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Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the ARPANSA 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 ARPANSA 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 7.0 parts in 10^3 for the 10 kV radiation quality and 3.7 parts in 10^3 for all other beam qualities. 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 Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. Two parallel-plate ionization chambers were used as transfer instruments. A third chamber, an ARPANSA transfer free-air chamber, was initially used in the comparison but failed to produce stable results. The measurements at the BIPM took place in November 2008 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 $\Pi\, k_{\text{i}}$ 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 [2] and the changes made to certain

[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction $k_{\text{h}} = 0.9980$. At the BIPM, 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.

correction factors in October 2003 and September 2009 given in [3, 4] and the references therein. Details of the ARPANSA standard are given in [5]. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

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

Constant	Value	u_i [a]
ρ_{air} [b]	1.293 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	ARPANSA
Aperture diameter / mm	9.941	4.9879
Air path length / mm	100.0	85.0
Collecting length / mm	15.466	20.197
Electrode separation / mm	70	60
Collector width / mm	71	80
Measuring volume / mm^3	1 200.4	394.65
Polarizing voltage / V	+1 500	–3 000

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

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

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

4.2 Details of the transfer instruments

Two thin-window parallel-plate ionization chambers belonging to the ARPANSA were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The reference point for each PTW chamber was taken to be on the axis defined by the entrance window. The reference plane for the chambers was taken to be that defined by the front surface of the casing.

Table 3. Main characteristics of the transfer chambers

Chamber type	PTW 23344	PTW 23344
Serial number	0858	0967
Window / mg cm^{-2}	2.5	2.5
Collector diameter / mm	13	13
Cavity height / mm	1.5	1.5
Nominal volume / cm^3	0.2	0.2
Polarizing potential[a] / V	+300	+300

a Potential applied to the chamber window, the collector remaining at virtual ground potential.

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 variation in the BIPM free-air chamber current over the duration of a comparison is normally not more 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 [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	0.037	0.169	0.242	1.017	2.262
$(\mu/\rho)_{air}{}^{a}$ / cm^2 g^{-1}	14.83	3.661	2.604	0.753	0.378
$\dot{K}_{BIPM}$ / mGy s^{-1}	1.00	1.00	1.00	1.00	1.00

a Measured for an air path length of 100 mm.

5.2 The 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.

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, relative to the ionization current, 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 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. 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. For the PTW chambers, a typical leakage current of around 3 fA was measured corresponding to less than 3 parts in 10^4.

For each of the two 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. All calibrations were repeated on subsequent days, after repositioning the chamber, giving rise to the additional uncertainty of 4 parts in 10^4 included in Table 12 to account for the short-term reproducibility of the BIPM measurements. The calibration coefficients are given in Table 9.

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

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a [a] (0.5 m)	1.1957	1.0451	1.0319	1.0091	1.0046	0.0002	0.0001
Scattered radiation k_{sc} [b]	0.9962	0.9972	0.9973	0.9977	0.9979	-	0.0003
Fluorescence k_{fl} [b]	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	1.0006	1.0007	1.0007	1.0007	1.0007	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 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_l for diaphragm transmission only. See reference [6]

6. Calibration at the ARPANSA

6.1 The ARPANSA irradiation facility and reference radiation qualities

The low-energy x-ray facility at the ARPANSA comprises of an RT100 x-ray unit and an AEG50 x-ray unit. Both units have a constant-potential generator and a tungsten-anode tube with an inherent filtration of 1 mm beryllium. The x-ray output is monitored by means of a transmission ionization chamber with transmission thickness of nominally 2 mm of beryllium. Each transfer chamber measurement, relative to the transmission monitor, is followed by a measurement with the standard, also relative to the monitor. At each radiation quality, a set of ten measurements of the standard-to-monitor ratio was made at the reference distance of 500 mm, each measurement with integration time 15 s. The relative standard uncertainty of the mean ratio for each set was around 5 parts in 10^4. The characteristics of the ARPANSA realization of the CCRI comparison qualities [1] are given in Table 6. Note that there are duplicates of the 10 kV and 30 kV radiation qualities from the two x-ray units.

