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Key comparison BIPM.RI(I)-K2 of the air-kerma standards of the GUM, Poland 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 GUM and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement to better than the expanded uncertainty ($k = 2$) for the comparison of 6.0 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 Główny Urząd Miar (GUM), Poland and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. A small parallel-plate free-air ionization chamber was used as the transfer instrument. The measurements at the BIPM took place in May 2010 using the reference conditions recommended by the CCRI [1].

2. Determination of the air-kerma rate

For a free-air ionization chamber primary standard with measuring volume V, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1 - g_{\mathrm{air}}} \prod_i k_i \qquad (1)$$

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost through radiative processes in air, and $\Pi\ k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with 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 GUM standard are given in [5]. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

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[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P and a humidity correction $k_{\mathrm{h}} = 0.9980$. At the BIPM, the 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} / kg m^{-3} (BIPM) [b]	1.293 0	0.000 1
ρ_{air} / kg m^{-3} (GUM) [c]	1.204 5	0.000 1
(W_{air} / e) / J C^{-1}	33.97	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.
c Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	GUM
Aperture diameter / mm	9.941	9.995_5
Air path length / mm	100.0	102.2
Collecting length / mm	15.466	20.273
Electrode separation / mm	70	69.9
Collector width / mm	71	70.4
Measuring volume / mm^3	1 200.4	1 590.8
Polarizing voltage / V	1 500	4 000

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

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

where $\dot{K}$ is the air-kerma rate determined by the standard using (1) and I_{tr} is the ionization current measured by the transfer instrument and the associated current-measuring system. The current I_{tr} is corrected to the reference conditions of ambient air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101325 kPa and h = 50 %).

To derive a comparison result from the calibration coefficients $N_{K,\mathrm{BIPM}}$ and $N_{K,\mathrm{NMI}}$ measured, respectively, at the BIPM and at a national 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 $N_{K,\mathrm{NMI}}$ determined at the NMI into one that applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

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

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

4.2 Details of the transfer instruments

A free-air parallel-plate ionization chamber belonging to the GUM was used as a transfer instrument for the comparison. The same instrument was used for the previous comparison reported in [5] and the main characteristics of the chamber are given in Table 3. The reference plane was taken to be that defined by the inner surface of the diaphragm. To the extent that the radiation qualities at the GUM and the BIPM are not perfectly matched, a correction is required for air attenuation within the chamber using the air-attenuation coefficients measured at each laboratory.

Table 3. Main characteristics of the GUM free-air transfer chamber

Characteristic	Value
Aperture diameter / mm	10
Air path length / mm	40
Collecting length / mm	25
Electrode separation / mm	50
Collector width / mm	47
Measuring volume / mm^3	1 960
Polarizing voltage / V	+2 000

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 2 parts in 10^4 and the standard deviation of repeat air-kerma determinations over the past few years is below 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 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 from 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
$(\mu/\rho)_{\mathrm{air}}{}^{\mathrm{a}}$ / cm^2 g^{-1}	14.83	3.66	2.60	0.75	0.38
$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	1.00	1.00	1.00	1.00	1.00

a Measured for an air path length of 100 mm using a variable-pressure tube.

5.2 The BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 500 mm from the window of the x-ray tube, with a reproducibility of 0.03 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. For chamber calibrations, the beam diameter in the reference plane is 84 mm for all radiation qualities.

During the calibration of the transfer chamber, 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 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 $(\mu/\rho)_{\mathrm{air}}$ 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 the transfer chamber was positioned in the reference plane with a reproducibility of 0.03 mm. The lateral alignment on the beam axis was to an estimated uncertainty of 0.1 mm. The chamber temperature was measured with an uncertainty below 0.1 °C using a BIPM mercury thermometer placed in the hole designed for this purpose. The leakage current was measured before and after each series of ionization current measurements and was always less than 1 part in 10^4.

For each radiation quality, two sets of seven measurements were made, each measurement with integration time 60 s. The standard uncertainty of the mean ionization current for each set was always below 2 parts in 10^4. Repeat measurements were made at the 10 kV and 30 kV radiation qualities. Based on these results and on experience of chamber calibrations in low-energy x-rays at the BIPM, an additional standard uncertainty component of 5 parts in 10^4 is included to account for the reproducibility of the calibrations. The results are shown in Table 8.

