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

D.T. Burns, C. Kessler, J.P. McCaffrey*

Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex
* National Research Council, 1200 Montreal Road, Ottawa, Canada,

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 2.8 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 (NRC), Canada 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 March 2007 using the reference conditions recommended by the CCRI [1].

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 $\Pi\, k_i$ 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 [2] and the changes made to certain correction factors in October 2003 and September 2009 given in [3, 4] and the references therein. Details of the NRC standard are given in [5]. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

[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 $k_h = 0.9980$. At the BIPM, the factor 1.0002 is included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

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

Constant	Value	u_i [a]
ρ_{air} [b]	1.293 0 kg m^{-3}	0.000 1
W_{air} / e	33.97 J C^{-1}	0.001 5

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.

Table 2. Main characteristics of the standards

Standard	BIPM	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	1 200.4	906.62
Polarizing voltage / V	1 500	1 200

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

$$N_K = \frac{\dot{K}}{I_{tr}} \qquad (2)$$

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 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

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

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

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 point for each chamber was taken to be on the axis defined by the entrance window. 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	2.5	2.5
Collector diameter / mm	30	30	13	13
Cavity height / mm	8.5	8.5	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 BIPM, the potential was positive and applied to the chamber window, with the collector remaining at virtual ground potential. At the NRC, the potential was negative and applied to the collector with the chamber window remaining at virtual ground potential. In both cases, positive charge was collected.

5. Calibration at the BIPM

5.1 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 variation in the BIPM free-air chamber current over the duration of a comparison is normally not more than 3×10^{-4} in relative terms. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI [1] and are given in Table 4 in ascending HVL from left to right.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.1 °C. Two thermistors, calibrated to a few mK, measure the temperature of the ambient air and the air inside the BIPM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 47 % to 53 % and consequently no humidity correction is applied to the current measured using transfer instruments.

Table 4. Characteristics of the BIPM reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV	10	30	25	50	50
Additional Al filtration / mm	0	0.208 2	0.372 3	1.008 2	3.989
Al HVL / mm (0.5 m)	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{air}$ [a] / cm^2 g^{-1} (0.5 m)	14.83	3.661	2.604	0.753	0.378
$(\mu/\rho)_{air}$ [a] / cm^2 g^{-1} (1 m)	11.90	3.23	2.36	0.72	0.38
$\dot{K}_{BIPM}$ / mGy s^{-1} (0.5 m)	1.00	1.00	1.00	1.00	1.00
$\dot{K}_{BIPM}$ / mGy s^{-1} (1 m)	0.27	0.21	0.22	0.25	0.25

a Measured for an air path length of 100 mm.

5.2 BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 500 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 84 mm for all radiation qualities. As the usual reference distance at the NRC is 1 000 mm, additional measurements were made for this distance at the BIPM. For these measurements, an additional tungsten collimator was used to give a beam diameter of around 100 mm at the greater distance.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using positive polarity only. A correction factor of 1.000 5 was 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 less than 1×10^{-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 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 500 mm using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 4. For the additional measurements at 1 000 mm the measured air-attenuation corrections are also given. 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 relative leakage current for the Radcal transfer chambers was always less than 1×10^{-4}. For the PTW chambers, a typical leakage current of 2 fA was measured corresponding in relative terms to around 2×10^{-4} for the measurements at 500 mm and 1×10^{-3} at 1 000 mm.

Table 5. Correction factors for the BIPM standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a[a] (0.5 m)	1.195 7	1.045 1	1.031 9	1.009 1	1.004 6	0.000 2	0.000 1
Air attenuation k_a[a] (1 m)	1.154 1	1.039 7	1.028 8	1.008 7	1.004 6	0.000 2	0.000 1
Scattered radiation k_{sc}[b]	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.000 3
Fluorescence k_{fl}[b]	0.9952	0.9971	0.9969	0.9980	0.9985	-	0.000 5
Electron loss k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1
Ion recombination k_s	1.000 6	1.000 7	1.000 7	1.000 7	1.000 7	0.000 1	0.000 1
Polarity k_{pol}	1.000 5	1.000 5	1.000 5	1.000 5	1.000 5	0.000 1	-
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 7
Diaphragm effects k_{dia}[c]	0.999 9	0.999 5	0.999 6	0.998 9	0.998 4	-	0.000 3
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.000 1	-
Humidity k_h	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	-	0.000 3
$1 - g_{air}$	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1

a Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
b Values for k_{sc} and k_{fl} adopted in October 2003, based on Monte Carlo calculations.
c Correction factor k_{dia} for diaphragm transmission, scatter and fluorescence adopted September 2009, replacing the factor k_d. See reference [6].