The irradiation area is temperature controlled at around 22 °C and is stable over the duration of a calibration to better than 0.5 °C. Two calibrated thermistors are used to measure the ambient air and monitor chamber temperature at the beginning of each set of measurements. A calibrated thermometer is used to measure the air inside the standard chamber, which in practice agrees with the ambient air temperature to 0.1 °C. Air pressure is measured by means of a calibrated barometer located in a separate partition of the basement laboratory. The pressure variation at different locations in the laboratory introduces a standard uncertainty of 2 parts in 10^4. The relative humidity is measured and falls in the range from 30 % to 70 %. A humidity correction is applied to the current measured using transfer instruments [7].

Table 6. Characteristics of the ARPANSA reference radiation qualities

Radiation quality X-ray tube	10 kV RT	10 kV AEG	30 kV RT	30 kV AEG	25 kV AEG	50 kVb RT	50 kVa RT
Generating potential / kV	10	10	30	30	25	50	50
Additional Al filtration / mm	0	0	0.205	0.205	0.375	1.0	4.0
Al HVL / mm	0.032	0.037	0.166	0.171	0.251	0.97	2.3
$(\mu/\rho)_{air}{}^{a}$ / cm^2 g^{-1}	14.60	13.38	3.701	3.663	2.555	0.820	0.463
$\dot{K}_{ARPANSA}$ / mGy s^{-1}	0.9	1.0	6.7	5.7	1.8	3.7	0.8

a Measured for an air path length of 85.0 mm.

6.2 The ARPANSA standard and correction factors

The reference plane for the ARPANSA standard was positioned at 500 mm from the radiation source, with a reproducibility of 0.3 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.5 mm. The beam diameter in the reference plane is 90 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the ARPANSA standard were made using negative polarity only. The polarity correction was previously measured to be less than 1 part in 10^3 [8]. No polarity correction is applied and a standard uncertainty component of 5 parts in 10^4 is included. The relative leakage current was measured to be 5 parts in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the ARPANSA standard are given in Table 7 and their associated uncertainties in Table 8.

The correction factor k_a is evaluated using the air-attenuation coefficients, measured at a reference distance of 500 mm, 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. The large air-attenuation correction for the 10 kV radiation qualities makes them susceptible to temperature drift during the course of a measurement, leading to a larger uncertainty (see Table 8). 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 ARPANSA

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.3 mm. Alignment on the beam axis was to an estimated uncertainty of 0.5 mm.

For each of the two transfer chambers and at each radiation quality, a set of ten measurements was made at the reference distance of 500 mm, each measurement with integration time 15 s. For each set the relative standard uncertainty of the mean ratio of the transfer chamber current relative to the transmission monitor current was always below 5 parts in 10^4. The leakage current was measured for each series and a correction applied. The relative leakage current for the transfer chambers was around 5 parts in 10^4.

Table 7. Correction factors for the ARPANSA standard

Radiation quality X-ray tube	10 kV RT	10 kV AEG	30 kV RT	30 kV AEG	25 kV AEG	50 kVb RT	50 kVa RT
Air attenuation k_a [a]	1.1613	1.1468	1.0386	1.0382	1.0265	1.0084	1.0048
Scattered radiation k_{sc}	0.9964	0.9964	0.9974	0.9975	0.9975	0.9979	0.9981
Fluorescence k_{fl}	0.9949	0.9949	0.9966	0.9966	0.9968	0.9979	0.9984
Electron loss k_e	1.0000	1.0000	1.0001	1.0001	1.0001	1.0002	1.0004
Ion recombination k_s	1.0005	1.0005	1.0005	1.0005	1.0005	1.0005	1.0005
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Diaphragm transmission k_{tr} [b]	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

a Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
b Monte Carlo evaluation including diaphragm transmission and scatter as well as penetration through the front wall.

Table 8. Uncertainties in the correction factors for the ARPANSA standard

	10 kV		25 kV to 50 kV	
Radiation quality	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Air attenuation k_a	-	0.0060	-	0.0010
Scattered radiation k_{sc}	-	0.0002	-	0.0002
Fluorescence k_{fl}	-	0.0004	-	0.0004
Electron loss k_e	-	0.0003	-	0.0003
Ion recombination k_s	-	0.0001	-	0.0001
Polarity k_{pol}	-	0.0005	-	0.0005
Field distortion k_d	-	0.0005	-	0.0005
Diaphragm transmission k_{tr}	-	0.0001	-	0.0001
Humidity k_h	-	0.0003	-	0.0003
$1 - g_{air}$	-	0.0001	-	0.0001