Table 5. Correction factors for the BIPM FAC-L-01 standard

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]	1.195 7	1.045 1	1.031 9	1.009 1	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
$1 - g_\mathrm{air}$	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_l. See reference [6].

6. Calibration at the GUM

6.1 The GUM irradiation facility and reference radiation qualities

The low-energy x-ray facility at the GUM comprises a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 2.5 mm aluminium. The x-ray output is monitored by means of a transmission ionization chamber whose windows of graphited cellophane foil introduce a filtration of 1.0 mg cm^{-2}. The resulting variation in the GUM free-air chamber current is normally around 4 parts in 10^4 for a series of chamber calibrations. The characteristics of the GUM realization of the CCRI comparison qualities [1] are given in Table 6.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 2 °C. Two PT-401 thermometers are used to measure the temperature of the ambient air and the air inside the standard. The air pressure is measured by means of a calibrated PTB-220 barometer positioned at the height of the beam axis. The relative humidity is controlled within the range from 30 % to 60 % and consequently no humidity correction is applied to transfer chamber calibrations.

Table 6. Characteristics of the GUM 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	0.019	0.219	0.377	1.055	3.993
Al HVL / mm	0.037	0.164	0.240	1.022	2.266
$(\mu/\rho)_{\mathrm{air}}{}^{\mathrm{a}}$ / cm^2 g^{-1}	14.75	3.649	2.677	0.738	0.360
$\dot{K}_{\mathrm{GUM}}$ / mGy s^{-1}	2.3	9.9	3.2	3.4	0.8

a Measured for an air path length of 92 mm.

6.2 The GUM standard and correction factors

The reference plane for the GUM standard was positioned at 500 mm from the radiation source, with a reproducibility of 0.1 mm. The lateral alignment on the beam axis was to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is approximately 85 mm for all radiation qualities.

The correction factors applied to the ionization current measured at each radiation quality using the GUM standard, together with their associated uncertainties, are given in Table 7. During the calibration of the transfer chamber, measurements using the GUM standard were made using positive polarity only. The polarity effect in the standard was corrected using the factors k_{pol} measured previously, as given in the table.

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.

6.3 Transfer chamber positioning and calibration at the GUM

The reference point for the transfer chamber was positioned in the reference plane with a reproducibility of 0.1 mm. The lateral alignment on the beam axis was to an estimated uncertainty of 0.1 mm. The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current was around 2 parts in 10^4.

Preceding the measurements at the BIPM and for each radiation quality, two sets of five calibrations were made, each calibration consisting of a single measurement with the standard followed by a measurement with the transfer chamber (each with integration time 80 s). The standard uncertainty of the mean calibration coefficient for each set was always below 1 part in 10^3 and the two sets typically agreed at this level. Similar measurements were made following those at the BIPM and the results are shown in Table 8.

Table 7. Correction factors for the GUM standard

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]	1.1991	1.0459	1.0335	1.0091	1.0044	0.0010	0.0002
Scattered radiation k_sc[b]	0.9962	0.9973	0.9974	0.9978	0.9979	-	0.0003
Fluorescence k_fl[b]	0.9947	0.9966	0.9967	0.9978	0.9983	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0001	-	0.0001
Ion recombination k_s	1.0000	1.0004	1.0001	1.0003	1.0001	0.0002	0.0002
Polarity k_pol	0.9987	0.9984	0.9989	0.9987	0.9986	0.0002	0.0002
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	-
Aperture transmission k_l	1.0000	0.9999	0.9999	0.9999	0.9998	-	0.0001
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_\mathrm{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001

a Values for 295.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
b These values for k_sc and k_fl were adopted during the comparison and are based on the Monte Carlo calculations of Burns [7] for the GUM standard.

