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

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Abstract A key comparison has been made between the air-kerma standards of the NRC and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement at the level of the combined standard uncertainty of 3.4 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 National Research Council Canada (NRC) and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. Four parallel-plate ionization chambers were used as transfer instruments. The measurements at the BIPM took place in February 2018 using the reference conditions recommended by the CCRI (CCEMRI 1972). Final results were received from the NRC in July 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

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

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 region. The BIPM air-kerma standard is described in Boutillon *et al* (1969) and the changes made to certain correction factors in October 2003 and September 2009 given in Burns (2004), Burns *et al* (2009) and the references therein. Details of the NRC standard are also given in

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[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction $k_{\text{h}} = 0.9980$. At both laboratories, the factor 1.0002 is included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

Boutillon *et al* (1969). The standard was most recently compared with the BIPM standard in an indirect comparison carried out in 2007, the results of which are reported in Burns *et al* (2011). The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

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

Constant	Value	u_i[a]
ρ_{air}[b] (BIPM)	1.2930 kg m^{-3}	0.0001
ρ_{air}[c] (NRC)	1.2045 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 used at the BIPM.
[c] Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa used at the NRC.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	NRC
Aperture diameter / mm	9.941	5.0089
Air path length / mm	100.0	98.98
Collecting length / mm	15.466	46.010
Electrode separation / mm	70	60.96
Collector width / mm	71	69
Measuring volume / mm^3	1200.4	906.62
Polarizing voltage / V	1500	1200

4. The transfer instruments

4.1 Determination of the calibration coefficient for a transfer instrument

The air-kerma calibration coefficient N_K for a transfer instrument is given by the relation

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

where $\dot{K}$ is the air-kerma rate determined by the standard using (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 reference conditions of ambient 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 $N_{K,BIPM}$ and $N_{K,NMI}$ measured, respectively, at the BIPM and at a national measurement 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) might differ. A radiation quality correction factor $k_{Q,NMI}$ is derived for each comparison quality Q. This corrects the calibration coefficient $N_{K,NMI}$ determined at the NMI into one that applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,NMI}$ values in terms of log(HVL). The comparison result at each quality is then taken as

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

In practice, the half-value layers normally differ by only a small amount and $k_{Q,NMI}$ is close to unity.

4.2 Details of the transfer instruments

Four thin-window parallel-plate ionization chambers belonging to the NRC were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The reference plane for the PTW chambers was taken to be that defined by the front surface of the casing, while for the Radcal chambers it was taken to be defined by the red line around the casing.

Table 3. Main characteristics of the transfer chambers

Chamber type	Radcal 10X5-6M	Radcal 10X5-6M	PTW 23344	PTW 23344
Serial number	9646	9642	0948	0949
Window / mg cm^{-2}	0.7	0.7	2.8	2.8
Collector diameter / mm	30	30	13	13
Cavity height / mm	9 [b]	9 [b]	1.5	1.5
Nominal volume / cm^3	6	6	0.2	0.2
Polarizing potential [a] / V	300	300	300	300

[a] At the NRC, a negative polarizing potential is applied to the collector. At the BIPM, the collector must remain at virtual ground potential and a positive polarizing potential was applied to the chamber window.

[b] The Radcal cavity dimensions are not stated by the manufacturer. From radiographic measurements, the collector diameter is known to be around 30 mm, and ionometric measurements confirm the cavity volume of around 6 cm^3 stated by the manufacturer. From these, the cavity height is deduced to be around 9 mm.

5. Calibration at the BIPM

5.1 The BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. A beryllium filter of thickness 2.16 mm is added (for all radiation qualities) so that the half-value layer (HVL) of the present 10 kV radiation quality matches that of the original BIPM x-ray tube when the same aluminium filter is used. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system of the BIPM. Rather than use a transmission monitor, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. The resulting BIPM air-kerma rate determination shows a long-term standard deviation of less than 3 parts in 10^4. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI (CCEMRI 1972) and are given in Table 4 in ascending HVL from left to right.

Note that the reference distance at the NRC is 1000 mm and so for the present comparison the BIPM measurements were also made at a distance of 1000 mm rather than at the usual reference distance of 500 mm.