7. Additional considerations for transfer chamber calibrations

7.1 Saturation, polarity, radial non-uniformity and field size

As can be seen from Tables 4 and 6, for certain radiation qualities there are significant differences in the air-kerma rates at the two laboratories, although no saturation correction factor $k_{s,tr}$ is applied. The effect on the calibration of a PTW 23344 type chamber of an increase in air-kerma rate from 1 mGy s^{-1} to 5 mGy s^{-1} was determined previously at the BIPM to be not more than 5 parts in 10^4 and this is included as an uncertainty component in Table 13.

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 factor $k_{rn,tr}$ is applied at either laboratory for the radial non-uniformity of the radiation fields. For a chamber with collector diameter 13 mm, the correction factor for the BIPM reference field is less than 5 parts in 10^4, and for the ARPANSA reference field a similar correction would apply. A standard uncertainty of 3 parts in 10^4 is introduced in Table 13 for this effect.

The field diameter at ARPANSA of 90 mm is similar to the BIPM field size of 84 mm and no corrections are applied for field size effects.

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 ARPANSA are reasonably matched in terms of HVL. The 10 kV and 30 kV radiation qualities are duplicated on the two x-ray units at the ARPANSA. For each transfer chamber the two 30 kV calibration coefficients agree within the standard uncertainty of 1 part in 10^3 for repeat measurements. Similarly, the two 10 kV calibration coefficients agree within the standard uncertainty of 6 parts in 10^3 for repeat measurements. Consequently, the ARPANSA results presented in Table 9 for these qualities are combined results for the two x-ray tubes and the correction factor k_Q is taken to be unity for all qualities, with no additional uncertainty.

8. Comparison results

The calibration coefficients determined at the BIPM and at the ARPANSA are given in Table 9.

Table 9. Calibration coefficients for the transfer chambers

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
PTW23344-0858					
$N_{K,\text{ARPANSA}}$ (pre-comp) / Gy µC^{-1}	84.40	83.42	83.11	81.65	81.30
$N_{K,\text{BIPM}}$ / Gy µC^{-1}	84.94	83.63	83.34	81.70	81.27
$N_{K,\text{ARPANSA}}$ (post-comp) / Gy µC^{-1}	85.07	83.42	83.08	81.50	81.19
PTW23344-0967					
$N_{K,\text{ARPANSA}}$ (pre-comp) / Gy µC^{-1}	91.95	89.71	89.19	87.81	87.93
$N_{K,\text{BIPM}}$ / Gy µC^{-1}	92.18	89.88	89.33	87.78	87.79
$N_{K,\text{ARPANSA}}$ (post-comp) / Gy µC^{-1}	92.29	89.61	89.09	87.67	87.77

The pre- and post-comparison calibrations at the ARPANSA agree at the level of 2 parts in 10^3 or better, rising to at most 8 parts in 10^3 for the 10 kV quality. These results are consistent with the uncertainties.

The comparison results are summarized in Table 10. The results obtained for the two transfer chambers agree at the level of 1 part in 10^3 or better for the 25 kV to 50 kV qualities. Agreement at the level of 2 parts in 10^3 for the 10 kV quality is better than one might expect from the stated uncertainties. The final comparison results, in bold, are the mean values for the two transfer chambers.

Table 10. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$N_{K,\text{ARPANSA}} / N_{K,\text{BIPM}}$ using PTW23344-0858	0.9976	0.9975	0.9970	0.9985	0.9997
$N_{K,\text{ARPANSA}} / N_{K,\text{BIPM}}$ using PTW23344-0967	0.9994	0.9975	0.9978	0.9995	1.0007
$R_{K,\text{ARPANSA}}$	**0.9985**	**0.9975**	**0.9974**	**0.9990**	**1.0002**

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 11 and those for the transfer chamber calibrations in Table 12.