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 at the GUM are from one to ten times larger than those at the BIPM. To estimate the effect of these differences, additional measurements were made in the BIPM 50 kVb quality at five times the reference anode current. From these results it was observed that an increase in current by a factor of ten will cause the free-air transfer chamber to under-read by over 2 parts in 10^3. As this effect is not negligible, a set of relative correction factors $k_\mathrm{s,tr}$ were applied to the comparison results, as indicated in Table 8. A corresponding standard uncertainty of 3 parts in 10^4 is included in Table 12.

The transfer chamber was used with the same polarity at each institute and so no corrections are applied for polarity effects in the transfer chamber. No correction is applied at either laboratory for the radial non-uniformity of the radiation field. This effect will be negligible for the transfer chamber with aperture diameter 10 mm. The field size is very similar at the two laboratories and no correction is applied.

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 GUM 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

The calibration coefficients $N_{K,\mathrm{GUM}}$ and $N_{K,\mathrm{BIPM}}$ for the free-air transfer chamber are presented in Table 8. The values $N_{\mathrm{K,GUM}}$ measured before and after the measurements at the BIPM give rise to the relative standard deviation σ_{dist}, which is taken to represent the combined stability of the transfer chamber and the GUM calibrations and whose mean value $\sigma_{\mathrm{tr}} = 0.0016$ is included as an uncertainty in Table 12. Also included in the table for each radiation quality is the ratio $N_{K,\mathrm{GUM}} / N_{K,\mathrm{BIPM}}$, evaluated using the mean value for $N_{K,\mathrm{GUM}}$, and the relative recombination correction $k_{\mathrm{s,tr}}$ accounting for differences in the air-kerma rates at the two laboratories.

Table 8. Calibration coefficients $N_{K,\mathrm{GUM}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chamber

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$N_{K,\mathrm{GUM}}$ (pre-BIPM)	13.993	14.087	14.091	14.167	14.255
$N_{K,\mathrm{GUM}}$ (post-BIPM)	14.045	14.071	14.103	14.100	14.269
σ_{dist} (relative)	0.002 6	0.000 8	0.000 6	0.003 4	0.000 7
$N_{K,\mathrm{BIPM}}$	14.086	14.098	14.089	14.163	14.255
$N_{K,\mathrm{GUM}} / N_{K,\mathrm{BIPM}}$	0.995 2	0.998 6	1.000 5	0.997 8	1.000 4
$k_{\mathrm{s,tr}}$	0.999 7	0.997 7	0.999 4	0.999 4	1.000 1

Consequently, the comparison result $R_{K,\mathrm{GUM}}$ for each radiation quality is evaluated as

$$R_{K,\mathrm{GUM}} = \frac{k_{\mathrm{s,tr}} N_{K,\mathrm{GUM}}}{N_{K,\mathrm{BIPM}}} \qquad (4)$$

and the values are given in Table 9. Also given in the table are the results of the previous, indirect comparison of the GUM and BIPM standards [5], revised for the published changes made to the BIPM standard in 2003 [3] and in 2009 [4] as given in the BIPM key comparison database and also corrected for the new factors k_{sc} and k_{fl} for the GUM standard. The results and combined uncertainties are discussed in Section 10.

Table 9. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$R_{K,\mathrm{GUM}}$	**0.994 9**	**0.996 3**	**0.999 9**	**0.997 2**	**1.000 5**
Previous results for $R_{K,\mathrm{GUM}}$	*0.996 2*	*0.998 5*	-	*0.998 2*	*0.999 4*

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 10, and those for the transfer chamber calibrations in Table 11. The combined standard uncertainty u_{c} for the comparison results $R_{K,\mathrm{GUM}}$ 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 [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, as is the case for the GUM standard.