The irradiation area is temperature controlled between 20 °C and 22 °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. 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 % and consequently no humidity correction is applied to the current measured using transfer instruments.

Table 4. Characteristics of the BIPM reference radiation qualities at 1000 mm

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.2082	0.3723	1.0082	3.989
Al HVL / mm (1000 mm) [a]	0.045	0.191	0.262	1.04	2.28
$(\mu/\rho)_{\mathrm{air}}$ [b] / cm^2 g^{-1} (1000 mm)	11.90	3.23	2.36	0.72	0.38
$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1} (1000 mm)	0.27	0.21	0.22	0.25	0.25

[a] The aluminium HVLs at 1000 mm are not measured, but are derived from the values measured at 500 mm by relative transmission measurements and by calculation using the known x-ray spectrum at each energy. They are used only for the interpolation procedure adopted to obtain the beam-quality correction factors $k_{\mathrm{Q,NRC}}$.
[b] Measured for an air-path length of 100 mm.

5.2 BIPM standard and correction factors

As noted above, for the present comparison the reference plane for the BIPM standard was positioned at 1000 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. Using an additional lead collimator positioned at the filter holder, the beam diameter in the reference plane was 88 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 1.0005 was applied to correct for the known polarity effect in the standard. The leakage current for the BIPM standard was measured to be less than 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 standard uncertainties, are given in Table 5.

The largest correction at low energies is that due to the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. The correction factor k_{a} is evaluated for the reference distance of 1000 mm using the measured mass attenuation coefficients $(\mu/\rho)_{\mathrm{air}}$ for 1000 mm 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 at the time of the measurements. Ionization 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 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 leakage current for the Radcal transfer chambers was always less than 1 part in 10^4. For the PTW chambers, a typical leakage current of 2 fA was measured corresponding in relative terms to around 7 parts in 10^4.

Table 5. Correction factors for the BIPM standard and their associated uncertainties

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA} [a]	u_{iB} [a]
Air attenuation k_a [b] (1 m)	1.1541	1.0397	1.0288	1.0087	1.0046	0.0002	0.0001
Scattered radiation k_{sc}	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.0003
Fluorescence k_{fl}	0.9952	0.9971	0.9969	0.9980	0.9985	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Ion recombination k_s	1.0003	1.0004	1.0004	1.0004	1.0004	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	1.0005	1.0005	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia} [c]	0.9999	0.9995	0.9996	0.9989	0.9984	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] u_{iA} represents the relative standard uncertainty estimated by statistical methods, type A. u_{iB} represents the relative standard uncertainty estimated by other means, type B.

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

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

For each of the four transfer chambers 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 always below 2 parts in 10^4. Repeat measurements for two of the chambers at several qualities showed a reproducibility of 2 to 4 parts in 10^4. An additional relative standard uncertainty component of 5 parts in 10^4 is included (Table 11) to account for the typical reproducibility of calibrations in low-energy x-rays at the BIPM. The calibration coefficients $N_{K,\mathrm{BIPM}}$ are given in Table 8.

6. Calibration at the NRC

6.1 NRC irradiation facility and reference radiation qualities

The low-energy x-ray facility at the NRC comprises a constant-potential low-ripple generator (Glassman PS/PK080N050Y31) and a 100 kV Philips MCN 101 tungsten-anode x-ray tube with an inherent filtration of 1.0 mm beryllium, a focal spot size of 1.5 mm by 1.5 mm and an anode angle of 22°. The generating potential is measured at 3 s intervals using a Park divider calibrated to 3 parts in 10^5, which is constant for a given radiation quality to better than 5 V. The x-ray tube current is stabilized over a wide dynamic range (μA to mA) using a feedback system developed at the NRC that controls the beam current. In relative terms, stability over the short term is approximately 5 parts in 10^5 and long-term stability (0.5 year) around 1 part in 10^3.

A parallel-plate transmission ionization chamber is employed as the primary beam monitor. This monitor chamber is located 34 cm from the focal spot and consists of five layers of aluminized Mylar, totalling 5.6 mg cm^{-2} of Mylar and 0.21 mg cm^{-2} of aluminium. The air temperature for this monitor chamber is measured by a sensor mounted inside the chamber. The x-ray output is switched on and off using a mechanical shutter with a timing uncertainty of approximately 15 ms. The combination of tube current and shutter time serves as a an independent secondary beam monitor. The two beam monitors typically agree at the level of 2 parts in 10^4. The characteristics of the NRC realization of the CCRI comparison qualities (CCEMRI 1972) are given in Table 6.

