Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the NPL, UK, 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 NPL, UK, 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 3.4 parts in 10^3, with some evidence of a dependence on radiation quality. 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 Physical Laboratory (NPL), UK, 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 October 2017 using the reference conditions recommended by the CCRI (CCEMRI 1972). Final results were supplied by the NPL in May 2018 and final information on the NPL standard and facilities in November 2018.

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 the 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 is described in Boutillon (1978) and the changes made to

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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 $k_{\mathrm{h}} = 0.9980$. At the BIPM, the reference temperature for ρ_{air} is $T_0 = 273.15$ K and a factor 1.0002 is included to account for the compressibility of dry air between T_0 and T.

certain correction factors in Burns (2004), Burns *et al* (2009) and the references therein. The NPL standard is described in Bass *et al* (2017) and details are given in the reports of previous comparisons with the BIPM in 2007 (Burns *et al* 2017) and in 1997 (Boutillon *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}[b] / kg m^{-3}	1.2930	0.0001
ρ_{air}[c] / kg m^{-3}	1.2045	0.0001
W_{air}/e / J C^{-1}	33.97	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 NPL.

Table 2. Main characteristics of the standards

Standard	BIPM M-01	NPL
Aperture diameter / mm	9.939	10.014
Air path length / mm	281.5	493
Collecting length / mm	60.004	100.258
Electrode separation / mm	180	264
Collector width / mm	200	410
Measuring volume / mm^3	4655.4	7896.3
Polarizing voltage / V	4000	3000

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 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 30 % to 70 %.

To derive a comparison result from the calibration coefficients $N_{K,\text{BIPM}}$ and $N_{K,\text{NMI}}$ 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 from a fit to the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

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

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

4.2 Details of the transfer instruments

Two thimble-type cavity ionization chambers belonging to the NPL were used as transfer instruments for the comparison, one of which (serial number 163) was used in the 2007 comparison. Their main characteristics are given in Table 3.

Table 3. Main characteristics of the transfer chambers

Chamber type	NE 2611	
Serial number	163	134
Geometry	thimble	
External diameter / mm	8.35	8.37
Wall material	graphite	
Nominal volume / cm^3	0.3	
Polarizing voltage / V	–200 [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] / cm^2 g^{-1}	0.290	0.190	0.162	0.137
$\dot{K}_{\mathrm{BIPM}}$ / 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 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. This correction is normally less than 5 parts in 10^4.

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, in the reference orientation, 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 the NE 2611-163 chamber was below 2 parts in 10^4. Leakage for the NE 2611-134 chamber was larger and not constant, introducing variability of the order of 3 parts in 10^4.

For each transfer chamber and at each radiation quality, two sets of ten measurements were made, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each pair was typically below 2 parts in 10^4. Repeat calibrations for both chambers (after repositioning) showed a reproducibility of around 1 part in 10^4 for the

NE 2611-163 and around 3 parts in 10^4 for the NE 2611-134, consistent with its variable leakage current. A value of 3 parts in 10^4 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 $1 - g_{air}$	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 NPL

6.1 The NPL irradiation facility and reference radiation qualities

The NPL medium-energy x-ray laboratory houses a high-stability generator and a tungsten-anode x-ray tube with a 3 mm beryllium window. A transmission monitor is used. The characteristics of the NPL realization of the CCRI comparison qualities (CCEMI 1972) are given in Table 6.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to around 0.3 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the NPL 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 30 % to 70 %.

6.2 The NPL standard and correction factors

The defining plane for the NPL standard was positioned at 750 mm from the radiation source, with a reproducibility of 0.01 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 NPL standard were made using negative polarity only; the polarity effect in the standard is taken into account by the corresponding uncertainty component included in Table 7. The relative leakage current was measured to be around 5 parts in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the NPL 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.

The magnitude of the NPL correction for ion recombination was questioned during the approval process for the present report. For a given air-kerma rate, the value of k_s for a free-air chamber with a given aperture radius and electric-field strength can be reasonably predicted from the ensemble of measured values obtained for free-air chambers. For the NPL standard, this indicates a value close to 1.002, which is significantly higher than the value 1.0007(3) presently in use. This factor is currently under review at the NPL.

Table 6. Characteristics of the NPL reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.5	1.2	1.0	0.9
Additional Cu filtration / mm	-	0.27	0.54	1.77
Al HVL / mm	4.0	-	-	-
Cu HVL / mm	0.15	0.50	1.0	2.5
$(\mu/\rho)_{\text{air}}$ [a]/ $\text{cm}^2\ \text{g}^{-1}$	0.280	0.193	0.162	0.137
$\dot{K}_{\text{NPL}}$ / mGy s^{-1}	1.7	1.7	1.7	1.7

[a] Measured at the NPL using an evacuated tube of length 493 mm.