Table 10. Uncertainties associated with the standards

Standard	BIPM L-01		GUM	
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 5	0.000 6
Volume	0.000 3	0.000 5	0.000 1	0.000 5
Positioning	0.000 1	0.000 1	0.000 1	0.000 1
Correction factors (excl. k_h)	0.000 3	0.001 0	0.001 0	0.000 9
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	0.001 1	0.001 9

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

Institute	BIPM		GUM	
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	0.001 1	0.001 9
Positioning of transfer chamber	0.000 1	-	0.000 1	0.000 1
I_{tr}	0.000 2	0.000 2	0.000 5	0.001 0
Short-term reproducibility	0.000 5	-	0.001 0	-
N_K	0.000 7	0.001 9	0.001 6	0.002 1

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{GUM}}$ / $N_{K,\mathrm{BIPM}}$	0.001 8	0.001 7[a]
σ_{tr}	-	0.001 6
$k_{s,tr}$	-	0.000 3
$R_{K,\mathrm{GUM}}$	0.001 8	0.002 4
	u_c = 0.003 0	

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

10. Discussion

The comparison results presented in Table 9 show the standards of the GUM and the BIPM to agree to better than the expanded uncertainty ($k = 2$) of 6.0 parts in 10^3. The low result at 10 kV might be related to the GUM air-attenuation correction, which is difficult to measure well at 10 kV, but this is not the case for the 30 kV and 50 kVb qualities, which are also somewhat low. Also of note is the difference of 3 parts in 10^3 between the results for the two 50 kV qualities. A small part of this difference, perhaps 5 parts in 10^4, is likely to be due to diaphragm effects as the GUM standard has no correction equivalent to the factor k_{dia} for the BIPM standard. It is perhaps relevant that the GUM air-kerma rate at 30 kV is very high, and that the rate at 50 kVb is significantly higher than that at 50 kVa. The effect of such differences is taken into account by the recombination corrections k_{s} and $k_{\mathrm{s,tr}}$. However, the GUM measurements for ion recombination using the method described by Boutillon [9] did not show the expected linear behaviour nor consistent results for different choices of the voltage ratio. Consequently, the values for k_{s} given in Table 7 are derived by assuming a linear relation between reciprocal current and the squared reciprocal voltage. Nevertheless, such effects are not likely to explain more than 1 part in 10^3 of any difference observed between the GUM and BIPM standards, which is within the stated uncertainty of k_{s}.

When corrected for the change to k_{sc} for the GUM standard, and for the introduction of k_{fl}, the results of the previous comparison in 1995 are within around 1 part in 10^3 of the present results. This is a satisfactory demonstration of chamber stability over the fifteen years between the comparisons. Note that the kerma rates at each laboratory were not the same for the previous comparison as they are now and no correction $k_{\mathrm{s,tr}}$ was applied to the results.

11. Degrees of Equivalence

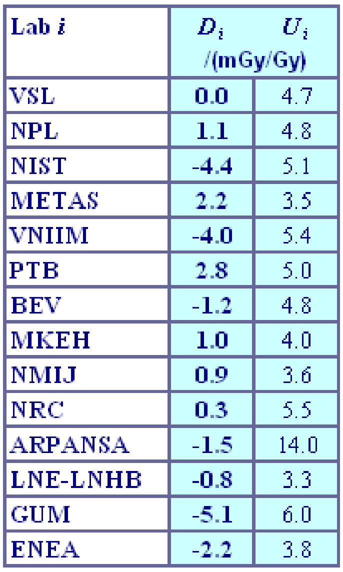
The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described in [8]. Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the key comparison reference value, for each of the CCRI radiation qualities. It follows 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 1.

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 [8].

12. Conclusions

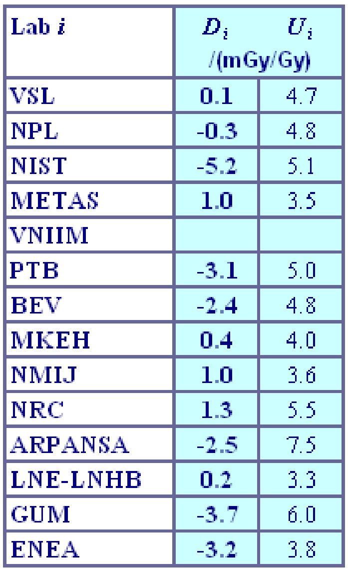
The key comparison BIPM.RI(I)-K2 for the determination of air kerma in low-energy x-rays shows the standards of the GUM and the BIPM to be in agreement to better than the expanded uncertainty ($k = 2$) for the comparison of 6.0 parts in 10^3. The results are in good agreement with those of the previous comparison between the two standards. Degrees of equivalence, including those for the GUM, 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.

