Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the LNE-LNHB, France and the BIPM in medium-energy x-rays

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Abstract A key comparison has been made between the air-kerma standards of the LNE-LNHB and the BIPM in the medium-energy x-ray range. The results show the standards to be in agreement at the level of the stated standard uncertainty when account is taken of the effect of the aperture support for the BIPM standard. 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 Laboratoire National Henri Becquerel (LNE-LNHB), France, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Three cavity ionization chambers were used as transfer instruments. The measurements at the BIPM took place in June 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

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

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 $\Pi\ k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard.

The reference for the air-kerma determination at both laboratories is dry air at a pressure P_0 of 101.325 kPa. However, the reference air temperature T_0 for the air-kerma determination is 293.15 K at the LNE-LNHB and 273.15 K at the BIPM. Consequently, the value used for ρ_{air} is not the same at the LNE-LNHB as at the BIPM. The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1.[1]

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design and are very similar in dimensions. 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

[1] At the BIPM, 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, a humidity correction $k_{\mathrm{h}} = 0.9980$, and the factor 1.0002 to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

changes made to certain correction factors in October 2003 given in [3] and the references therein. Details of the LNE-LNHB standard are given in [4]. 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	$u_i^{\dagger}$
$\rho_{air}^{\ddagger}$ (BIPM)	1.2930 kg m^{-3}	0.0001
$\rho_{air}^{\P}$ (LNE-LNHB)	1.2048 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0015

† u_i is the relative standard uncertainty.
‡ Density of dry air at T_0 = 273.15 K and P_0 = 101.325 kPa.
¶ 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	LNE-LNHB
Aperture diameter / mm	9.939	10.074
Air path length / mm	281.5	317.9
Collecting length / mm	60.004	60.004
Electrode separation / mm	180	180
Collector width / mm	200	231
Measuring volume / mm^3	4655.4	4782.7
Polarizing voltage / V	4000	5000

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 $N_{K,\mathrm{BIPM}}$ 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) may differ. A radiation quality correction factor k_Q is derived for each comparison quality Q. This corrects the calibration coefficient $N_{K,\mathrm{NMI}}$ determined at the NMI into one which 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

Three cavity ionization chambers belonging to the LNE-LNHB were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. Following the procedure used at the LNE-LNHB, but contrary to normal practice for BIPM comparisons, each NE 2571 chamber was measured with the build-up cap supplied by the manufacturer. Each of the three chambers was oriented so that the line on the chamber stem was facing the source.

Table 3. Main characteristics of the transfer chambers

Chamber type	NE 2571	NE 2571	LNE-LNHB
Serial number	3537	3501	21
LNE-LNHB reference	CI75	CI56	CI29
Geometry	thimble	thimble	cylindro-spheric
Reference point (on axis)	13 mm from tip	13 mm from tip	line on body
External diameter / mm	6.99	6.96	15.07
Nominal volume / cm^3	0.7	0.7	0.7
Polarizing potential† / V	+300	+300	+200

† Potential applied to the chamber wall, the collector remaining at virtual ground potential.

5. Calibration at the BIPM

5.1 BIPM irradiation facility and reference radiation qualities

The BIPM medium-energy x-ray laboratory houses a high-stability generator and a tungsten-anode x-ray tube with a 3 mm beryllium window. An aluminium filter of thickness 2.228 mm is added (for all radiation qualities) to compensate for the decrease in attenuation that occurred when the original BIPM x-ray tube (with an aluminium window of approximately 3 mm) was replaced in June 2004. A pair of voltage dividers are used to monitor the tube voltage and a voltage-to-frequency converter combined with data transfer by optical fibre measures the anode current. No transmission monitor is used. For a given radiation quality, the standard uncertainty of the distribution of the air-kerma rate determinations over the past year is around 2×10^{-4} in relative value. The radiation qualities used in the range from 100 kV to 250 kV are those recommended by the CCRI [1] and are given in Table 4.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.1 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the BIPM standard (which is controlled at 25 °C). Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 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	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Inherent Be filtration / mm	3	3	3	3
Additional Al filtration / mm	3.431	2.228	2.228	2.228
Additional Cu filtration / mm	-	0.232	0.485	1.570
Al HVL / mm	4.030	-	-	-
Cu HVL / mm	0.149	0.489	0.977	2.484
$(\mu/\rho)_{air}$ † / cm^2 g^{-1}	0.290	0.190	0.162	0.137
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.50	0.50	0.50	0.50

† Measured at the BIPM for an air path length of 270 mm.

