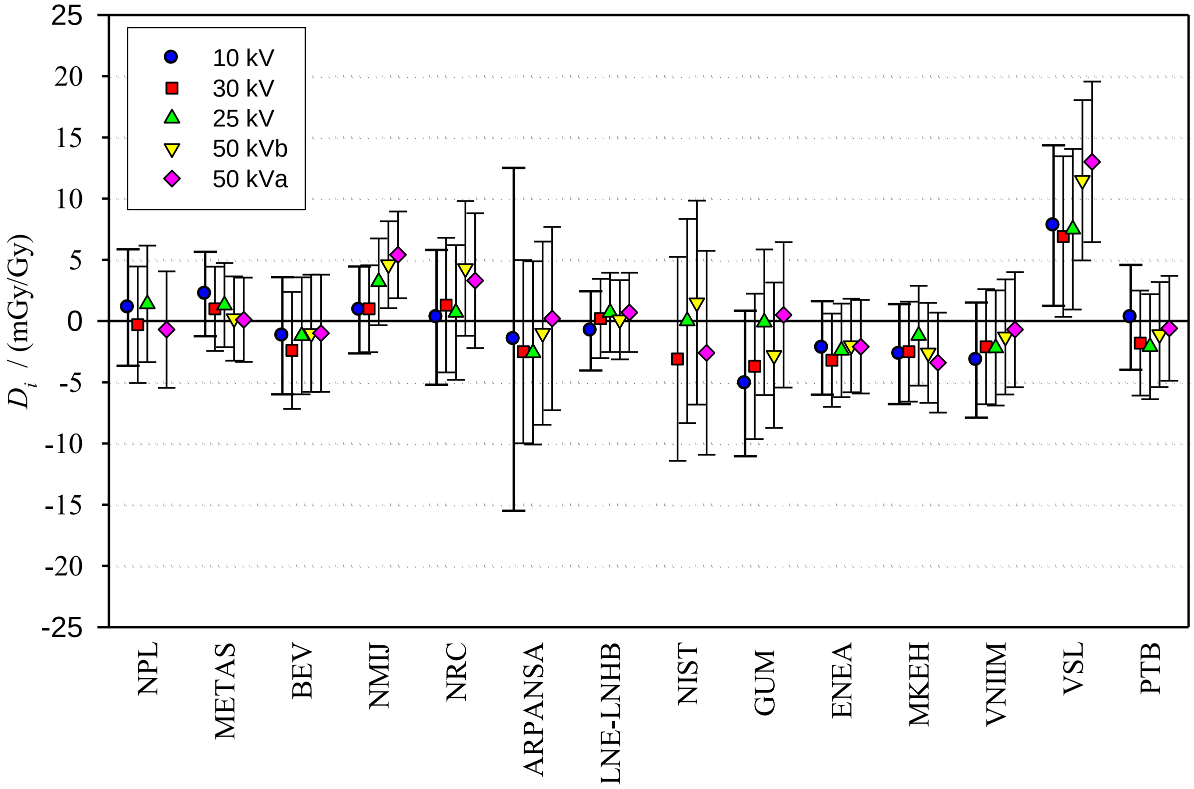

Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value

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KCDB 2014 The BIPM key comparison database is available online at http://kcdb.bipm.org/