The irradiation area is temperature controlled at around 22 °C and is stable over the duration of a calibration to better than 0.1 K. A calibrated temperature sensor measures the temperature at the position of the instrument being calibrated, and this temperature generally follows the ambient air temperature to within 0.05 K. The 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 60 % and a humidity correction of nominally 0.998 is calculated, based on Fig. 5.14 of ICRU Report 31 (ICRU 1979), and applied to the calibration measurements.

Table 6. Characteristics of the NRC reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.188	0.344	0.993	4.125
Al HVL / mm	0.041	0.166	0.238	1.022	2.252
$(\mu/\rho)_{air}$[a] / cm^2 g^{-1}	13.50	3.62	2.58	0.841	0.421
$\dot{K}_{NRC}$ / mGy s^{-1}(PTW)	0.52	2.0	1.8	1.8	0.55
$\dot{K}_{NRC}$ / mGy s^{-1}(Radcal)	0.27	0.20	0.35	0.14	0.15

[a] Measured for an air path length of 98.98 mm and for the reference distance of nominally 1000 mm.

6.2 NRC standard and correction factors

The reference plane for the NRC 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 0.2 mm. The beam diameter in the reference plane is approximately 90 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the NRC standard were made using positive polarity only. No polarity correction factor was applied as the polarity effect in the standard measured for each radiation quality is negligible. The leakage current for the NRC standard was measured to be less than 1 part in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the NRC standard, together with their associated uncertainties, are given in Table 7.

The correction factors k_a are evaluated using the measured air-attenuation coefficients 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. Ionization measurements (standard and transfer chambers) are also corrected for variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

6.3 Transfer chamber positioning and calibration at the NRC

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.1 mm. Alignment on the beam axis was to an estimated uncertainty of 0.2 mm.

After each series of measurements, the leakage current was measured with and without load and a leakage correction made using the mean value. The relative leakage current for the Radcal chambers was always less than 4 parts in 10^4 and for the PTW chambers less than 6 parts in 10^4.

For each of the four transfer chambers and at each radiation quality, three or four sets of measurements were made, each measurement with integration time 30 s to 60 s for the Radcal chambers and 60 s to 120 s for the PTW chambers, depending on beam quality. The relative standard uncertainty of the mean ionization current for each set was less than 4 parts in 10^4. The results for $N_{K,\mathrm{NRC}}$ are given in Table 8.

Table 7. Correction factors for the NRC standard and their associated uncertainties

Radiation quality [a]	10 kV	30 kV	25 kV	50 kVb	50 kVa	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a[b] (1 m)	1.1733	1.0439	1.0310	1.0100	1.0050	0.0002	0.0007
Scattered radiation k_{sc}	0.9953	0.9955	0.9957	0.9968	0.9974	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0007
Ion recombination k_s	1.0007	1.0007	1.0007	1.0007	1.0007	0.0001	0.0002
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0015
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0002
Humidity k_h[c]	0.9980	0.9980	0.9980	0.9980	0.9980	0.0001	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

[a] The NRC standard does not presently incorporate corrections for fluorescence or aperture transmission.
[b] Values for 295.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
[c] Nominal values. The actual value of the humidity correction applied to each measurement is based on the humidity measured at the time and the data given in ICRU Report 31 (ICRU 1979).

7. Additional considerations for transfer chamber calibrations

7.1 Ion recombination, polarity, radial non-uniformity and field diameter

As can be seen from Tables 4 and 6, the air-kerma rates for the calibration of the Radcal chamber are similar at the two laboratories. However, for the PTW chamber calibrations at the NRC the air-kerma rate was higher than at the BIPM by up to a factor of 10. From experience with this chamber type, the effect of this increase is not likely to be more than 5 parts in 10^4 and a corresponding uncertainty is included in Table 12.

Each transfer chamber was used with the same polarity at each institute and so no corrections are applied for polarity effects in the transfer chambers.