5.2 BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 1 200 mm from the radiation source, with a reproducibility of 0.03 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is 98 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using positive polarity only. A correction factor of 1.00015 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 around 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 factor k_a corrects for the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. It is evaluated using the measured air-attenuation coefficients given in Table 4. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard. Ionization current measurements (both for the standard and for transfer chambers) are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each chamber was positioned in the reference plane (1 200 mm from the radiation source), with a reproducibility of 0.03 mm. Each transfer chamber was aligned on the beam axis to an estimated uncertainty of 0.1 mm.

Table 5. Correction factors for the BIPM standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a †	1.0099	1.0065	1.0055	1.0047	0.0002	0.0001
Scattered radiation k_{sc} ‡	0.9952	0.9959	0.9964	0.9974	-	0.0003
Fluorescence k_{fl} ‡	0.9985	0.9992	0.9994	0.9999	-	0.0003
Electron loss k_e ‡	1.0000	1.0016	1.0043	1.0073	-	0.0009
Ion recombination k_s	1.0010	1.0010	1.0010	1.0010	0.0002	0.0001
Polarity k_{pol}	1.0002	1.0002	1.0002	1.0002	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0007
Aperture edge transmission k_l	0.9999	0.9998	0.9997	0.9996	-	0.0001
Wall transmission k_p	1.0000	1.0000	0.9999	0.9988	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	0.9999	0.9999	0.9998	0.9997	-	0.0001

† Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
‡ Values for k_{sc}, k_{fl} and k_e adopted in October 2003, based primarily on Monte Carlo calculations.

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 NE2571 transfer chambers was typically less than 3×10^{-4}. For chamber LNE-LNHB-21, a radiation-induced leakage current was observed, decaying over a period of ten minutes from a relative value of up to 4×10^{-3} (reproducible at the level of 3×10^{-4} for a given radiation quality) to a stable background level of around 4×10^{-4} (in relative terms). The calibration procedure for this chamber at the LNE-LNHB is to correct for the stable background leakage, ignoring the radiation-induced component. The same procedure was therefore adopted for this chamber at the BIPM.

For each transfer chamber 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 2×10^{-4} and repeatability was in general consistent with this uncertainty. For each chamber, repeat calibrations were made at one or more radiation qualities after having removed and replaced the chamber. Based on these measurements, which showed a reproducibility consistent with the statistical uncertainties, and on experience with other chambers, an uncertainty component of 3×10^{-4} in relative value is introduced to account for the short-term reproducibility of chamber calibration coefficients at the BIPM.

6. Calibration at the LHE-LNHB

6.1 LNE-LNHB irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the LNE-LNHB comprises a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 3.14 mm aluminium. The generator was allowed to stabilize for more than one hour before measurements. No monitor chamber was used. Output stability is around 5 parts in 10^4 and the reproducibility of air-kerma determinations is around 8 parts in 10^4. The characteristics of the LNE-LNHB realization of the CCRI comparison qualities [1] are given in Table 6.

Table 6. Characteristics of the LNE-LNHB reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	0.318	-	-	-
Additional Cu filtration / mm	-	0.213	0.477	1.641
Al HVL / mm	4.044	-	-	-
Cu HVL / mm	-	0.488	0.977	2.484
$(\mu/\rho)_{air}^{\dagger}$ / cm^2 g^{-1}	0.280	0.201	0.179	0.155
$\dot{K}_{LNHB}$ / mGy s^{-1}	0.51	0.47	0.48	0.49

† Calculated at the LNE-LNHB using the mono-energetic data of reference [5] and x-ray spectra measured at the BIPM.