For each of the four transfer chambers and at each radiation quality, a set of seven measurements was made at the usual reference distance of 500 mm, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each set was always below 2×10^{-4}. An additional relative standard uncertainty component of 5×10^{-4} is included to account for the typical reproducibility of calibrations in low-energy x-rays at the BIPM. This procedure (all four chambers at all five radiation qualities) was repeated for the non-standard reference distance of 1 000 mm. The results are shown 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 5×10^{-5} and long-term stability (0.5 year) around 1×10^{-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 [1] 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 [7], 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
$(\mu/\rho)_{\rm air}{}^{\rm a}$ / cm^2 g^{-1}	12.72	3.60	2.56	0.835	0.418
$\dot{K}_{\rm NRC}$ / mGy s^{-1}	0.26	0.20	0.35	0.27	0.18

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 1 000 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. Because the usual reference distance at the BIPM is 500 mm, additional measurements were made for this distance at the NRC. For these measurements, no change was made to the collimation and so the beam diameter was nominally 45 mm (significantly smaller than the BIPM field diameter at this distance).

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 was negligible.

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 $k_{\rm a}$ are evaluated using the measured air-attenuation coefficients given in Table 6. In practice, the values used for $k_{\rm a}$ 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.

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 Radcal chambers was typically 1×10^{-4} and for the PTW chambers around 2×10^{-4}.

For each of the four transfer chamber and at each radiation quality, three or four sets of at least 10 measurements were made at the usual reference distance of 1 000 mm, each measurement with integration time of 30 s to 60 seconds 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 around 2×10^{-4}. This procedure was repeated (all four chamber at all five radiation qualities) for the non-standard reference distance of 500 mm. The results are shown in Table 8.

Table 7. Correction factors for the NRC standard

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] (0.5 m)	1.2175	1.0434	1.0299	1.0101	1.0050	0.0002	0.0007
Air attenuation k_a [b] (1 m)	1.1638	1.0439	1.0310	1.0100	1.0050	0.0002	0.0007
Scattered radiation k_{sc}	0.9953	0.9956	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	-	0.0003
$1 - g_{air}$	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 A humidity correction of nominally 0.998 was applied during each measurement based on the measured humidity at the time and the data given in ICRU Report 31 [7].

7. Additional considerations for transfer chamber calibrations

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

As can be seen from Tables 4 and 6, the air-kerma rates are similar at the two laboratories and so no corrections are applied for ion recombination. 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, the correction factor for the BIPM reference field is around 1.002 and this effect is likely to cancel to some extent at the two laboratories. A relative standard uncertainty of 5×10^{-4} is introduced for this effect.

It is of note that the field diameter of 47 mm at the NRC (at 500 mm) is much smaller than that of 84 mm for the same distance at the BIPM. Measurements at the BIPM over a range of field sizes have shown that under these conditions the calibration coefficient can change by over 1 % for the PTW-23344 chamber-type at the 50 kV(a) quality. For the Radcal chamber type, the effect is much smaller. The effect of this on the present comparison is assessed in the analysis of the results for the different chambers at difference distances presented in Section 8.

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}. However, from Tables 4 and 6 it is evident that the radiation qualities at the BIPM and at the NRC are closely matched in terms of HVL and so the correction factor k_{Q} is taken to be unity for all qualities, with a negligible uncertainty.

8. Comparison results

As the transfer chambers used for this comparison are intended to be used for future comparisons, values for the calibration coefficients are not given and only the ratios $N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ are presented in Table 8.