Table 11. Uncertainties associated with the standards

Standard	BIPM		ARPANSA			
Radiation quality	10 kV to 50 kV		10 kV		25 kV to 50 kV	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.000 2	0.000 2	0.0005	0.0020	0.0005	0.0020
Volume	0.000 3	0.000 5	-	0.0003	-	0.0003
Positioning	0.000 1	0.000 1	-	0.0010	-	0.0010
Correction factors (excl. k_h)	0.000 3	0.001 0	-	0.0061	-	0.0013
Humidity k_h	-	0.000 3	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5	-	0.001 5
$\dot{K}$	0.000 5	0.001 9	0.0005	0.0067	0.0005	0.0030

The combined standard uncertainty u_c of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction. Correlation in the values for the correction factors k_{sc} and k_{fl} at the two laboratories, derived from Monte Carlo calculations in each laboratory, are taken into account in an approximate way by assuming half of the uncertainty value at each laboratory. This is consistent with the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described in [9].

Table 12. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		ARPANSA			
Radiation quality	10 kV to 50 kV		10 kV		25 kV to 50 kV	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}$	0.000 5	0.001 9	0.0005	0.0067	0.0005	0.0030
Positioning of transfer chamber	0.000 1	-	-	0.0010	-	0.0010
I_{tr}	0.000 2	0.000 2	0.0005	0.0020	0.0005	0.0020
Short-term reproducibility	0.000 4	-	-	-	-	-
N_K	0.000 7	0.001 9	0.0007	0.0070	0.0007	0.0038

Table 13. Uncertainties associated with the comparison results

Radiation quality	10 kV		25 kV to 50 kV	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{ARPANSA}}$ / $N_{K,\mathrm{BIPM}}$	0.001 0	0.006 9[a]	0.001 0	0.003 6[a]
$k_{\mathrm{s,tr}}$	-	-	-	0.000 5
$k_{\mathrm{rn,tr}}$	-	0.000 3	-	0.000 3
$R_{K,\mathrm{ARPANSA}}$	0.001 0	0.006 9	0.001 0	0.003 6
u_{c}	0.007 0		0.003 7	

a Takes account of correlation in type B uncertainties.

10. Discussion

The comparison results presented in Table 10 show general agreement between the ARPANSA and BIPM standards at the level of 2 to 3 parts in 10^3, which is within the combined standard uncertainty of 3.7 parts in 10^3 for the 25 kV to 50 kV qualities and well within the combined standard uncertainty of 7 parts in 10^3 for the 10 kV quality. No significant trend with radiation quality is observed.

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 [9]. 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 14 and in Figure 1.

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 [9], 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 ARPANSA, are also given in Table 14 and in Figure 2. 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.

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, and with respect to laboratory j is the difference D_{ij} and its expanded uncertainty U_{ij}. Here j represents the ARPANSA. 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}
NRC	3.5	6.6	5.0	15.1
GUM	-0.9	5.3	0.6	14.6
VSL	0.0	4.7	1.5	14.4
NPL	1.1	4.8	2.6	14.4
NIST	-4.4	5.1	-2.9	14.6
METAS	2.2	3.5	3.7	14.0
ENEA	0.0	5.0	1.5	14.5
VNIIM	-4.0	5.4	-2.5	14.6
PTB	2.8	5.0	4.3	14.5
BEV	-1.2	4.8	0.3	14.4
MKEH	1.0	4.0	2.5	14.2
NMIJ	0.9	3.6	2.4	14.1
ARPANSA	-1.5	14.0		

30 kV

Lab i	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
NRC	2.0	6.6	4.5	9.4
GUM	-1.0	5.3	1.5	8.6
VSL	0.1	4.7	2.6	8.2
NPL	-0.3	4.8	2.2	8.3
NIST	-5.2	5.1	-2.7	8.5
METAS	1.0	3.5	3.5	7.6
ENEA	-2.5	5.0	0.0	8.4
VNIIM				
PTB	-3.1	5.0	-0.6	8.4
BEV	-2.4	4.8	0.1	8.3
MKEH	0.4	4.0	2.9	7.8
NMIJ	1.0	3.6	3.5	7.6
ARPANSA	-2.5	7.5		

25 kV

Lab i	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
NRC				
GUM				
VSL				
NPL	1.4	4.8	4.0	8.3
NIST	-4.9	5.1	-2.3	8.5
METAS	1.3	3.5	3.9	7.6
ENEA	-2.5	5.0	0.1	8.4
VNIIM	-3.3	5.4	-0.7	8.5
PTB	-1.8	5.0	0.8	8.4
BEV	-1.2	4.8	1.4	8.3
MKEH	1.0	4.0	3.6	7.8
NMIJ	3.2	3.6	5.8	7.6
ARPANSA	-2.6	7.5		

