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Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the NIST, USA 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 NIST, USA and the BIPM in the medium-energy x-ray range. The results show the standards to be in agreement at the level of the standard uncertainty of the comparison of 3.8 parts in 10^3, except at 250 kV where the difference is 1.5 times the standard uncertainty. 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 National Institute of Standards and Technology (NIST), USA, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Three cavity ionization chambers were used as transfer instruments. The measurements at the BIPM took place in May 2016 using the reference conditions recommended by the Consultative Committee for Ionizing Radiation (CCRI) (CCEMRI 1972). Final results were supplied by the NIST in November 2016.

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

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

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

[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, a factor 1.0002 is also included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

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 NIST Wyckoff-Attix standard is described in Wyckoff and Attix (1957) and Lamperti and O'Brien (2001) and was previously compared with the BIPM standard in an indirect comparison carried out in 2003, the results of which are reported in Burns and O'Brien (2006). 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]	1.2930 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 both laboratories.

Table 2. Main characteristics of the standards

Standard	BIPM M-01	NIST Wyckoff-Attix
Aperture diameter / mm	9.939	9.999
Air path length / mm	281.5	308
Collecting length / mm	60.004	100.8
Electrode separation / mm	180	200
Collector width / mm	200	268
Measuring volume / mm^3	4655.4	7915
Polarizing voltage / V	+4000	–5000

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

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

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 and pressure chosen for the comparison (T = 293.15 K, P = 101.325 kPa). No humidity correction has been applied to the current measured using the transfer instruments, on the basis that both measurement laboratories are operated with a relative humidity in the range from 35 % to 65 %.

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 spherical cavity ionization chambers belonging to the NIST were used as transfer instruments for the comparison, the same three chambers used in the 2003 comparison. Their main characteristics are given in Table 3.

Table 3. Main characteristics of the transfer chambers

Chamber type	Shonka-Wyckoff	Shonka-Wyckoff	Exradin A3
Serial number	2022	2023	260
Geometry	spherical	spherical	spherical
External diameter / mm	19.1	19.1	19.5
Wall material	C552	C552	C552
Wall thickness / mm	0.25	0.25	0.25
Nominal volume / cm^3	3.6	3.6	3.6
Reference point	centre of sphere	centre of sphere	centre of sphere
Polarizing potential / V	–300[a]	–300[a]	–300[a]

[a] Potential of the chamber wall with respect to the central 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 around 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 positioned at the height of the beam axis. The relative humidity is controlled within the range 40 % to 50 %.

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

[a] Measured at the BIPM for an air path length of 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 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. 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 mass attenuation coefficients for air 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 each transfer chamber 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 pair was below 2 parts in 10^4. Repeat calibrations for all three chambers (after repositioning) showed a reproducibility below 2 parts in 10^4, which is included in Table 11 for the short-term reproducibility of the calibration coefficients determined 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	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	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 the BIPM reference conditions of 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

6. Calibration at the NIST

6.1 The NIST irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the NIST comprises a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 3 mm beryllium. No transmission monitor is used. The characteristics of the NIST realization of the CCRI comparison qualities (CCEMRI 1972) are given in Table 6.

A calibrated thermistor was used to measure the ambient air temperature. Air pressure was recorded using a calibrated barometer positioned at the approximate height of the beam axis. The relative humidity in the NIST measurement area was controlled in the range from 35 % to 55 %.

6.2 The NIST standard and correction factors

The defining plane for the NIST standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.1 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 70 mm for all radiation qualities. During the calibration of the transfer chambers, measurements using the NIST standard were made using negative polarity only. No polarity correction has been applied. An uncertainty component of 1 part in 10^3 is included for the polarity effect. The relative leakage 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 NIST standard, together with their associated uncertainties, are given in Table 7. The correction factor k_a is evaluated using the measured mass attenuation coefficients for air given in Table 6; note that these values are for the NIST reference temperature of 295.15 K. 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.

Table 6. Characteristics of the NIST reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.248	1.060	3.842	3.842
Additional Cu filtration / mm	-	0.265	0.482	1.618
Al HVL / mm	3.943	-	-	-
Cu HVL / mm	0.149	0.496	1.003	2.502
$(\mu/\rho)_{air}$ [a]/ $cm^2\ g^{-1}$	0.409	0.225	0.212	0.149
$\dot{K}_{NIST}$ / $mGy\ s^{-1}$	0.97	0.96	1.19	1.50

[a] Measured at the NIST for an air path length of 308 mm.