Table 8. Ratios of calibration coefficients $N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ for the transfer chambers

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
Radcal 9646					
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (1 m)	0.999 3	1.002 2	1.002 4	1.003 5	1.004 5
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (0.5 m)	1.000 2	0.998 8	0.998 7	1.001 9	1.001 4
Radcal 9642					
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (1 m)	0.998 1	1.000 6	0.999 6	1.003 7	1.002 0
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (0.5 m)	1.001 7	0.999 0	0.999 6	1.006 2	1.005 2
PTW 0948					
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (1 m)	0.999 5	1.002 5	1.002 2	1.001 3	0.999 4
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (0.5 m)	1.003 9	1.002 8	1.000 6	1.005 5	1.004 6
PTW 0949					
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (1 m)	0.999 2	1.000 7	0.998 8	1.000 8	0.998 8
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ (0.5 m)	1.002 3	1.000 7	1.000 5	1.004 3	1.003 2

The results are presented graphically in Figure 1 as the ratios $N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ for each transfer chamber at each distance, as a function of log(HVL). The results show a significant spread, the relative standard deviation of the distribution ranging from 1.4×10^{-3} for the 30 kV quality to 2.4×10^{-3} for the 50 kVa quality. This is significantly greater than the statistical standard uncertainty of each calibration coefficient. However, no clear trends emerge, except perhaps that at 10 kV the results for 1 m (dotted lines) are lower than those for 0.5 m (solid lines). This might be related to the attenuation correction; it is of note that the change in k_a at 10 kV between 0.5 m and 1 m is quite different at the two laboratories. The field size effect for the PTW chambers (in red) at 50 kV, anticipated in Section 7.1, appears to have no significant effect on the results within the overall spread.