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



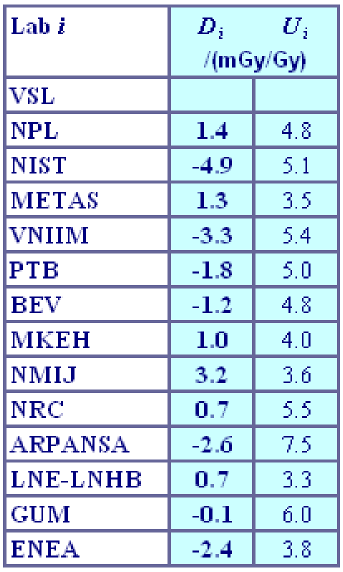
10 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
VSL	0.0	4.7
NPL	1.1	4.8
NIST	-4.4	5.1
METAS	2.2	3.5
VNIIM	-4.0	5.4
PTB	2.8	5.0
BEV	-1.2	4.8
MKEH	1.0	4.0
NMIJ	0.9	3.6
NRC	0.3	5.5
ARPANSA	-1.5	14.0
LNE-LNHB	-0.8	3.3
GUM	-5.1	6.0
ENEA	-2.2	3.8



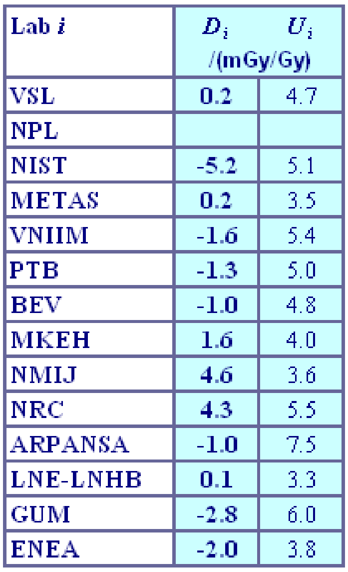
30 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
VSL	0.1	4.7
NPL	-0.3	4.8
NIST	-5.2	5.1
METAS	1.0	3.5
VNIIM		
PTB	-3.1	5.0
BEV	-2.4	4.8
MKEH	0.4	4.0
NMIJ	1.0	3.6
NRC	1.3	5.5
ARPANSA	-2.5	7.5
LNE-LNHB	0.2	3.3
GUM	-3.7	6.0
ENEA	-3.2	3.8



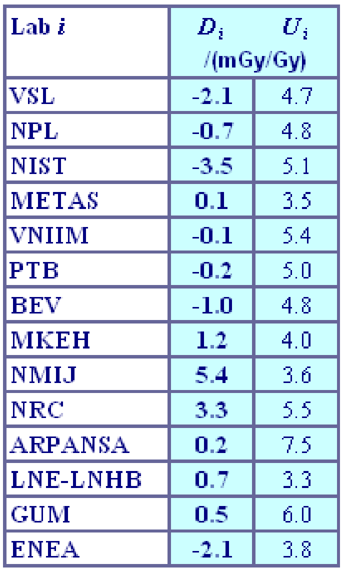
25 kV

Lab *i*	D_i	U_i
	/(mGy/Gy)	
VSL		
NPL	1.4	4.8
NIST	-4.9	5.1
METAS	1.3	3.5
VNIIM	-3.3	5.4
PTB	-1.8	5.0
BEV	-1.2	4.8
MKEH	1.0	4.0
NMIJ	3.2	3.6
NRC	0.7	5.5
ARPANSA	-2.6	7.5
LNE-LNHB	0.7	3.3
GUM	-0.1	6.0
ENEA	-2.4	3.8



50 kVb

Lab *i*	D_i	U_i
	/(mGy/Gy)	
VSL	0.2	4.7
NPL		
NIST	-5.2	5.1
METAS	0.2	3.5
VNIIM	-1.6	5.4
PTB	-1.3	5.0
BEV	-1.0	4.8
MKEH	1.6	4.0
NMIJ	4.6	3.6
NRC	4.3	5.5
ARPANSA	-1.0	7.5
LNE-LNHB	0.1	3.3
GUM	-2.8	6.0
ENEA	-2.0	3.8



