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Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the PTB, Germany 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 PTB, Germany and the BIPM in the medium-energy x-ray range. The results show the standards to be in general agreement at the level of the expanded uncertainty (k = 2) of the comparison of 5.0 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. Three cavity ionization chambers of two different types were used as transfer instruments. The measurements at the BIPM took place in March/April 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

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

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 $\Pi\, k_{\mathrm{i}}$ 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

The free-air chamber standard M-01 of the BIPM is of the parallel-plate design, while the PTB 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. This latter design requires the use of an additional correction factor k_{sh} to

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

account for the shadow effect of the central electrode. 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 described in Boutillon (1978) and the changes made to certain correction factors in Burns (2004), Burns *et al* (2009) and the references therein. The PTB standard was previously compared with the BIPM standard in an indirect comparison carried out in 1999, the results of which are reported in Burns *et al* (2002). 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} (BIPM)[b]	1.2930 kg m^{-3}	0.0001
ρ_{air} (PTB)[c]	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] Density of dry air at T_0 = 273.15 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 Faßkammer
Aperture diameter / mm	9.939	10.016
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	15759.0
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

$$N_K = \frac{\dot{K}}{I_{\text{tr}}} \tag{2}$$

where $\dot{K}$ is the air-kerma rate determined by the standard using (1) and I_{tr} is the ionization current measured by the transfer instrument and the associated current-measuring system. The current I_{tr} is corrected to the standard conditions of air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101.325 kPa and h = 50 %).

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 at each institute, but the half-value layers (HVLs) may differ. 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

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

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

4.2 Details of the transfer instruments

Three cavity ionization chambers belonging to the PTB were used as transfer instruments for the comparison, the same spherical (Exradin) chamber used in the 1999 comparison and two Farmer-type (PTW) thimble chambers new to the present comparison. Their main characteristics are given in Table 3.

Table 3. Main characteristics of the transfer chambers

Chamber type	Exradin A3	PTW TM30013	PTW TM30013
Serial number	169	7045	7046
Geometry	spherical	thimble	
External diameter / mm	19.0	6.95	
Wall material	C552	0.335 mm PMMA + 0.09 mm graphite	
Wall thickness	0.025 cm	0.0565 g cm^{-2}	
Nominal volume / cm^3	3.6	0.6	
Reference point	centre of sphere	on central axis, 13 mm from tip	
Polarizing potential / V	+300[a]	+400[a]	

[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. An aluminium filter of thickness 2.228 mm is added (for all radiation qualities) to compensate for the decrease in attenuation 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 uncertainty of the distribution of repeat air-kerma rate determinations over many months is better than 3 parts in 10^4. The radiation qualities used in the range from 100 kV to 250 kV are those recommended by the CCRI (CCEMRI 1972) 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 better than 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 positioned at the height of the beam axis. The relative humidity is controlled within the range 47% to 53% and consequently no humidity correction is applied to the current measured using transfer instruments.

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 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.

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
Inherent Be filtration / mm	3	3	3	3
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
$(\mu/\rho)_{\text{air}}$ / cm^2 g^{-1}	0.290	0.190	0.162	0.137
$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	0.50	0.50	0.50	0.50

During the calibration of the transfer chambers, measurements using the BIPM standard were 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 air-attenuation coefficients given in Table 4. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard. Ionization current measurements (both for the standard and for transfer chambers) are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each chamber was positioned in the reference plane (1200 mm from the radiation source), with a reproducibility of 0.03 mm. Each transfer chamber was aligned 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 all three transfer chambers was below 1 part in 10^4.

For each transfer chamber and at each radiation quality, two sets of seven measurements were made, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each set was typically below 1 part in 10^4 for the Exradin chamber and below 2 parts in 10^4 for the PTW chambers. Repeat calibrations for PTW chamber 7045 showed a short-term reproducibility of around 3 parts in 10^4. Furthermore, comparison of the Exradin chamber results with those obtained in 1999 for this chamber showed agreement at the level of 2 to 4 parts in 10^4, a remarkable long-term stability. Based on these measurements, an uncertainty component of 3 parts in 10^4 is introduced to account for the short-term reproducibility of the chamber calibration coefficients at the BIPM.