6.3 Transfer chamber positioning and calibration at the NIST

The reference point for each transfer chamber was positioned at the reference distance (at the NIST 1000 mm from the radiation source), with a reproducibility of 0.1 mm. Alignment on the beam axis was 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 less than 1 part in 10^4. The relative standard uncertainty of the calibration coefficient for each transfer chamber at each radiation quality was typically 3 parts in 10^4.

7. Additional corrections to transfer chamber measurements

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

As can be seen from Tables 4 and 6, the air-kerma rates at the NIST are up to three times higher than those at the BIPM. Thus volume recombination effects will be greater for the transfer chamber calibrations at the NIST, although no recombination corrections have been applied at either laboratory. Additional measurements at the BIPM using the Exradin chamber at different air-kerma rates showed the effect to be not more than 2 parts in 10^4 when increasing from 0.2 mGy s^{-1} to 0.6 mGy s^{-1}. Based on these results, an uncertainty component of 5 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 fields. For the spherical chambers used, the effective diameter[2] is similar to the diameter of the free-air chamber apertures used and the relative correction required would be less than 1 part in 10^4. No additional uncertainty component is included.

The reference distance is 1000 mm at the NIST and 1200 mm at the BIPM, and the field diameter is smaller, 70 mm at the NIST and 98 mm at the BIPM. It is known that transfer chambers respond to scattered radiation in a way that free-air chambers do not, so that calibration coefficients can show some sensitivity to field size. However, the difference in field size is not large and the magnitude of field-size effects, at least for thimble chambers, is relatively small. An uncertainty component of 5 parts in 10^4 is introduced in Table 12 for this effect.

Table 7. Correction factors for the NIST standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a [a]	1.0152	1.0083	1.0079	1.0055	0.0012	0.0002
Photon scatter k_sc	0.9942	0.9952	0.9958	0.9969	-	0.0007
Fluorescence k_fl	0.9981	0.9991	0.9995	0.9999	-	0.0003
Electron loss k_e	1.0000	1.0006	1.0027	1.0055	-	0.0005
Ion recombination k_s	1.0004	1.0004	1.0004	1.0004	0.001	-
Polarity k_pol	1.0000	1.0000	1.0000	1.0000	0.001	-
Field distortion k_d	1.0015	1.0015	1.0015	1.0015	-	0.002
Aperture edge transmission k_l	1.0000	1.0000	1.0000	1.0000	-	0.0004
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	-	0.0001
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
Radiative loss $1 - g_\mathrm{air}$	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] Values for the NIST reference conditions of 295.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

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, depending on the energy response of the transfer chamber. From Tables 4 and 6 it is evident that the BIPM and NIST radiation qualities are reasonably matched in terms of HVL, and the energy dependence of the transfer chambers is sufficiently small, such that the required correction is at most 5 parts in 10^4 with a mean value of 2 parts in 10^4. Consequently, k_Q is taken to be unity for all chambers and qualities, with a standard uncertainty of 4 parts in 10^4 included in Table 12.

[2] It can be shown that beam non-uniformity for spherical chambers can be treated as for a flat chamber (or a free-air chamber aperture) by replacing the true diameter with an effective diameter that is smaller by the factor $\sqrt{(2/5)}$.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{NIST}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8. The values $N_{K,\mathrm{NIST}}$ measured before and after the measurements at the BIPM give rise to the relative standard uncertainties $s_{\mathrm{tr},1}$, $s_{\mathrm{tr},2}$ and $s_{\mathrm{tr},3}$ for the three chambers, which represent the uncertainty in N_K arising from transfer chamber stability.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Shonka 2022				
$N_{K,\mathrm{NIST}}$ (pre-comp) / Gy μC^{-1}	8.341	8.415	8.541	8.661
$N_{K,\mathrm{NIST}}$ (post-comp) / Gy μC^{-1}	8.329	8.394	8.518	8.636
$s_{\mathrm{tr},1}$ (relative) [a]	0.0009	0.0016	0.0018	0.0019
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	8.360	8.435	8.553	8.698
Shonka 2023				
$N_{K,\mathrm{NIST}}$ (pre-comp) / Gy μC^{-1}	8.420	8.464	8.581	8.692
$N_{K,\mathrm{NIST}}$ (post-comp) / Gy μC^{-1}	8.415	8.458	8.569	8.675
$s_{\mathrm{tr},2}$ (relative) [a]	0.0004	0.0005	0.0009	0.0013
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	8.446	8.498	8.605	8.739
Exradin A3 260				
$N_{K,\mathrm{NIST}}$ (pre-comp) / Gy μC^{-1}	7.941	8.023	8.117	8.180
$N_{K,\mathrm{NIST}}$ (post-comp) / Gy μC^{-1}	7.944	8.030	8.112	8.181
$s_{\mathrm{tr},3}$ (relative) [a]	0.0002	0.0006	0.0004	0.0001
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	7.943	8.042	8.131	8.223