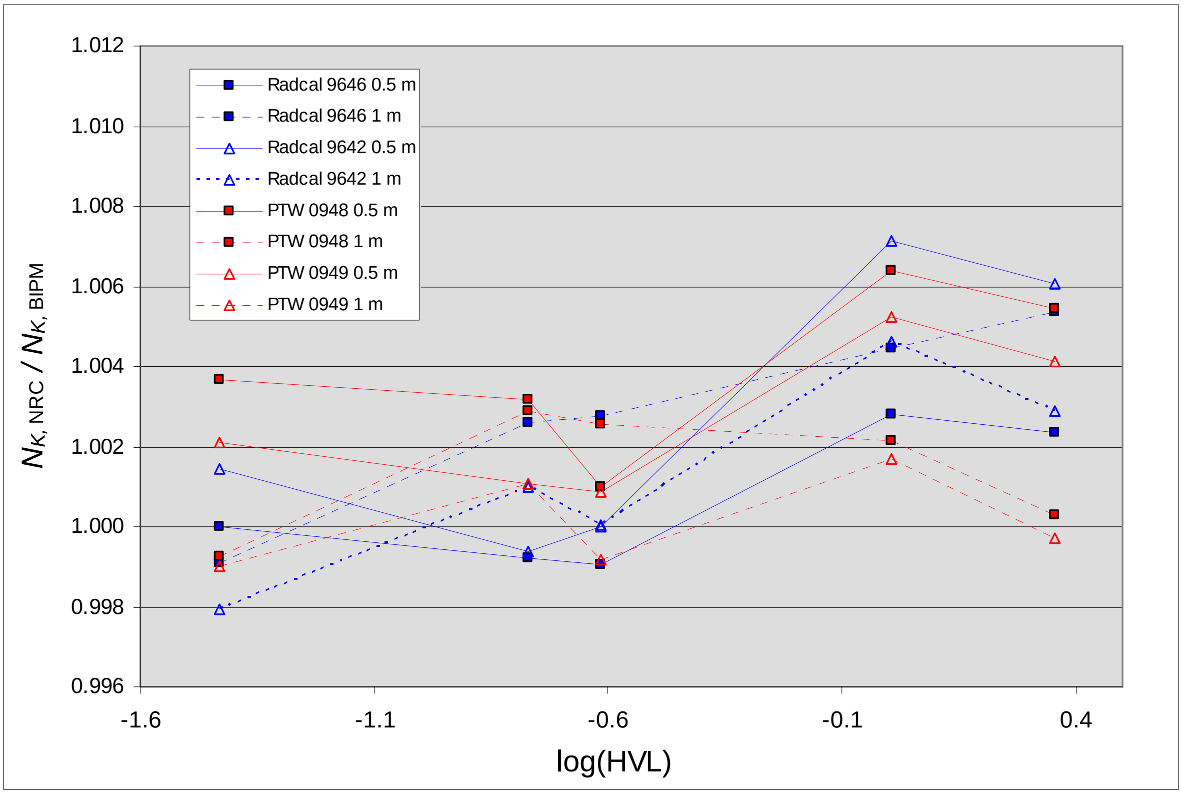

Figure 1. Comparison results $N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ for the four transfer chamber at two reference distances.

Consequently, the best estimate of the comparison result $R_{K,\mathrm{NRC}}$ for each radiation quality is considered to be the mean value. These values are given in Table 9 along with the standard uncertainty of the distribution, σ_{dist}, for the different chambers and the standard uncertainty of each mean value, σ_{mean}. Also given in the table are the results of the previous, direct comparison of the NRC and BIPM standards [5], revised for the published changes made to the BIPM standard in 2003 [3] and in 2009 [4]. The results and combined uncertainties are discussed in Section 10.

Table 9. Combined comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$R_{K,\mathrm{NRC}}$	**1.000 3**	**1.001 3**	**1.000 7**	**1.004 3**	**1.003 3**
σ_{dist}	0.001 9	0.001 5	0.001 4	0.002 0	0.002 4
σ_{mean}	0.000 7	0.000 5	0.000 5	0.000 7	0.000 8
Previous result for $R_{K,\mathrm{NRC}}$	*1.003 5*	*1.002 0*	-	-	*1.001 1*

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 $R_{K,\mathrm{NRC}}$, presented in Table 12, includes a component of 8 parts in 10^4 arising from the spread of the results for the different transfer chambers and distances and is essentially the value for σ_{mean} of Table 9.

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	0.000 2	0.000 2	0.000 3	0.000 3
Volume	0.000 3	0.000 5	0.000 1	0.000 4
Positioning	0.000 1	0.000 1	0.000 2	0.000 1
Correction factors (excl. k_{h})	0.000 3	0.001 0	0.000 2	0.002 1
Humidity k_{h}	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}$	0.000 5	0.001 9	0.000 4	0.002 6

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

Institute	BIPM		NRC	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}$	0.000 5	0.001 9	0.000 4	0.002 6
Positioning of transfer chamber	0.000 1	-	0.000 2	0.000 2
I_{tr}	0.000 2	0.000 2	0.000 2	0.000 2
Short-term reproducibility	0.000 5	-	0.000 5	-
N_K	0.000 7	0.001 9	0.000 7	0.002 6

The combined standard uncertainty u_c of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction. In the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described in [8], 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 12. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$	0.001 0	0.002 4[a]
$k_{\mathrm{rn,tr}}$	-	0.000 5
Results for different chambers and distances	0.000 8	-
$R_{K,\mathrm{NRC}}$	0.001 3	0.002 5
	u_c = 0.002 8	

a Takes account of correlation in type B uncertainties.

10. Discussion

The comparison results presented in Table 9 show general agreement at the level of the combined standard uncertainty of 2.8 parts in 10^3. A slight trend with radiation quality is observed, which might be due in part to the fact that no diaphragm correction k_{dia} is applied to the NRC standard. Interestingly, the implementation of a correction for fluorescence k_{fl} for the NRC standard would increase the dependence of the comparison results on radiation quality. Although agreement with the results of the previous comparison is reasonable, the slight trend with radiation quality is reversed. This might be related to the fact that the present comparison employs transfer chambers whereas the previous comparison was direct. While the use of transfer chambers might introduce more uncertainty in the comparison of the primary standards, useful information is gained on the reproducibility of calibration coefficients, particularly in the present work with the exceptional use of four transfer instruments and two calibration distances.

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 [8]. 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 2.