Table 5. Correction factors for the BIPM M-01 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[b]	1.0000	1.0015	1.0047	1.0085	-	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 correction k_dia[b]	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
Radiative loss $1 - g_\mathrm{air}$	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 density measured at the time.

[b] Values for k_e and k_dia adopted in September 2009 (Burns *et al* 2009). The diaphragm correction, described in Burns and Kessler (2009), is evaluated by Monte Carlo calculation and includes the effect of photon transmission and scatter in the diaphragm as well as fluorescence and secondary electron production in the diaphragm.

6. Calibration at the PTB

6.1 The PTB irradiation facility and reference radiation qualities

The x-ray source used for the calibrations at the PTB is of type MGC41, manufactured by YXLON International X-Ray GmbH. The converter-type generators of type MGG43 and MGG42 operate at a frequency of 40 kHz and yield a constant potential that can be varied between 20 kV and 320 kV in steps of 20 V. The bipolar x-ray tube Philips MCN 323 has a tungsten anode with an angle of 22° and a 4 mm beryllium exit window. The high voltage is measured invasively with a frequency compensated voltage divider manufactured at the PTB and traceable to the PTB primary standard for dc high voltage. A high purity Ge spectrometer was used to measure the x-ray spectra from which the characteristic beam parameters shown in Table 6 were deduced. The measured x-ray spectra were also used for the calculation of mean values of the correction factors for the free-air chamber given in Table 7.

The irradiation area at the PTB is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.1 °C. Three thermistors, calibrated with an uncertainty of 20 mK, measure, respectively, the temperature of the air inside the PTB standard and of the ambient air close to the monitor and transfer chamber. The ambient air pressure is measured using a barometer (Setra capacitance-sensing circuit system) calibrated with an uncertainty of 6 Pa. All ionization current measurements are corrected for air temperature and pressure. There is no air humidity control in the laboratory but the relative humidity cannot exceed 60%. Variations in the humidity are taken into account by a type B relative standard uncertainty of 4 parts in 10^4 for the PTB standard (Table 7) and similarly for the transfer chamber calibration (Table 9). No humidity correction is applied to the ionization current measured using transfer instruments.

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	3.506	2.302	2.302	2.302
Additional Cu filtration / mm	-	0.222	0.512	1.590
Al HVL / mm	4.142	-	-	-
Cu HVL / mm	0.157	0.489	1.013	2.482
$(\mu/\rho)_{\mathrm{air}}$ / cm^2 g^{-1}	0.287	0.196	0.168	0.143
$\dot{K}_{\mathrm{PTB}}$ / mGy s^{-1}	0.50	0.50	0.50	0.50

6.2 The PTB standard and correction factors

The defining 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. The polarity correction in the standard was measured previously and is within 5 parts in 10^4 of unity. The relative leakage current was measured to be less than 3 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 factor k_a is evaluated using the mean mass attenuation coefficients $(\mu/\rho)_{\mathrm{air}}$ 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.

Two differences in the PTB and BIPM correction factors are noted. The PTB standard involves the correction factor k_{sh} for the shadow effect of the central collector in the cylindrical free-air chamber design. The PTB correction factor for ionization gain k_{sc} includes not only the effect of scattered photons, but also that of fluorescence photons (treated separately as k_{fl} for the BIPM standard).

Table 7. Correction factors for the PTB Faßkammer standard [a]

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a [b]	1.0168	1.0114	1.0098	1.0083	-	0.0005
Ionization gain k_{sc} [c]	0.9917	0.9936	0.9946	0.9958	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0004	1.0019	-	0.0005
Ion recombination k_s	1.0013	1.0013	1.0013	1.0013	0.0005	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0005	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0010
Shadow effect k_{sh}	1.0005	1.0014	1.0018	1.0029	-	0.0005
Aperture edge transmission k_l	1.0000	1.0000	0.9998	0.9988	-	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0005	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0004
Radiative loss $1 - g_{air}$	0.9999	0.9999	0.9998	0.9997	-	-

[a] Component uncertainties below 0.0002 have been neglected.
[b] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
[c] This corrects for the re-absorption of scattered radiation and fluorescence photons.