No correction $k_{\mathrm{rn,tr}}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For a chamber with collector radius 15 mm (Radcal type), $k_{\mathrm{rn,tr}}$ for the BIPM reference fields at 1000 mm is around 1.001 and the effect is likely to be similar for the radiation fields at the NRC. A relative standard uncertainty of 3 parts in 10^4 is introduced for this effect in Table 12.

As the field diameter is similar at the two laboratories (close to 88 mm) no correction is applied. It is noted, however, that this was not the case for the comparison at 1000 mm in 2007, when the BIPM field was defined using a tungsten collimator (placed mid-way between the source and the reference plane) giving a field diameter of 103 mm. To assess the effect of this change, additional measurements were made using the 2007 arrangement, the values for $N_{K,\mathrm{BIPM}}$ for the PTW23344 chamber-type decreasing by up to 3 parts in 10^3 (for the 50 kVa quality). The effect for the Radcal chamber type is much smaller, as is the effect for the lowest qualities. Differences between the 2007 and 2018 comparison results are discussed later.

7.2 Radiation quality correction factors $k_{Q,\mathrm{NMI}}$

As noted in Section 4.1, slight differences in the realizations of the CCRI radiation qualities at the NRC and the BIPM might require a correction factor $k_{\mathrm{Q,NMI}}$. Although the HVL values for the NRC at the reference distance of 1000 mm (Table 6) are reasonably matched to those of the BIPM for the usual reference distance of 500 mm, matching is less good for BIPM measurements at 1000 mm as used for the present comparison (Table 4). Using the HVL values for 1000 mm at each laboratory, interpolation of the N_K values as described in Section 4.1 results in the $k_{Q,\mathrm{NRC}}$ factors given in Table 8. The uncertainty of these values is taken to be 3 parts in 10^4 and included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{NRC}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8 along with the correction factors $k_{Q,\mathrm{NRC}}$ evaluated as described in Section 7.2. The values $N_{K,\mathrm{NRC}}$ measured before and after the measurements at the BIPM give rise to the relative standard uncertainties $s_{\mathrm{tr},1}$, $s_{\mathrm{tr},2}$, $s_{\mathrm{tr},3}$ and $s_{\mathrm{tr},4}$ for the four 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 calibrations at the NRC).

For each chamber at each radiation quality, the mean of the NRC results before and after the BIPM measurements and the corresponding value for $k_{Q,\mathrm{NRC}}$ are combined to evaluate the comparison result $R_{K,\mathrm{NRC}}$ according to Equation (3). The results are given in Table 9. For each quality, the final result in bold in Table 9 is evaluated as the mean for the four transfer chambers. 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

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

if this is larger (on the basis that the agreement between transfer chambers should, on average, not be better than their combined stability estimated using $s_{\mathrm{tr},1}$, $s_{\mathrm{tr},2}$, $s_{\mathrm{tr},3}$ and $s_{\mathrm{tr},4}$ from Table 8). The mean value of s_{tr} for the five qualities, $s_{\mathrm{tr,comp}} = 0.0008$, 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	10 kV	30 kV	25 kV	50 kVb	50 kVa
Radcal 9642					
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	4.844	4.768	4.748	4.807	4.878
$N_{K,\mathrm{NRC}}$ (post-BIPM)	4.837	4.774	4.762	4.823	4.891
$s_{\mathrm{tr},1}$ (relative) [a]	0.0009	0.0008	0.0019	0.0021	0.0017
$N_{K,\mathrm{BIPM}}$	4.827	4.774	4.757	4.809	4.881
$k_{Q,\mathrm{NRC}}$	0.9986	0.9996	1.0000	1.0003	1.0003
Radcal 9646					
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	4.848	4.769	4.751	4.785	4.842
$N_{K,\mathrm{NRC}}$ (post-BIPM)	4.848	4.765	4.749	4.787	4.836
$s_{\mathrm{tr},2}$ (relative) [a]	0.0000	0.0005	0.0003	0.0003	0.0008
$N_{K,\mathrm{BIPM}}$	4.835	4.771	4.751	4.774	4.829
$k_{Q,\mathrm{NRC}}$	0.9986	0.9993	0.9997	1.0002	1.0002
PTW 0948					
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	79.38	76.37	75.85	72.84	71.89
$N_{K,\mathrm{NRC}}$ (post-BIPM)	79.36	76.43	75.84	72.94	71.84
$s_{\mathrm{tr},3}$ (relative) [a]	0.0002	0.0005	0.0001	0.0009	0.0004
$N_{K,\mathrm{BIPM}}$	79.21	76.45	75.87	72.95	71.93
$k_{Q,\mathrm{NRC}}$	0.9975	0.9966	0.9977	0.9996	0.9997
PTW 0949					
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	78.07	76.22	75.88	73.99	73.31
$N_{K,\mathrm{NRC}}$ (post-BIPM)	78.05	76.29	76.00	74.09	73.38
$s_{\mathrm{tr},4}$ (relative) [a]	0.0002	0.0006	0.0010	0.0009	0.0006
$N_{K,\mathrm{BIPM}}$	78.02	76.33	76.00	74.08	73.38
$k_{Q,\mathrm{NRC}}$	0.9985	0.9980	0.9986	0.9997	0.9998