6.3 *Transfer chamber positioning and calibration at the NPL*

The reference point for each transfer chamber was positioned at the reference distance (at the NPL 750 mm from the radiation source), with a reproducibility of 0.01 mm. Alignment on the beam axis, in the reference orientation, 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 was around 5 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 NPL are a factor of three higher than those at the BIPM. However, for thimble-type chambers, the difference in volume recombination should be small and no correction factors for ion recombination are applied. A corresponding standard uncertainty 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 thimble-type chambers used, the relative correction required would be only a few parts in 10^4 and should be similar at the two laboratories. No additional uncertainty component is included.

The reference distance is 750 mm at the NPL and 1200 mm at the BIPM and the field diameter is correspondingly smaller, 70 mm at the NPL and 98 mm at the BIPM. 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 magnitude of field-size effects for thimble-type 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 NPL standard

Radiation quality	100 kV	135 kV	180 kV	250 kV[a]	u_{iA}	u_{iB}
Air attenuation k_a [b]	1.0168	1.0116	1.0097	1.0082	0.0013	-
Photon scatter k_{sc}	0.9932	0.9945	0.9952	0.9962	0.0010	-
Fluorescence k_{fl}	1.0000	1.0000	1.0000	1.0000	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0012	-	0.0005
Ion recombination k_s [c]	1.0007	1.0007	1.0007	1.0007	0.0003	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0004	-
Field distortion k_d	1.0003	1.0003	1.0003	1.0003	0.0001	-
Aperture edge transmission k_l	1.0000	1.0000	1.0000	1.0000	-	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0003	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0005
Radiative loss $1 - g_{air}$	0.9999	0.9999	0.9998	0.9997	-	0.0002

[a] As the 250 kV quality is not used routinely at the NPL, the correction factors for this quality have not been evaluated explicitly by the NPL. Instead, the overall chamber sensitivity at 250 kV (3.5888 Gy µC^{-1}) is interpolated from the sensitivity at 220 kV and 280 kV. The values stated here for the individual correction factors at 250 kV, notably those with an energy dependence (k_a, k_{sc} and k_e), are the best estimates consistent with this interpolated value for the sensitivity.

[b] Values for the NPL reference conditions of 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

[c] The ion recombination correction is currently under review at the NPL. See text.

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 NPL radiation qualities are closely matched in terms of HVL, and the energy dependence of the transfer chambers is sufficiently small, such that no correction is required. A corresponding uncertainty of 3 parts in 10^4 is included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{NPL}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8. The values $N_{K,\mathrm{NPL}}$ measured before and after the measurements at the BIPM give rise to the relative standard uncertainties $s_{tr,1}$ and $s_{tr,2}$ for the two chambers, which are taken to represent the uncertainty in N_K arising from transfer chamber stability (although this is not distinguishable from the reproducibility of the calibrations at the NPL).

For each chamber at each radiation quality, the mean of the NPL results before and after the BIPM measurements is used to evaluate the comparison results $N_{K,\mathrm{NPL}} / N_{K,\mathrm{BIPM}}$ given in Table 9. The final results $R_{K,\mathrm{NPL}}$ in Table 9 are evaluated as the mean for the two 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

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

if this is larger (on the basis that the agreement between the comparison results for transfer chambers should not, on average, be better than their combined stability estimated using $s_{\mathrm{tr},1}$, and $s_{\mathrm{tr},2}$ from Table 8). The mean value of s_{tr} for the four qualities, $s_{\mathrm{tr,comp}} = 0.0012$, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 12.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
NE 2611 sn 163				
$N_{K,\mathrm{NPL}}$ (pre-comp) / Gy μC^{-1}	90.75	91.35	91.45	91.55
$N_{K,\mathrm{NPL}}$ (post-comp) / Gy μC^{-1}	90.73	91.44	91.44	91.61
$s_{\mathrm{tr},1}$ (relative) [a]	0.0001	0.0006	0.0001	0.0004
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	90.88	91.50	91.73	91.99
NE 2611 sn 134				
$N_{K,\mathrm{NPL}}$ (pre-comp) / Gy μC^{-1}	91.18	92.00	92.40	92.93
$N_{K,\mathrm{NPL}}$ (post-comp) / Gy μC^{-1}	91.30	92.02	92.41	92.89
$s_{\mathrm{tr},2}$ (relative) [a]	0.0009	0.0001	0.0001	0.0003
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	91.03	91.91	92.58	93.31

[a] For each pre-post pair of $N_{K,\mathrm{NPL}}$ 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 $n = 2$, $s_{\mathrm{tr},i} = 1.3d$.