6.3 Transfer chamber positioning and calibration at the PTB

The reference point for each transfer chamber was positioned at the reference distance (at the PTB 1000 mm from the radiation source), with a reproducibility of 0.05 mm. Alignment on the beam axis was to an estimated uncertainty of 0.2 mm.

The leakage current was measured before and after each series of five ionization current measurements and a correction made using the mean value. The relative leakage current for each transfer chamber was less than 5 parts in 10^4. The relative standard uncertainty of the sample of five repeat current measurements at each radiation quality was typically about 5 parts in 10^4.

7. Additional corrections to transfer chamber measurements

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

As can be seen from Tables 4 and 6, the air-kerma rates are the same at the two laboratories and so no corrections are applied for ion recombination. 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; any small effect of non-uniformity over the dimensions of the transfer chambers is likely to cancel at the two laboratories.

The PTB field size of 80 mm is smaller than that at the BIPM (98 mm). It is known that transfer chambers respond to changes in field size in a way that free-air chambers do not, so that calibration coefficients can show some sensitivity to field size. Measurements at the PTB under reference conditions (distance 1000 mm, field size 80 mm) were augmented by measurements at a distance of 1200 mm where the field size is 96 mm, conditions close to those at the BIPM. While the results for N_K were not different by more than 5 parts in 10^4, those for the Exradin chamber were systematically higher by around 3 parts in 10^4, while those for the PTW-7045 chamber were lower by around 5 parts in 10^4. As the net effect is of the order of 1 part in 10^3, a standard uncertainty of this amount is included (Table 10).

7.2 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities may 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. Even for the Exradin chamber, whose value for N_K varies by 4% over the energy range, the k_Q factor differs from unity by only 0.05% (for the 100 kV and 180 kV qualities). For this reason, k_Q is taken to be unity for all chambers and qualities, with a negligible uncertainty.

8. Uncertainties

The uncertainties associated with the primary standards are listed in Table 8, those for the transfer chamber calibrations in Table 9 and those for the comparison results $R_{K,\mathrm{PTB}}$ in Table 10. The combined uncertainty for the comparison results presented in Table 10 includes a component of 8 parts in 10^4 arising from the different results obtained for the three transfer chambers and is essentially the r.m.s. value for σ_{mean} of Table 12.

Table 8. Uncertainties associated with the standards

Standard	BIPM		PTB[a]	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Ionization current	0.0002	0.0002	0.0004	-
Volume	0.0001	0.0005	0.0004	-
Positioning	0.0001	0.0001	-	-
Correction factors (excl. k_h)	0.0003	0.0010	0.0009	0.0015
Humidity k_h	-	0.0003	-	0.0004
Physical constants	-	0.0015	-	0.0015
$\dot{K}_{\mathrm{std}}$	0.0004	0.0019	0.0011	0.0022

[a] For the PTB, component uncertainties below 0.0002 have been neglected.

The combined standard uncertainty u_c of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction. Correlation in the values for k_e and k_sc (including k_fl at the BIPM), 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).

Table 9. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		PTB	
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	0.0019	0.0011	0.0022
Positioning of transfer chamber	0.0001	-	0.0002	-
I_{tr}	0.0002	0.0002	0.0005	-
Reproducibility	0.0003	-	0.0005[a]	-
$N_{K,\mathrm{std}}$	0.0005	0.0019	0.0013	0.0022

[a] As noted in Section 9, this represents the reproducibility of the pre- and post-comparison measurements.