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

Also given in the final row of Table 9 are the results of the 2007 comparison of the NRC and BIPM standards (Burns *et al* 2011, KCDB 2018), made indirectly using the same four transfer chambers.

Table 9. Combined comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$R_{K,\mathrm{NRC}}$ using Radcal 9642	1.0014	0.9990	0.9996	1.0015	1.0010
$R_{K,\mathrm{NRC}}$ using Radcal 9646	1.0013	0.9985	0.9995	1.0027	1.0023
$R_{K,\mathrm{NRC}}$ using PTW 0948	0.9995	0.9959	0.9974	0.9988	0.9988
$R_{K,\mathrm{NRC}}$ using PTW 0949	0.9990	0.9970	0.9978	0.9992	0.9993
s_{tr}	0.0007	0.0008	0.0006	0.0010	0.0009
Final $R_{K,\mathrm{NRC}}$	**1.0003**	**0.9976**	**0.9986**	**1.0006**	**1.0004**
Results of 2007 comparison	*1.0003*	*1.0013*	*1.0007*	*1.0043*	*1.0033*

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 uncertainty for the comparison results $R_{K,\mathrm{NRC}}$ 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. In the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described in Burns *et al* (2003), correlation in the values for the correction factors k_{e}, k_{sc} and k_{fl} are taken into account if the NMI has used values derived from Monte Carlo calculations. This is not presently the case for the NRC standard and consequently no such correlation is assumed.

Table 10. Uncertainties associated with the standards

Standard	BIPM		NRC	
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	0.0003	0.0003
Positioning	0.0001	0.0001	0.0002	0.0001
Volume	0.0003	0.0005	0.0001	0.0004
Correction factors (excl. k_{h})	0.0003	0.0010	0.0002	0.0021
Humidity k_{h}	-	0.0003	0.0001	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0004	0.0026

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

Institute	BIPM		NRC	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}$	0.0005	0.0019	0.0004	0.0026
I_{tr}	0.0002	0.0002	0.0004	0.0015
Positioning of transfer chamber	0.0001	-	0.0002	0.0002
Short-term reproducibility	0.0005	-	0.0010	-
N_K	0.0007	0.0019	0.0012	0.0030

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$	0.0014	0.0029[a]
Ion recombination	-	0.0005
$k_{\mathrm{rn,tr}}$	-	0.0003
$k_{Q,\mathrm{NRC}}$	-	0.0003
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0008	-
$R_{K,\mathrm{NRC}}$	0.0016	0.0030
	u_c = 0.0034	

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

10. Discussion

The comparison results $R_{\mathrm{K,NRC}}$ show the NRC and BIPM standards to agree at the level of the standard uncertainty of the comparison of 3.4 parts in 10^3, with no evidence of any significant dependence on energy.

As noted in Section 7.1, for the indirect comparison made in 2007 the field size at the BIPM was larger, resulting in lower $N_{K,\mathrm{BIPM}}$ values for the PTW chambers by around 3 parts in 10^3 for the 50 kV qualities. Correcting for this effect has the effect of reducing the 2007 comparison results at 50 kV, bringing them closer to the present results by half this amount (as the two Radcal chambers show no significant effect).