[a] For each pre-post pair of $N_{K,\mathrm{NIST}}$ values with half-difference d, the standard uncertainty of the mean is taken to be $s_{\mathrm{tr},i} = d / \sqrt{(n–1.4)}$, where the term $(n–1.4)$ is found empirically to be a better choice than $(n–1)$ to estimate the standard uncertainty for low values of n. For $n = 2$, $s_{\mathrm{tr},i} = 1.3d$.

For each chamber at each radiation quality, the mean of the NIST results before and after the BIPM measurements is used to evaluate the comparison results $N_{K,\mathrm{NIST}} / N_{K,\mathrm{BIPM}}$ given in Table 9. The final results $R_{K,\mathrm{NIST}}$ in Table 9 are evaluated as the mean for the three transfer chambers. For each quality, the corresponding uncertainty s_{tr} is the standard uncertainty of this mean (using again the choice $(n–1.4)$ introduced in the footnote to Table 8), or taken as

$$s_{\mathrm{tr}} = \sqrt{\left(s_{\mathrm{tr},1}^2 + s_{\mathrm{tr},2}^2 + s_{\mathrm{tr},3}^2\right)} / 3 \qquad (4)$$

if this is larger (on the basis that the agreement between the comparison results for transfer chambers should, on average, not be better than their combined stability estimated using $s_{\mathrm{tr},1}$, $s_{\mathrm{tr},2}$ and $s_{\mathrm{tr},3}$ from Table 8). The mean value of s_{tr} for the four qualities, $s_{\mathrm{tr,comp}} = 0.0009$, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 12.

Also given in Table 9 are the results of the previous comparison of the NIST and BIPM standards (Burns and O'Brien 2006), revised for the published changes made to the BIPM standard in 2003 (Burns 2004) and in 2009 (Burns *et al* 2009).

Table 9. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$N_{K,\mathrm{NIST}}$ /$N_{K,\mathrm{BIPM}}$ using Shonka 2022	0.9970	0.9964	0.9973	0.9943
$N_{K,\mathrm{NIST}}$ /$N_{K,\mathrm{BIPM}}$ using Shonka 2023	0.9966	0.9956	0.9965	0.9936
$N_{K,\mathrm{NIST}}$ /$N_{K,\mathrm{BIPM}}$ using Exradin A3 260	0.9999	0.9981	0.9980	0.9948
s_{tr}	0.0012	0.0008	0.0007	0.0008
$R_{K,\mathrm{NIST}}$	**0.9978**	**0.9967**	**0.9973**	**0.9942**
Previous results for $R_{K,NIST}$	*1.0030*	*1.0002*	*1.0021*	*1.0004*

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 $R_{K,\mathrm{NIST}}$ is presented in Table 12. This combined uncertainty 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}, 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).

Table 10. Uncertainties associated with the standards

Standard	BIPM		NIST	
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	0.0017	0.0006
Volume	0.0001	0.0005	0.0004	0.0001
Positioning	0.0001	0.0001	-	0.0001
Correction factors (excl. k_{h})	0.0003	0.0010	0.0019	0.0023
Humidity k_{h}	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}_{\mathrm{std}}$	0.0004	0.0019	0.0025	0.0028

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

Institute	BIPM		NIST	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}_{std}$	0.0004	0.0019	0.0025	0.0028
Positioning of transfer chamber	0.0001	-	-	0.0001
I_{tr}	0.0002	0.0002	0.0003	0.0006
Short-term reproducibility	0.0002	-	- [a]	-
$N_{K,std}$	0.0005	0.0019	0.0026	0.0029

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

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,NIST}/N_{K,BIPM}$	0.0026	0.0025[a]
Ion recombination in transfer chambers	-	0.0005
Field size / distance	-	0.0005
k_Q	-	0.0004
Transfer chambers $s_{tr,comp}$	-	0.0009
$R_{K,NIST}$	u_c = 0.0038	

[a] Takes account of correlation in type B uncertainties as noted in Section 9.