Table 10. 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	0.0017[a]
Field size	-	0.0010
Different transfer chambers	-	0.0008
$R_{K,\mathrm{PTB}}$	$u_{\mathrm{c}} = 0.0025$	

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

9. Results and discussion

The calibration coefficients determined at the BIPM and at the PTB before and after the BIPM measurements are given in Table 11. The transfer chamber stability $\sigma_{\mathrm{stab},Q}$ for each radiation quality is evaluated as the relative standard deviation of each pre- and post-BIPM pair. For the two PTW chambers stability is 2 to 3 parts in 10^4 (6 parts in 10^4 for chamber 7045 at 100 kV) and for the Exradin chamber around 1 part in 10^3 (4 parts in 10^4 at 250 kV). This apparent instability of the Exradin chamber does not appear to be inherent in the chamber sensitivity itself; as the BIPM results for this chamber agree with those measured in 1999 (corrected for the changes to the standard in the interim period) at the level of 3 parts in 10^4. Based on the results for all three chambers, an additional uncertainty component of 5 parts in 10^4 is included for reproducibility in Table 9.

The comparison results evaluated using each transfer chamber are given in Table 12. The stability estimate for each transfer chamber, σ_{stab}, is the mean for the four radiation qualities of the values $\sigma_{\mathrm{stab},Q}$ given in Table 11. For each radiation quality, the final comparison result (in bold) is taken as the arithmetic mean of the results for the three transfer chambers (the reasons for not using a weighted mean are discussed below). The value σ_{mean} for each radiation quality is the standard uncertainty of this arithmetic mean. The r.m.s value for σ_{mean} of 8 parts in 10^4 is included in Table 10 as an uncertainty arising from the results for the different transfer chambers.

Table 11. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Transfer chamber PTW TM30013-7045				
$N_{K,\text{PTB}}$ (pre-comp) / Gy μC^{-1}	48.60	48.54	48.51	48.62
$N_{K,\text{BIPM}}$ / Gy μC^{-1}	48.44	48.29	48.28	48.32
$N_{K,\text{PTB}}$ (post-comp) / Gy μC^{-1}	48.64	48.55	48.53	48.61
Chamber stability $\sigma_{\text{stab},Q}$	0.06%	0.02%	0.03%	0.02%
Transfer chamber PTW TM30013-7046				
$N_{K,\text{PTB}}$ (pre-comp) / Gy μC^{-1}	48.31	48.24	48.27	48.37
$N_{K,\text{BIPM}}$ / Gy μC^{-1}	48.17	47.99	47.97	48.08
$N_{K,\text{PTB}}$ (post-comp) / Gy μC^{-1}	48.32	48.26	48.29	48.38
Chamber stability $\sigma_{\text{stab},Q}$	0.02%	0.03%	0.03%	0.02%
Transfer chamber Exradin A3-169				
$N_{K,\text{PTB}}$ (pre-comp) / Gy μC^{-1}	7.746	7.833	7.938	8.066
$N_{K,\text{BIPM}}$ / Gy μC^{-1}	7.739	7.818	7.917	8.035
$N_{K,\text{PTB}}$ (post-comp) / Gy μC^{-1}	7.757	7.845	7.949	8.071
Chamber stability $\sigma_{\text{stab},Q}$	0.10%	0.11%	0.10%	0.04%

The results show the standards to be in general agreement at the level of the expanded uncertainty ($k = 2$) of the comparison of 5.0 parts in 10^3. A slight trend with energy of up to 3 parts in 10^3 is observed.

The present results can be compared to those obtained for the PTB in the comparison carried out in 1999. These results, updated for the changes made to the BIPM standard in the interim period (Burns 2004, Burns *et al* 2009), are shown in the penultimate row of Table 12. The two sets of results agree at the level of 1 to 2 parts in 10^3, those determined from the 1999 measurements being closer to unity. The trend with energy observed in the present results is also apparent in the earlier results, although to a lesser extent.

Common to both comparisons is the Exradin A3-169 chamber, the updated results from 1999 for this chamber being shown in the final row of Table 12. With the exception of the present result at 100 kV, the seven remaining results have a mean of 1.0036, the standard uncertainty of the distribution being only 7 parts in 10^4. The results for the PTW chambers are generally higher, 1.005 to 1.006 (except at 100 kV). In view of the reproducible behaviour of the Exradin chamber over the fifteen-year period, it is considered that it should not be given less weight despite its poorer pre- and post- comparison stability (σ_{stab} in Table 12). For this reason an arithmetic mean, rather than a weighted mean, is used for the final comparison result. Regarding the difference of around 2 parts in 10^3 in the results obtained for the two chamber types, about half of this could be due to the differences in distance and field size at the two laboratories, as noted in Section 7.1. The possibility of ion recombination differences has been eliminated by PTB measurements at a series of dose rates (for the PTW chambers in 2014 and for the Exradin chamber in 1999).