Table 9. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$N_{K,\mathrm{NPL}} / N_{K,\mathrm{BIPM}}$ using NE 2611 sn 163	0.9985	0.9989	0.9969	0.9955
$N_{K,\mathrm{NPL}} / N_{K,\mathrm{BIPM}}$ using NE 2611 sn 134	1.0023	1.0011	0.9981	0.9957
s_{tr}	0.0025	0.0014	0.0008	0.0003
$R_{K,\mathrm{NPL}}$	**1.0004**	**1.0000**	**0.9975**	**0.9956**
Results for $R_{K,\mathrm{NPL}}$ determined in 2007	*1.0002*	*1.0003*	*0.9974*	*0.9956*
Results for $R_{K,\mathrm{NPL}}$ determined in 1997	*0.9999*	*1.0005*	*1.0013*	*0.9993*

Also given in Table 9 are the results of the previous comparison of the NPL and BIPM standards in 2007 (Burns *et al* 2017) and in 1997 (Boutillon *et al* 2002), revised for the published changes made to the BIPM standard in 2003 (Burns 2004) and in 2009 (Burns *et al* 2009). Because of the difficulties experienced in 2007, as described in Burns *et al* 2017, it is the results for the 1997 comparison that currently appear in the BIPM key comparison database (KCDB 2018).

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 $R_{K,\mathrm{NPL}}$ 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.

Table 10. Uncertainties associated with the standards

Standard	BIPM		NPL	
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	0.0012	0.0011
Positioning	0.0001	0.0001	-	-
Volume	0.0001	0.0005	-	0.0001
Correction factors (excl. k_h)	0.0003	0.0010	0.0017	0.0009
Humidity k_h	-	0.0003	-	0.0005
Physical constants	-	0.0015	-	0.0015
$\dot{K}_\mathrm{std}$	0.0004	0.0019	0.0021	0.0021

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

Institute	BIPM		NPL	
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	0.0021	0.0021
I_tr	0.0002	0.0002	0.0007	0.0006
Positioning of transfer chamber	0.0001	-	-	0.0005
Short-term reproducibility	0.0003	-	- [a]	-
$N_{K,\mathrm{lab}}$	0.0005	0.0019	0.0022	0.0022

[a] The reproducibility of the NPL transfer chamber 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.

10. Discussion

The comparison results presented in Table 9 show the NPL and BIPM standards to be in general agreement at the level of the standard uncertainty of the comparison of 3.4 parts in 10^3. The results agree very closely with those obtained in 2007. However, both sets of results show a dependence on radiation quality, amounting to around 5 parts in 10^3 over the range from 100 kV to 250 kV. A possible source of energy dependence is the values adopted for the energy-dependent correction factors, notably k_e, k_{sc}, k_{fl} and the air attenuation correction.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{NPL}}$ / $N_{K,\mathrm{BIPM}}$	0.0023	0.0020[a]
Ion recombination in transfer chambers	-	0.0005
Field size / distance	-	0.0005
k_Q	-	0.0003
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0012	-
$R_{K,\mathrm{NPL}}$	u_c = 0.0034	

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

Burns (2001) used Monte Carlo methods to evaluate k_e, k_{sc} and k_{fl} for a large number of national primary standards, including that of the NPL. The results are summarized in Table 13, from which it can be seen (in the final row) that the energy dependence of 5 parts in 10^3 is largely eliminated if the revised correction factors are used. It might also be noted that, under such a revision, the mean value for $R_{K,\mathrm{NPL}}$ would be around 0.997, still within the standard uncertainty of the comparison.

Table 13. Analysis using revised correction factors for NPL standard

Radiation quality	100 kV	135 kV	180 kV	250 kV
k_e from Burns (2001)	1.0000	1.0000	1.0008	1.0025
k_{sc} from Burns (2001)	0.9923	0.9934	0.9942	0.9957
k_{fl} from Burns (2001)	0.9983	0.9991	0.9994	0.9998
Combined change to NPL standard	0.9974	0.9980	0.9992	1.0006

Table 9 also shows the results of the comparison made in 1997. As noted above, the results for the previous comparisons (1997 and 2007) have been corrected for the changes made to the BIPM standard in the intervening period. No changes have been made to the NPL standard over this period. No explanation has been found for the change in the comparison results between 1997 and 2007. While the use of the revised Monte Carlo correction factors for the NPL standard given in Table 13 largely removes the energy dependence seen in the 2017 and 2007 results, their use introduces an energy dependence in the opposite sense to the otherwise ‘flat’ results of the 1997 comparison seen in Table 9.