10. Discussion

The comparison results presented in Table 9 show the NIST and BIPM standards to be in agreement at the level of the standard uncertainty of the comparison of 3.8 parts in 10^3, except at 250 kV where the difference is 1.5 times the standard uncertainty. There is nothing in the Monte Carlo corrections for k_e, k_{sc} and k_{fl} to indicate why the result is lower at 250 kV. A set of BIPM calculations for the NIST standard gives values that are within 2 parts in 10^4 for all three parameters at all four energies. Furthermore, the NIST corrections for aperture and wall transmission are unity and if any correction was indeed required it would further reduce the NIST standard at 250 kV.

The only remaining parameter known to have an impact on the energy dependence is the air attenuation correction. It is notable that the NIST values for $(\mu/\rho)_{air}$ in Table 6 (unchanged from the values used for the 2003 comparison) are higher, particularly at 100 kV, than those measured at the BIPM (given in Table 4) and at other NMIs with similar beam qualities in terms of the HVL in copper. It can be shown that the use of the BIPM $(\mu/\rho)_{air}$ values for the NIST standard yields comparison results $R_{K,NIST}$ of 0.994 to 0.995 for all four qualities. While better in terms of energy dependence, these results are farther from unity (although still within two standard uncertainties).

The present results are lower than those obtained during the 2003 comparison, shown in the final row of Table 9, by 4 to 6 parts in 10^3. The results from 2003 have been corrected for the changes made to the BIPM standard in the intervening period. During this period the NIST standard has been reduced by 1 part in 10^3 arising from a different treatment of the polarity effect. The remaining reduction in the results of 3 to 5 parts in 10^3 between 2003 and the present comparison remains unexplained.

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, which include the linked results of the corresponding regional key comparisons APMP.RI(I)-K3 (Lee *et al* 2008) and SIM.RI.(I)-K3 (O'Brien *et al* 2015).

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

12. Conclusions

The key comparison BIPM.RI(I)-K3 for the determination of air kerma in medium-energy x-rays shows the NIST and BIPM standards to be in agreement at the level of the standard uncertainty of the comparison of 3.8 parts in 10^3, except at 250 kV where the difference is 1.5 times the standard uncertainty. These results are 4 to 6 parts in 10^3 lower than those obtained for the previous comparison in 2003.

Tables and graphs of degrees of equivalence, including those for the NIST, are presented for entry in the BIPM key comparison database. Note that the data presented in the tables, 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 (KCDB 2016).

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, blue in APMP.RI(I)-K3 and green in SIM.RI(I)-K3.

Lab i	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)
NPL	-0.1	6.4	0.5	6.4	1.3	6.4	-0.7	6.4
NIM	4.3	6.0	1.9	6.0	2.0	6.0	0.3	6.0
LNE-LNHB	0.4	7.8	1.2	7.8	-0.1	7.8	-2.0	7.8
GUM	0.9	5.6	3.8	5.6	3.5	5.6	4.5	5.6
ARPANSA	3.7	7.6	5.6	7.6	6.0	7.6	5.3	7.6
MKEH	-0.4	6.8	0.9	6.8	0.4	6.8	0.4	6.8
VNIIM	1.4	3.6	1.8	3.6	2.6	3.6	2.6	3.6
PTB	2.7	5.0	4.5	5.0	4.9	5.0	5.5	5.0
ENEA	3.9	6.2	4.2	6.2	7.3	6.2	5.6	6.2
BEV	3.2	6.4	4.7	6.4	4.1	6.4	1.1	6.4
NRC	3.1	6.6	2.3	6.6	1.3	6.6	0.4	6.6
NMIJ	-0.8	6.2	-1.4	6.2	-2.4	6.2	-3.7	6.2
VSL	-1.0	6.4	-0.4	6.4	0.0	6.4	-2.1	6.4
NIST	-2.2	7.6	-3.3	7.6	-2.7	7.6	-5.8	7.6
INER	3.7	7.8	4.3	7.8	6.0	7.8	5.5	7.8
Nuc. Malaysia	14.2	12.8	16.2	12.8	15.0	12.8	15.9	12.8
DMSc	-3.1	13.4	4.2	13.4	9.6	13.4	13.0	13.4
BARC	8.5	15.2					14.8	15.2
NMISA	4.5	5.6	2.0	5.6	4.8	5.6	7.5	5.6
KRISS	-8.4	5.2	1.1	5.2	6.6	5.2	7.6	5.2
IAEA	4.3	7.4	9.2	7.4	13.1	7.4	14.0	7.4
CNEA	-6.0	14.3	1.1	14.3	2.1	14.3	1.4	14.3
LMNRI/IRD	-9.5	12.1	-9.4	12.1	-8.0	12.1	-8.5	12.1
ININ	-9.3	16.1	-12.1	16.1	-11.1	16.1	-12.0	16.1