It should be noted that after the chamber measurements at the BIPM, but before the comparison results were revealed, the NRC considered changing the 10 kV attenuation correction given by their calibration software (1.1733 at 293.15 K and 101.325 kPa) to the value measured using an attenuation tube (1.1638), as had been done for the 2007 comparison. These two values differ in the main because the evacuation tube used to measure the attenuation has Be windows totalling 1 mm in thickness, which increase the Al HVL (from 0.041 mm to 0.043 mm) and decrease the attenuation correction. As the calibration beam at the NRC does not incorporate this Be (the technique used at the BIPM) it was decided that the higher attenuation correction was appropriate, thus the value 1.1733 given in Table 7. The lower value of 1.1638 used for the 2007 comparison (as given in Table 7 of the report of that comparison, Burns *et al* 2011) yields the same comparison result for 10 kV (as seen in Table 9) due to fortuitous cancellation of the changes in the $N_{K,\mathrm{BIPM}}$ and $N_{K,\mathrm{NRC}}$ values for 10 kV between 2007 and 2018.

11. Degrees of Equivalence

The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described in Burns (2003). Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the key comparison reference value, for each of the CCRI radiation qualities. It follows that for each laboratory i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$. The results for D_i and U_i, expressed in mGy/Gy and including those of the present comparison, are shown in Table 13 and in Figure 1, which include the linked results of the corresponding regional key comparison APMP.RI(I)-K2 (Tanaka *et al* 2014).

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

Table 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. The results in red are for comparison BIPM.RI(I)-K2 and those in blue for APMP.RI(I)-K2.

Lab i	10 kV D_i /(mGy/Gy)	10 kV U_i /(mGy/Gy)	30 kV D_i	30 kV U_i	25 kV D_i	25 kV U_i	50 kVb D_i	50 kVb U_i	50 kVa D_i	50 kVa U_i
NPL	1.1	4.8	-0.3	4.8	1.4	4.8			-0.7	4.8
METAS	2.2	3.4	1.0	3.4	1.3	3.4	0.2	3.4	0.1	3.4
ARPANSA	-1.5	14.0	-2.5	7.5	-2.6	7.5	-1.0	7.5	0.2	7.5
LNE-LNHB	-0.8	3.2	0.2	3.2	0.7	3.2	0.1	3.2	0.7	3.2
NIST			-3.1	8.4	0.0	8.4	1.5	8.4	-2.6	8.4
GUM	-5.1	6.0	-3.7	6.0	-0.1	6.0	-2.8	6.0	0.5	6.0
ENEA	-2.2	3.8	-3.2	3.8	-2.4	3.8	-2.0	3.8	-2.1	3.8
MKEH	-2.7	4.1	-2.5	4.1	-1.2	4.1	-2.6	4.1	-3.4	4.1
VNIIM	-3.2	4.7	-2.1	4.7	-2.2	4.7	-1.3	4.7	-0.7	4.7
VSL	7.8	6.6	6.9	6.6	7.5	6.6	11.5	6.6	13.0	6.6
PTB	0.3	4.3	-1.8	4.3	-2.1	4.3	-1.1	4.3	-0.6	4.3
BEV	-2.0	13.6	-0.8	9.5	-1.3	9.5	-0.8	9.5	-1.6	9.5
NMIJ	3.2	6.0	1.0	6.0	-2.3	6.0	-0.9	6.0	-2.6	6.0
CMI	5.5	7.0	3.9	7.0	4.5	7.0	4.2	7.0	4.4	7.0
NRC	0.3	6.7	-2.4	6.7	-1.4	6.7	0.6	6.7	0.4	6.7
Nuc. Malaysia	42.0	14.0	25.7	14.0	25.9	14.0	34.9	14.0	37.0	14.0
BARC			13.5	100.0	42.8	100.0	30.9	100.0	19.0	100.0
INER	2.8	13.4	8.6	13.4	8.3	13.4	6.4	13.4	10.2	13.4
IAEA	4.5	10.8	2.8	10.8	4.3	10.8	4.9	10.8	4.8	10.8
NIM	14.7	12.4	11.7	12.4	10.7	12.4	7.8	12.4	6.1	12.4

12. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the NRC and BIPM standards to be in agreement at the level of the standard uncertainty of the comparison of 3.4 parts in 10^3. Degrees of equivalence, including those for the NRC, 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.