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 14 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).

Table 14. 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.

	100 kV		135 kV		180 kV		250 kV	
Lab *i*	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i
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
NIM	**7.2**	6.0	**5.4**	6.0	**6.1**	6.0	**6.0**	6.0
NPL	**0.4**	6.8	**0.0**	6.8	**-2.5**	6.8	**-4.4**	6.8
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

12. Conclusions

The key comparison BIPM.RI(I)-K3 for the determination of air kerma in medium-energy x-rays shows the NPL and BIPM standards to be in general agreement of the level of the standard uncertainty of the comparison of 3.4 parts in 10^3, with some evidence of a dependence on radiation quality that would be largely eliminated if the results of Monte Carlo calculations were used for the energy-dependent correction factors k_e, k_{sc} and k_{fl}.

Tables and graphs of degrees of equivalence, including those for the NPL, 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 2018).

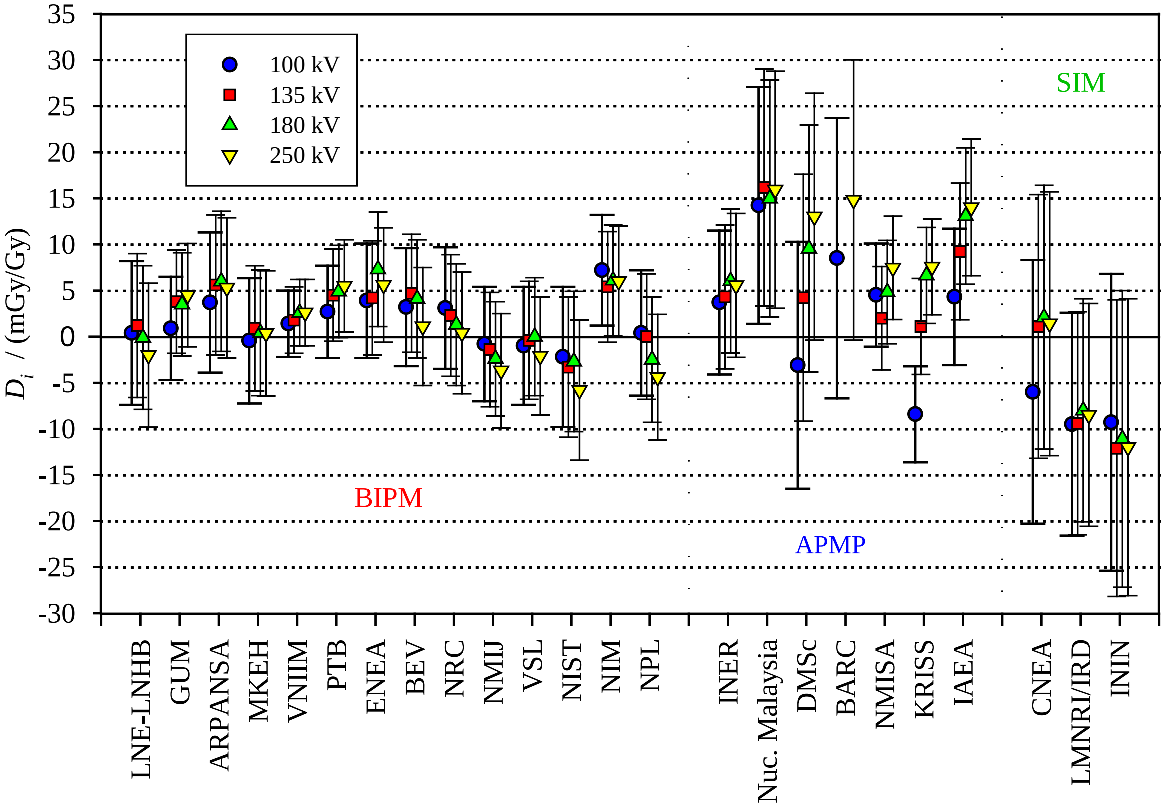

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K3, those in the middle section for the regional comparison APMP.RI(I)-K3 and those to the right for the regional comparison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

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