6.2 LNE-LNHB standard and correction factors

The reference plane for the LNE-LNHB standard was positioned at 1 200 mm from the radiation source, with a reproducibility of 0.5 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.3 mm. The beam diameter in the reference plane is 70 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the LNE-LNHB standard were made using positive polarity only. A correction factor k_{pol} was applied to correct for the polarity effect in the standard measured for each radiation quality. The relative leakage 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 LNE-LNHB standard, together with their associated uncertainties, are given in Table 7.

The correction factor k_a is evaluated using the calculated air-attenuation coefficients given in Table 6. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard at the time of the measurements. Ionization measurements (standard and transfer chambers) are also corrected for variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

6.3 Transfer chamber positioning and calibration at the LNE-LNHB

The reference point for each transfer chamber was positioned at the reference distance (1200 mm from the radiation source), with a reproducibility of 0.5 mm. Alignment on the beam axis was to an estimated uncertainty of 0.5 mm.

A calibrated platinum resistance thermometer was used to measure the air temperature. Air pressure was recorded using a calibrated barometer positioned at the height of the transfer chambers. The relative humidity in the LNE-LNHB measurement area is controlled around 50 % and no humidity correction is applied.

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 NE2571 transfer chambers was typically less than 2×10^{-4}. As noted in Section 5.3, the LNE-LNHB-21 chamber suffered from a radiation-induced leakage current and all leakage measurements for this chamber were made after this leakage was allowed to decay for around fifteen minutes. The leakage measured under these conditions was around 8×10^{-4} (in relative terms).

The relative standard uncertainty of the mean of five sets of fifty measurements, each with an integration time of 5 s, was typically 3×10^{-4} for each transfer chamber at each radiation quality.

Table 7. Correction factors for the LNE-LNHB standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a†	1.0108	1.0077	1.0069	1.0060	-	0.001 0
Scattered radiation k_{sc}	0.9942	0.9952	0.9958	0.9968	-	0.000 7
Electron loss k_e	1.000 1	1.0011	1.0032	1.006 5	-	0.001 0
Ion recombination k_s	1.0006	1.0006	1.0006	1.0006		0.0003
Polarity k_{pol}	0.999 4	0.999 5	0.999 2	0.999 4	0.000 5	-
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	-	0.001 0
Aperture edge transmission k_l	0.999 9	0.999 9	0.999 9	0.999 9	-	0.000 1
Wall transmission k_p	1.0000	1.0000	0.9999	0.999 8	-	0.000 1
Humidity k_h	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	-	0.000 1

† Nominal values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

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 very closely matched 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 $k_{rn,tr}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For small cylindrical transfer chambers with cavity dimensions below around 2 cm, the effect should be small and will cancel to some extent at the two laboratories. A relative standard uncertainty of 3×10^{-4} is introduced for this effect.

It is of note that the field diameter of 70 mm at the LNE-LNHB is smaller than that of 98 mm at the BIPM. It is known that transfer chambers respond to scattered radiation in a way that free-air chambers do not, so that calibration coefficients can show some sensitivity to field size. Furthermore, the effect of field size might change with HVL (this is seen, for example, in certain parallel-plate chamber types calibrated in low-energy x-rays). The magnitude of such effects for small thimble chamber types calibrated in medium-energy x-rays can not at present be well estimated, but a relative standard uncertainty of 1×10^{-3} is introduced for this effect.

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 LNE-LNHB are very 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. Uncertainties

The uncertainties associated with the primary standards are listed in Table 8, those for the transfer chamber calibrations in Table 9 and those for the comparison results $R_{K,\mathrm{LNHB}}$ in Table 10.