50 kVb

Lab i	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
NRC				
GUM	-1.4	5.3	-0.4	8.6
VSL	0.2	4.7	1.2	8.2
NPL				
NIST	-5.2	5.1	-4.2	8.5
METAS	0.2	3.5	1.2	7.6
ENEA	-1.6	5.0	-0.6	8.4
VNIIM	-1.6	5.4	-0.6	8.5
PTB	-1.3	5.0	-0.3	8.4
BEV	-1.0	4.8	0.0	8.3
MKEH	1.6	4.0	2.6	7.8
NMIJ	4.6	3.6	5.6	7.6
ARPANSA	-1.0	7.5		

50 kVa

Lab i	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}
NRC	1.1	6.6	0.9	9.4
GUM	-0.7	5.3	-0.9	8.6
VSL	-2.1	4.7	-2.3	8.2
NPL	-0.7	4.8	-0.9	8.3
NIST	-3.5	5.1	-3.7	8.5
METAS	0.1	3.5	-0.1	7.6
ENEA	-1.8	5.0	-2.0	8.4
VNIIM	-0.1	5.4	-0.3	8.5
PTB	-0.2	5.0	-0.4	8.4
BEV	-1.0	4.8	-1.2	8.3
MKEH	1.2	4.0	1.0	7.8
NMIJ	5.4	3.6	5.2	7.6
ARPANSA	0.2	7.5		