Table 12. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV	σ_{stab}
R_K for PTW TM30013-7045	1.0037	1.0053	1.0050	1.0061	0.0003
R_K for PTW TM30013-7046	1.0029	1.0054	1.0064	1.0061	0.0003
R_K for Exradin A3-169	1.0016	1.0027	1.0033	1.0042	0.0009
$R_{K,\text{PTB}}$	**1.0027**	**1.0045**	**1.0049**	**1.0055**	
σ_{mean}	0.0006	0.0009	0.0009	0.0006	
Updated $R_{K,\text{PTB}}$ from 1999	1.0024	1.0028	1.0039	1.0037	
Updated Exradin R_K from 1999	1.0034	1.0031	1.0047	1.0035	

10. 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 $D_i = (K_i - K_{\text{BIPM},i}) / K_{\text{BIPM},i} = x_\text{i} - 1$ 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, which include the linked results of the corresponding regional key comparison APMP.RI(I)-K3 (Lee *et al* 2008). 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 BIPM key comparison database.

When required, the degree of equivalence between two laboratories i and j can be evaluated by a pair of terms: $D_{ij} = D_i - D_j$ and $U_{ij} = 2u_{ij}$, its expanded uncertainty ($k = 2$), both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j (Burns 2003).

11. 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 be in general agreement at the level of the expanded uncertainty ($k = 2$) of the comparison of 5.0 parts in 10^3. The present results agree at the level of 1 to 2 parts in 10^3 with those of the previous comparison in 1999 when account is taken of changes to the BIPM standard. Tables and graphs of degrees of equivalence, including those for the PTB, are presented for entry in the BIPM key comparison database.

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. Tables formatted as they appear in the BIPM key comparison database; red indicates paricipation in BIPM.RI(I)-K3 and blue in APMP.RI(I)-K3.

100 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	-0.1	6.4
ENEA	4.0	7.2
NRC	-2.1	5.2
NIM	4.3	6.0
BEV	2.5	6.6
VSL	4.5	8.0
NIST	3.0	7.2
NMIJ	-2.5	6.0
LNE-LNHB	0.4	7.8
GUM	0.9	5.6
ARPANSA	3.7	7.6
MKEH	-0.4	6.8
VNIIM	1.4	3.6
PTB	2.7	5.0
INER	3.7	7.8
Nuc. Malaysia	14.2	12.8
DMSc	-3.1	13.4
BARC	8.5	15.2
NMISA	4.5	5.6
KRISS	-8.4	5.2
IAEA	4.3	7.4

135 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	0.5	6.4
ENEA	7.4	7.2
NRC	-0.5	5.2
NIM	1.9	6.0
BEV	4.4	6.6
VSL	3.6	8.0
NIST	0.2	7.2
NMIJ	-3.7	6.0
LNE-LNHB	1.2	7.8
GUM	3.8	5.6
ARPANSA	5.6	7.6
MKEH	0.9	6.8
VNIIM	1.8	3.6
PTB	4.5	5.0
INER	4.3	7.8
Nuc. Malaysia	16.2	12.8
DMSc	4.2	13.4
BARC		
NMISA	2.0	5.6
KRISS	1.1	5.2
IAEA	9.2	7.4

180 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	1.3	6.4
ENEA	2.5	7.2
NRC	-1.6	5.2
NIM	2.0	6.0
BEV	2.8	6.6
VSL	3.3	8.0
NIST	2.1	7.2
NMIJ	-4.8	6.0
LNE-LNHB	-0.1	7.8
GUM	3.5	5.6
ARPANSA	6.0	7.6
MKEH	0.4	6.8
VNIIM	2.6	3.6
PTB	4.9	5.0
INER	6.0	7.8
Nuc. Malaysia	15.0	12.8
DMSc	9.6	13.4
BARC		
NMISA	4.8	5.6
KRISS	6.6	5.2
IAEA	13.1	7.4