Table 8. Uncertainties associated with the standards

Standard	BIPM		LNE-LNHB	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.000 2	0.000 2	0.000 7	0.001 1
Volume	0.000 1	0.000 5	-	0.000 5
Positioning	0.000 1	0.000 1	-	0.001 0
Correction factors (excl. k_h)	0.000 3	0.001 2	0.000 5	0.001 9
Humidity k_h	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}$	0.000 4	0.002 0	0.000 9	0.002 9

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 product $k_e\, k_{sc}\, k_{fl}$ at the BIPM and the product $k_e\, k_{sc}$ at the LNE-LNHB, 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 [6].

9. Results and discussion

The calibration coefficients determined at the BIPM and at the LNE-LNHB are given in Table 11. For the NE2571 chambers, the pre- and post-comparison calibrations at the LNE-LNHB agree at the level 1 part in 10^3 or better, consistent with the uncertainties associated with chamber positioning and ionization current measurements. However, for chamber LNE-LNHB-21, a change in response of up to 4 parts in 10^3 was observed (less at 250 kV), perhaps related to the radiation-induced leakage current measured for this chamber. For this reason, the results for this chamber have not been included in the evaluation of the final comparison results.

Table 9. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		LNE-LNHB	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}$	0.000 4	0.002 0	0.000 9	0.002 9
Positioning of transfer chamber	0.000 1	0.000 1	-	0.001 0
I_{tr}	0.000 2	0.000 2	0.002 0	0.001 1
Short-term reproducibility	0.000 3	-	-	-
N_K	0.000 5	0.002 0	0.002 2	0.003 3

Table 10. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,\mathrm{LNHB}}/N_{K,\mathrm{BIPM}}$	0.002 2	0.002 9†
$k_{rn,tr}$	-	0.000 3
Field size	-	0.001 0
$R_{K,\mathrm{LNHB}}$	0.002 2	0.003 1
	u_c = 0.003 8	

† Takes account of correlation in type B uncertainties.

The comparison results are summarized in Table 12. It is clear from the final results for $R_{K,\mathrm{LNHB}}$ (in bold) that there is a significant trend with radiation quality. This has been seen in a number of previous BIPM comparisons with other laboratories and the reason for this is now known. The aperture of the BIPM standard has an aluminium support that touches the outer surface of the aperture, the support itself having an aperture of diameter 12 mm and length 22 mm. It was identified recently that this support introduces significant scatter into the standard. This effect has now been measured for the four radiation qualities, giving correction factors to the BIPM standard of 0.998 4(2), 0.996 4(2), 0.995 0(2) and 0.993 5(2) at 100 kV, 135 kV, 180 kV and 250 kV, respectively. However, as the BIPM standard is the key comparison reference value, it cannot be changed without the approval of the CCRI. This change will be documented in the open literature and implemented in due course. For this reason, the present report does not include these correction factors in the final comparison results. It should be noted that the degrees of equivalence between any pair of national laboratories is independent of this effect (see Section 10).

Table 11. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Transfer chamber NE2571-3537				
$N_{K,\mathrm{LNHB}}$ (pre-comp) / Gy μC^{-1}	42.86	41.08	40.67	40.66
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	43.00	41.23	40.93	41.00
$N_{K,\mathrm{LNHB}}$ (post-comp) / Gy μC^{-1}	42.94	41.10	40.68	40.58
Transfer chamber NE2571-3501				
$N_{K,\mathrm{LNHB}}$ (pre-comp) / Gy μC^{-1}	42.76	40.97	40.72	40.76
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	42.84	41.13	40.94	41.15
$N_{K,\mathrm{LNHB}}$ (post-comp) / Gy μC^{-1}	42.80	41.03	40.73	40.76
Transfer chamber LNHB-21				
$N_{K,\mathrm{LNHB}}$ (pre-comp) / Gy μC^{-1}	40.64	39.03	39.03	39.45
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	40.68	39.15	39.25	39.80
$N_{K,\mathrm{LNHB}}$ (post-comp) / Gy μC^{-1}	40.80	39.17	39.13	39.48

When correcting for this effect, the trend with radiation quality is removed and general agreement is observed, as seen in the final row of Table 12 where the deviations from unity are well within the stated comparison uncertainty of 3.8×10^{-3} (Table 10). The results obtained for the two transfer chambers are in agreement at the level of around 5×10^{-4}, which is perhaps better than one might expect from the stated uncertainties associated with current measurements and chamber positioning at the LNE-LNHB. The result obtained for the 250 kV quality is lower than that for the other qualities by 2 to 3 parts in 10^3. Around half of this effect can be explained by the different values used at the LNE-LNHB and the BIPM for the electron loss, photon scatter and fluorescence corrections, which should be the same because of the very similar chamber dimensions.