50 kVa

Lab *i*	D_i	U_i
	/(mGy/Gy)	
VSL	-2.1	4.7
NPL	-0.7	4.8
NIST	-3.5	5.1
METAS	0.1	3.5
VNIIM	-0.1	5.4
PTB	-0.2	5.0
BEV	-1.0	4.8
MKEH	1.2	4.0
NMIJ	5.4	3.6
NRC	3.3	5.5
ARPANSA	0.2	7.5
LNE-LNHB	0.7	3.3
GUM	0.5	6.0
ENEA	-2.1	3.8

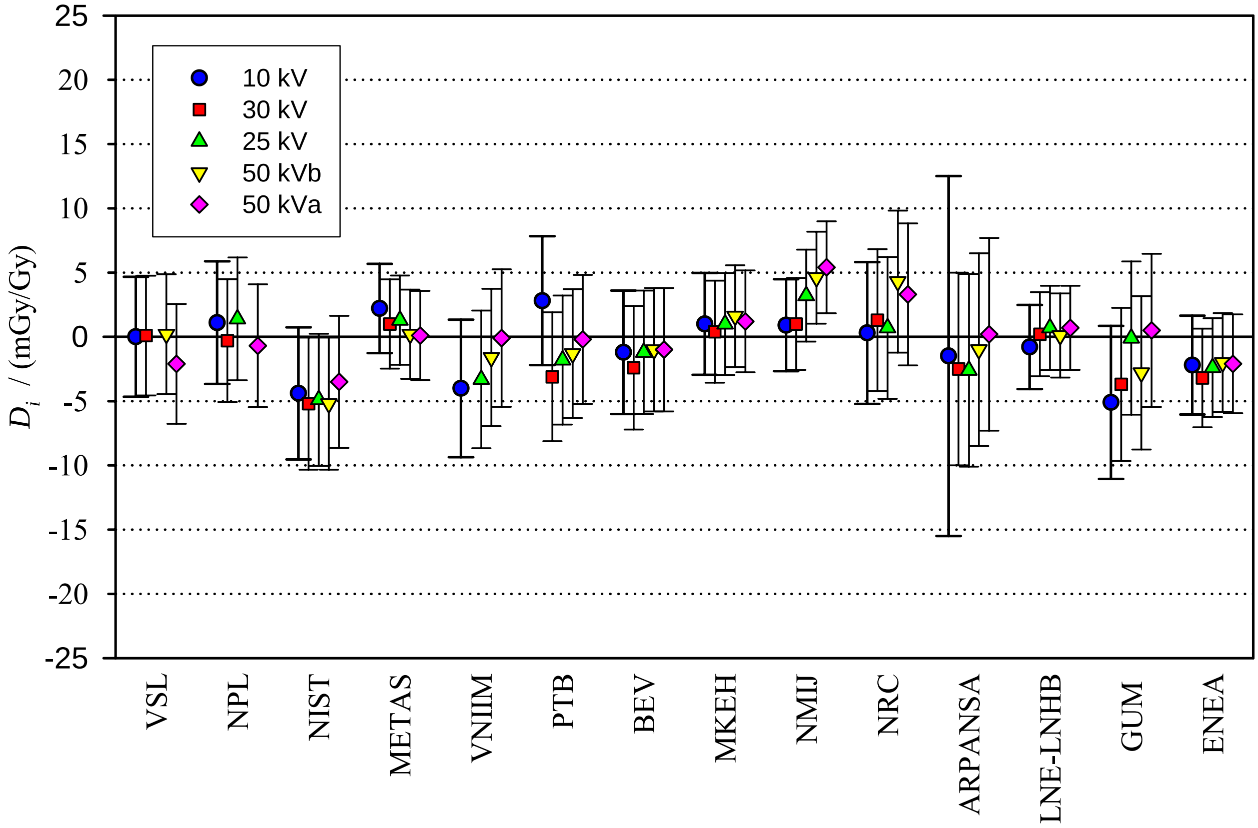


Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value

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