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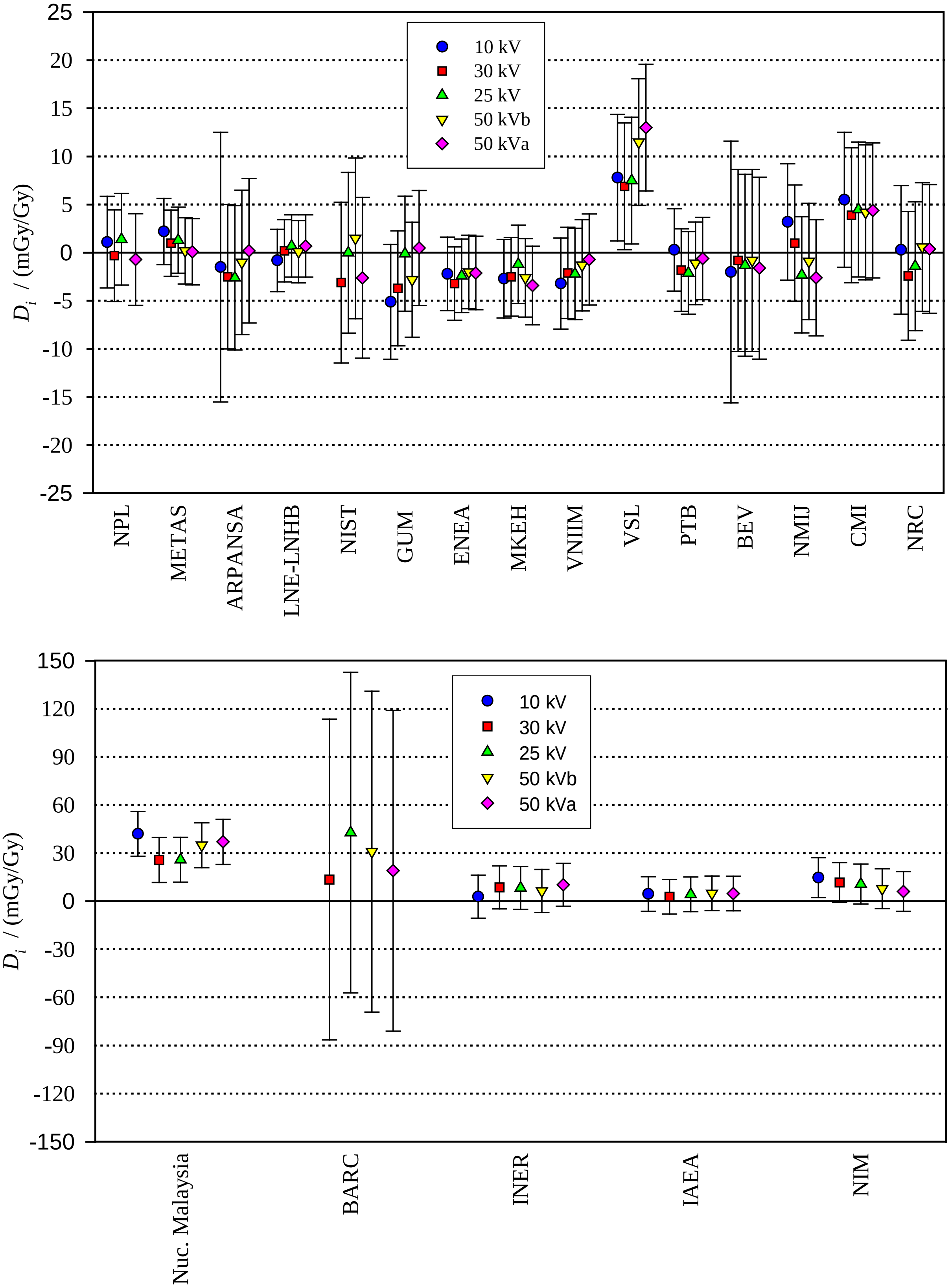

Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value. The top graph shows the results for the comparison BIPM.RI(I)-K2 and the bottom graph those for the regional comparison APMP.RI(I)-K2 (note the expanded ordinate axis for the latter).