The degree of equivalence of laboratory i with respect to each laboratory j that has taken part in a BIPM comparison is the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$. The combined standard uncertainty u_{ij} is mainly the combined uncertainty of the air-kerma rate determinations for laboratories i and j. In evaluating each u_{ij}, correlation between the standards is removed, notably that arising from k_e, k_{sc} and k_{fl}. As described in [8], if correction factors based on Monte Carlo calculations are used by both laboratories, or by neither, then half the uncertainty value is taken for each factor. Note that the uncertainty of the BIPM determination of air-kerma rate does not enter in u_{ij}, although the uncertainty arising from the comparison procedure is included. The results for D_{ij} and U_{ij} when j represents the NRC are also given in Table 13 and in Figure 3. 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.

12. Conclusions

The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the NRC and the BIPM to be in general agreement at the level of the standard uncertainty for the comparison of 2.8 parts in 10^3. A slight trend with radiation quality is observed, which is discussed in terms of the correction factors k_{dia} and k_{fl}. The results are in moderately good agreement with those of the previous, direct comparison between the two standards. The exceptional use of four transfer chambers and two calibration distances, while time consuming, adds a degree of robustness to the present comparison. Tables and graphs of degrees of equivalence, including those for the NRC, are presented for entry in the BIPM key comparison database.

Table 13. Degrees of equivalence. For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i, and with respect to laboratory *j* is the difference D_{ij} and its expanded uncertainty U_{ij}. Here *j* represents the NRC. Tables formatted as they appear in the BIPM key comparison database.

10 kV

Lab *i*	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
GUM	-0.9	5.3	-1.2	5.9
VSL	0.0	4.7	-0.3	5.5
NPL	1.1	4.8	0.8	5.6
NIST	-4.4	5.1	-4.7	7.1
METAS	2.2	3.5	1.9	4.7
ENEA	0.0	5.0	-0.3	5.7
VNIIM	-4.0	5.4	-4.3	6.1
PTB	2.8	5.0	2.5	6.7
BEV	-1.2	4.8	-1.5	5.7
MKEH	1.0	4.0	0.7	6.5
NMIJ	0.9	3.6	0.6	5.8
NRC	0.3	5.5		
ARPANSA	-1.5	14.0	-1.8	14.7

30 kV

Lab *i*	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
GUM	-1.0	5.3	-2.3	5.9
VSL	0.1	4.7	-1.2	5.5
NPL	-0.3	4.8	-1.6	5.6
NIST	-5.2	5.1	-6.5	7.1
METAS	1.0	3.5	-0.3	4.7
ENEA	-2.5	5.0	-3.8	5.7
VNIIM				
PTB	-3.1	5.0	-4.4	6.7
BEV	-2.4	4.8	-3.7	5.7
MKEH	0.4	4.0	-0.9	6.5
NMIJ	1.0	3.6	-0.3	5.8
NRC	1.3	5.5		
ARPANSA	-2.5	7.5	-3.8	8.6

25 kV

Lab *i*	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
GUM				
VSL				
NPL	1.4	4.8	0.7	5.6
NIST	-4.9	5.1	-5.6	7.1
METAS	1.3	3.5	0.6	4.7
ENEA	-2.5	5.0	-3.2	5.7
VNIIM	-3.3	5.4	-4.0	6.1
PTB	-1.8	5.0	-2.5	6.7
BEV	-1.2	4.8	-1.9	5.7
MKEH	1.0	4.0	0.3	6.5
NMIJ	3.2	3.6	2.5	5.8
NRC	0.7	5.5		
ARPANSA	-2.6	7.5	-3.3	8.6

50 kVb

Lab *i*	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
GUM	-1.4	5.3	-5.7	5.9
VSL	0.2	4.7	-4.1	5.5
NPL				
NIST	-5.2	5.1	-9.5	7.1
METAS	0.2	3.5	-4.1	4.7
ENEA	-1.6	5.0	-5.9	5.7
VNIIM	-1.6	5.4	-5.9	6.1
PTB	-1.3	5.0	-5.6	6.7
BEV	-1.0	4.8	-5.3	5.7
MKEH	1.6	4.0	-2.7	6.5
NMIJ	4.6	3.6	0.3	5.8
NRC	4.3	5.5		
ARPANSA	-1.0	7.5	-5.3	8.6