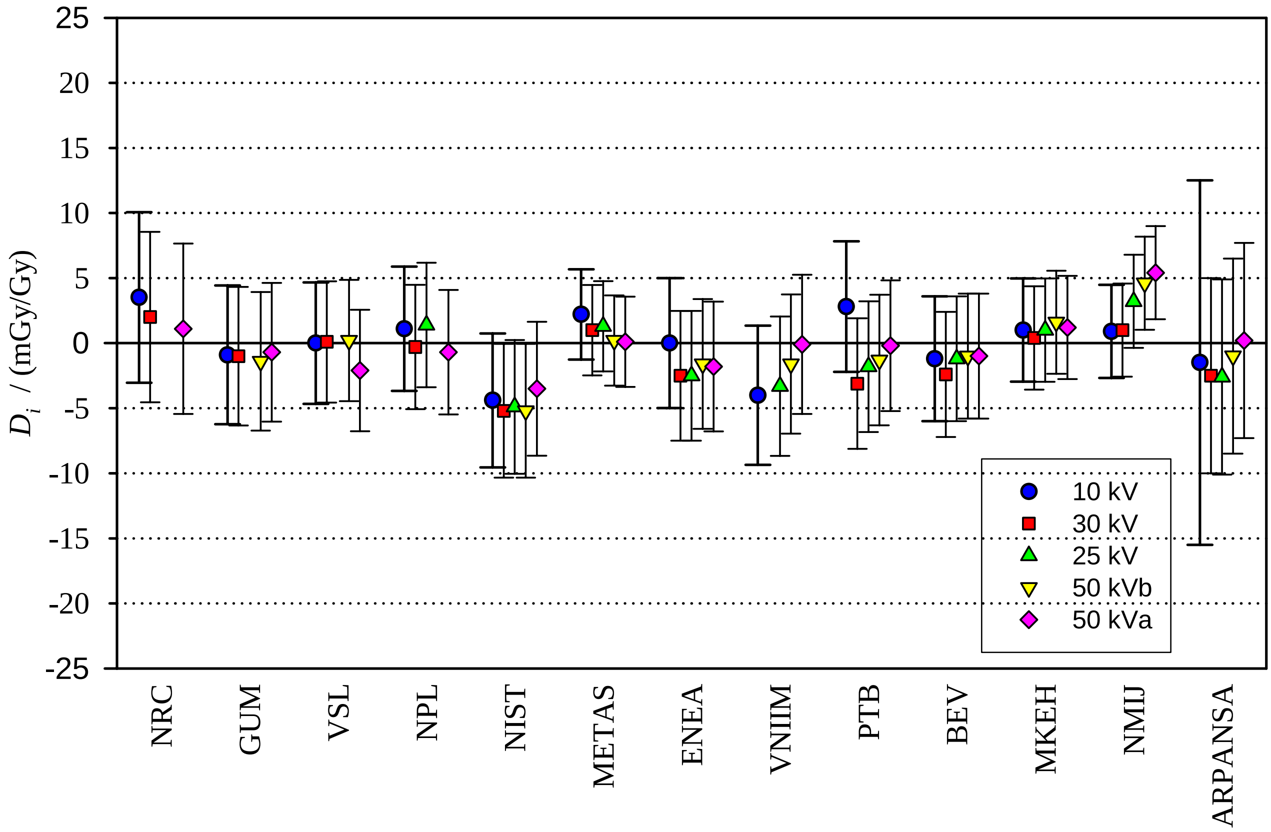

Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value

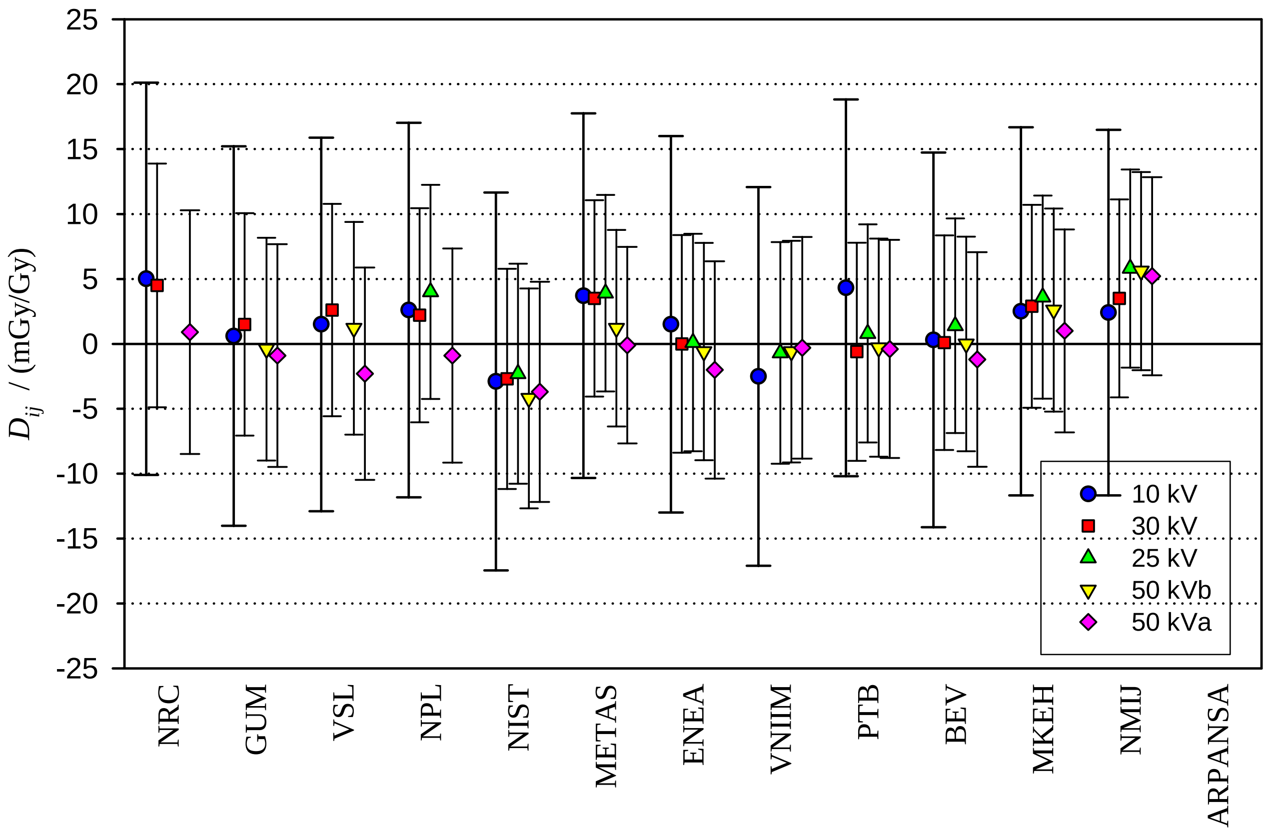

Figure 2. Degrees of equivalence for each NMI *i* with respect to the ARPANSA

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