Table 12. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$N_{K,\mathrm{LNHB}}/N_{K,\mathrm{BIPM}}$ using NE2571-3537	0.997 7	0.996 6	0.993 7	0.990 7
$N_{K,\mathrm{LNHB}}/N_{K,\mathrm{BIPM}}$ using NE2571-3501	0.998 7	0.996 8	0.994 8	0.990 5
$R_{K,\mathrm{LNHB}}$	**0.998 2**	**0.996 7**	**0.994 3**	**0.990 6**
Corrected for aperture support	0.999 8	1.000 3	0.999 3	0.997 1

10. Degrees of Equivalence

The analysis of the results of BIPM comparisons in medium-energy x-rays in terms of degrees of equivalence is described in [6]. Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as the basis of 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 $D_i = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$. The results for D_i and U_i, including those of the present comparison, are shown in Table 13 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 [6], 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 LNE-LNHB, are also given in Table 13 and in Figure 2. Note that the data presented in the tables, while correct at the time of publication of the present report, will become out of date as laboratories make new comparisons with the BIPM. The up-to-date results are those appearing 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 LNE-LNHB. Tables formatted as they appear in the BIPM key comparison database.

100 kV

Lab i	D_i	U_i	D_{ij}	U_{ij}
	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}
ARPANSA	4.9	4.8	6.7	8.6
NMi-VSL	2.9	8.4	4.7	11.0
GUM	-0.4	7.1	1.4	10.0
NPL	-2.3	6.6	-0.5	9.7
ENEA	1.8	7.5	3.6	10.3
MKEH	-0.1	5.1	1.7	8.7
NRC	-4.3	5.5	-2.5	9.0
VNIIM	-1.0	5.1	0.8	8.7
PTB	0.2	5.2	2.0	8.7
NIM	2.1	6.2	3.9	9.4
BEV	0.3	6.8	2.1	9.8
NIST	0.8	7.3	2.6	10.1
LNE-LNHB	-1.8	7.8		

135 kV

Lab i	D_i	U_i	D_{ij}	U_{ij}
	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}
ARPANSA	5.6	4.8	8.9	8.6
NMi-VSL	-0.7	8.4	2.6	11.0
GUM	-1.4	7.1	1.9	10.0
NPL	-4.0	6.6	-0.7	9.7
ENEA	2.9	7.5	6.2	10.3
MKEH	-1.0	5.1	2.3	8.7
NRC	-5.0	5.5	-1.7	9.0
VNIIM	-0.2	5.1	3.1	8.7
PTB	-1.7	5.2	1.6	8.7
NIM	-2.6	6.2	0.7	9.4
BEV	-0.1	6.8	3.2	9.8
NIST	-4.3	7.3	-1.0	10.1
LNE-LNHB	-3.3	7.8		

180 kV

Lab i	D_i	U_i	D_{ij}	U_{ij}
	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}
ARPANSA	5.0	4.8	10.7	8.6
NMi-VSL	-3.2	8.4	2.5	11.0
GUM	-2.3	7.1	3.4	10.0
NPL	-4.3	6.6	1.4	9.7
ENEA	-3.1	7.5	2.6	10.3
MKEH	-0.2	5.1	5.5	8.7
NRC	-7.2	5.5	-1.5	9.0
VNIIM	1.4	5.1	7.1	8.7
PTB	-1.7	5.2	4.0	8.7
NIM	-3.6	6.2	2.1	9.4
BEV	-2.8	6.8	2.9	9.8
NIST	-3.5	7.3	2.2	10.1
LNE-LNHB	-5.7	7.8		