50 kVa

Lab *i*	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
GUM	-0.7	5.3	-4.0	5.9
VSL	-2.1	4.7	-5.4	5.5
NPL	-0.7	4.8	-4.0	5.6
NIST	-3.5	5.1	-6.8	7.1
METAS	0.1	3.5	-3.2	4.7
ENEA	-1.8	5.0	-5.1	5.7
VNIIM	-0.1	5.4	-3.4	6.1
PTB	-0.2	5.0	-3.5	6.7
BEV	-1.0	4.8	-4.3	5.7
MKEH	1.2	4.0	-2.1	6.5
NMIJ	5.4	3.6	2.1	5.8
NRC	3.3	5.5		
ARPANSA	0.2	7.5	-3.1	8.6

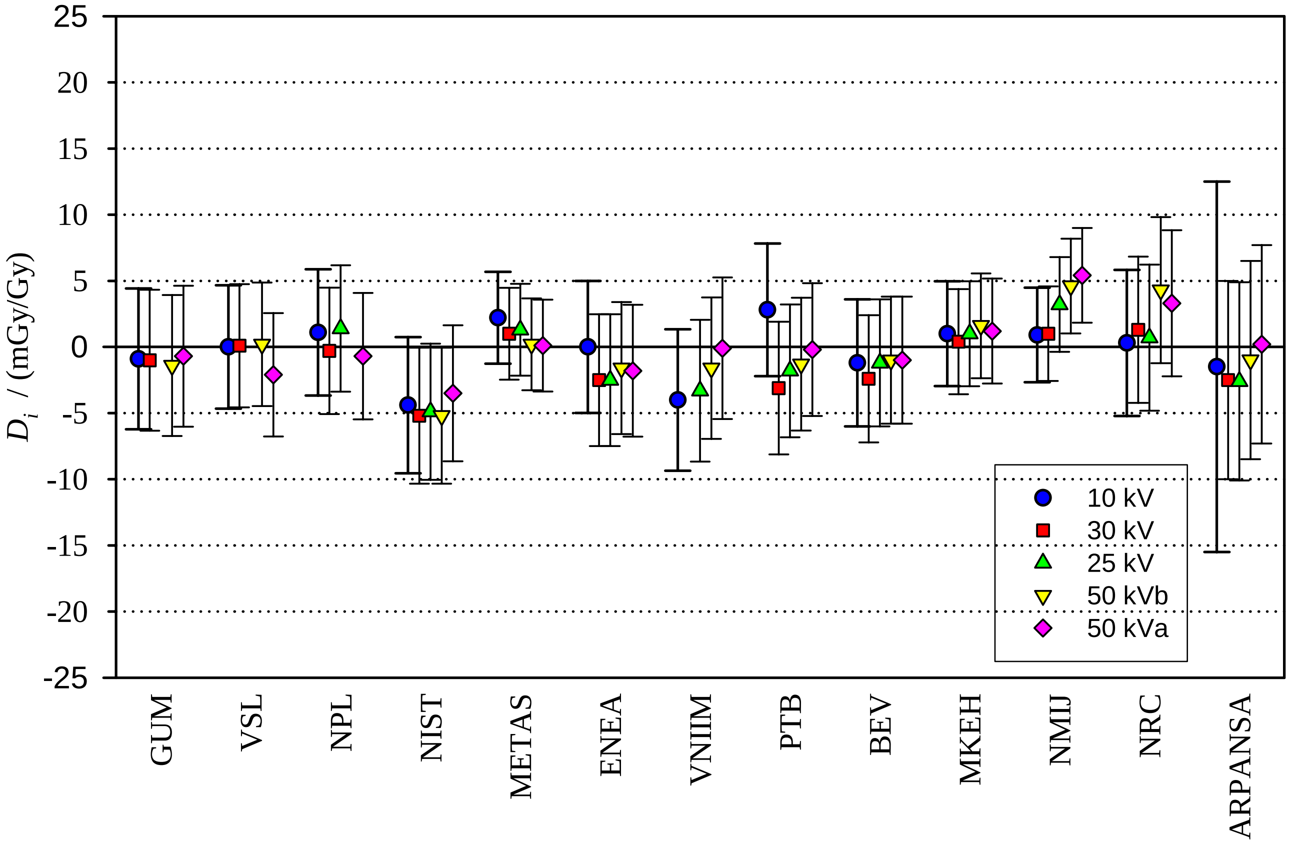

Figure 2. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value

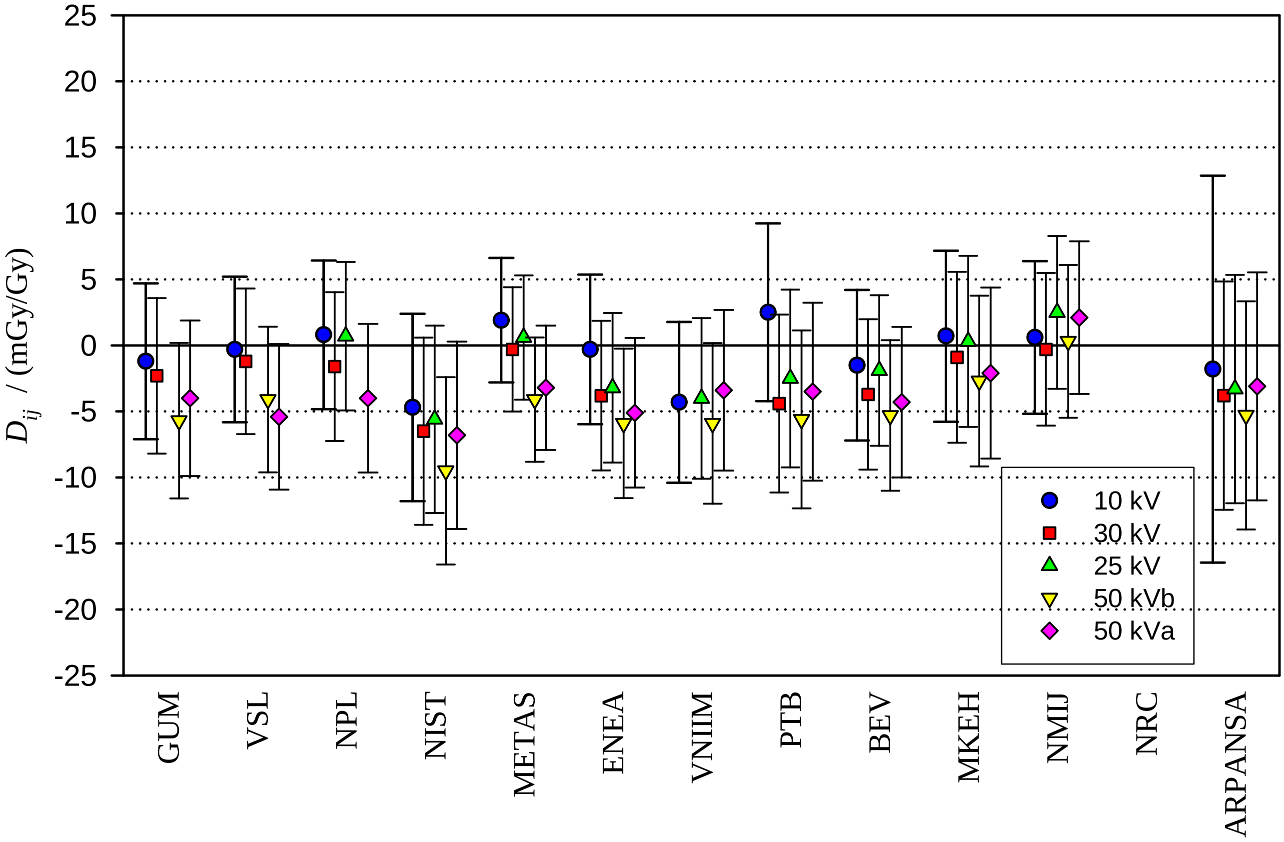

Figure 3. Degrees of equivalence for each NMI *i* with respect to the NRC

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