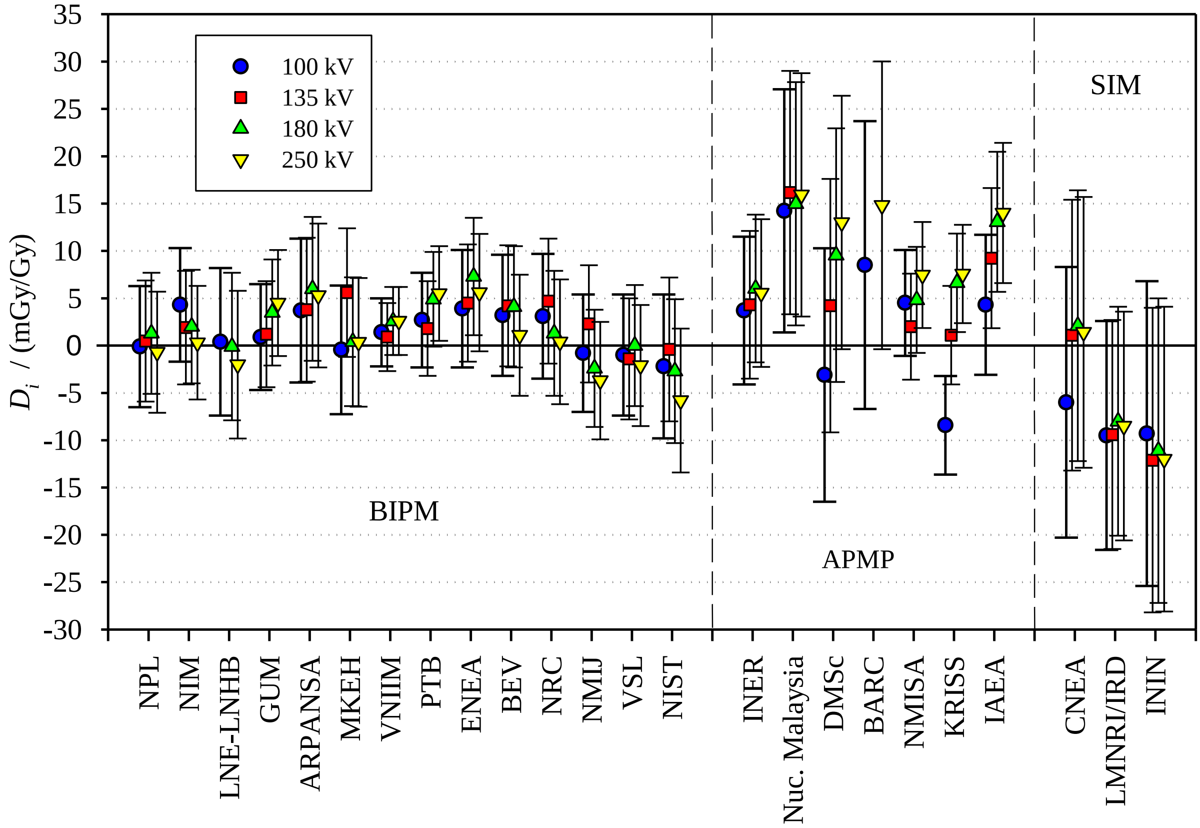

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K3, those in the middle section for the regional comparison APMP.RI(I)-K3 and those to the right for the regional comparison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

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