250 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
NPL	-0.7	6.4
ENEA	3.8	7.2
NRC	-2.0	5.2
NIM	0.3	6.0
BEV	0.0	6.6
VSL	1.2	8.0
NIST	0.4	7.2
NMIJ	-6.6	6.0
LNE-LNHB	-2.0	7.8
GUM	4.5	5.6
ARPANSA	5.3	7.6
MKEH	0.4	6.8
VNIIM	2.6	3.6
PTB	5.5	5.0
INER	5.5	7.8
Nuc. Malaysia	15.9	12.8
DMSc	13.0	13.4
BARC	14.8	15.2
NMISA	7.5	5.6
KRISS	7.6	5.2
IAEA	14.0	7.4

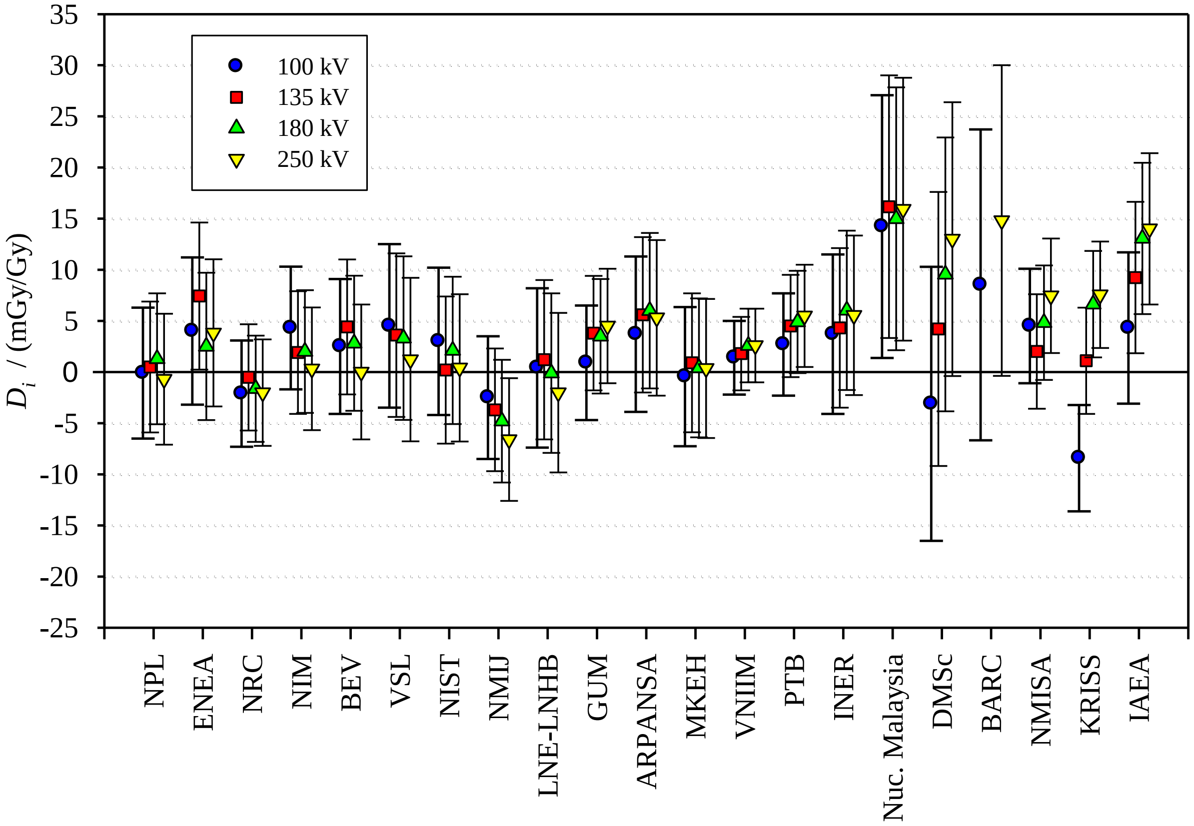

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value

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

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