250 kV

Lab i	D_i	U_i	D_{ij}	U_{ij}
	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}	/ 10^{-3}
ARPANSA	5.1	4.8	14.5	8.6
NMi-VSL	-6.2	8.4	3.2	11.0
GUM	-5.5	7.1	3.9	10.0
NPL	-8.1	6.6	1.3	9.7
ENEA	-3.6	7.5	5.8	10.3
MKEH	-2.5	5.1	6.9	8.7
NRC	-9.4	5.5	0.0	9.0
VNIIM	-1.8	5.1	7.6	8.7
PTB	-3.7	5.2	5.7	8.7
NIM	-7.1	6.2	2.3	9.4
BEV	-7.4	6.8	2.0	9.8
NIST	-7.0	7.3	2.4	10.1
LNE-LNHB	-9.4	7.8		

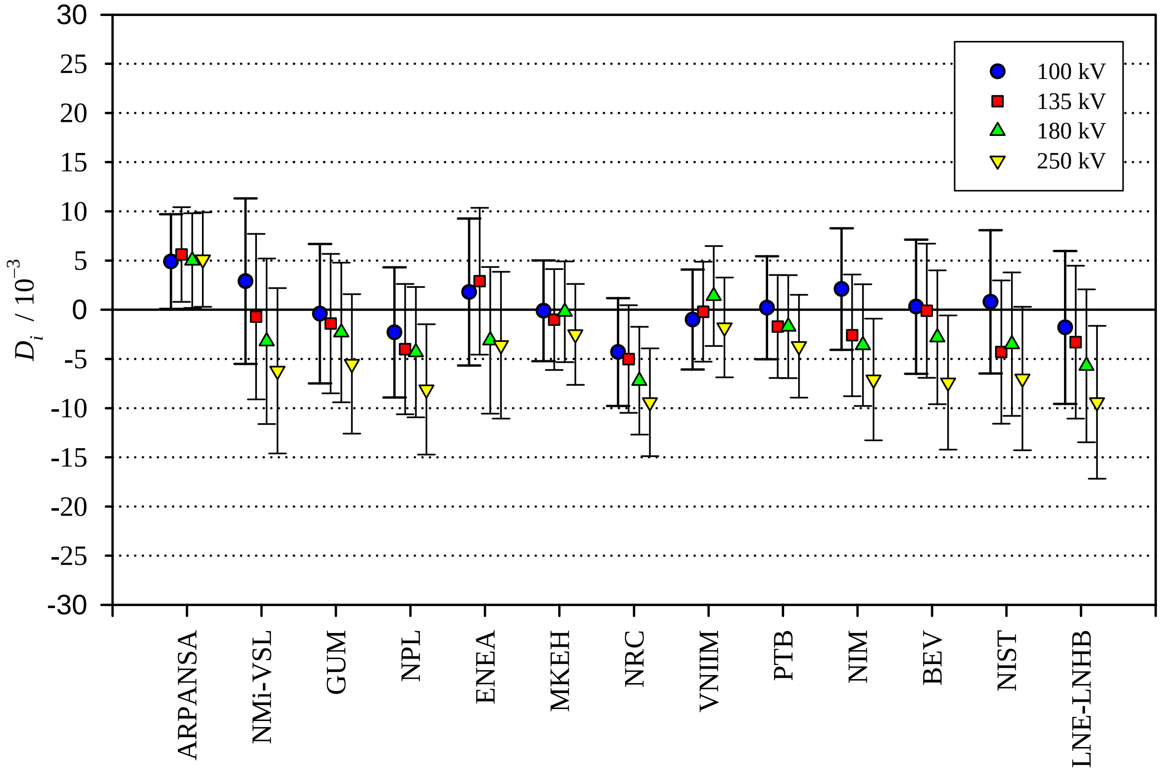

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value

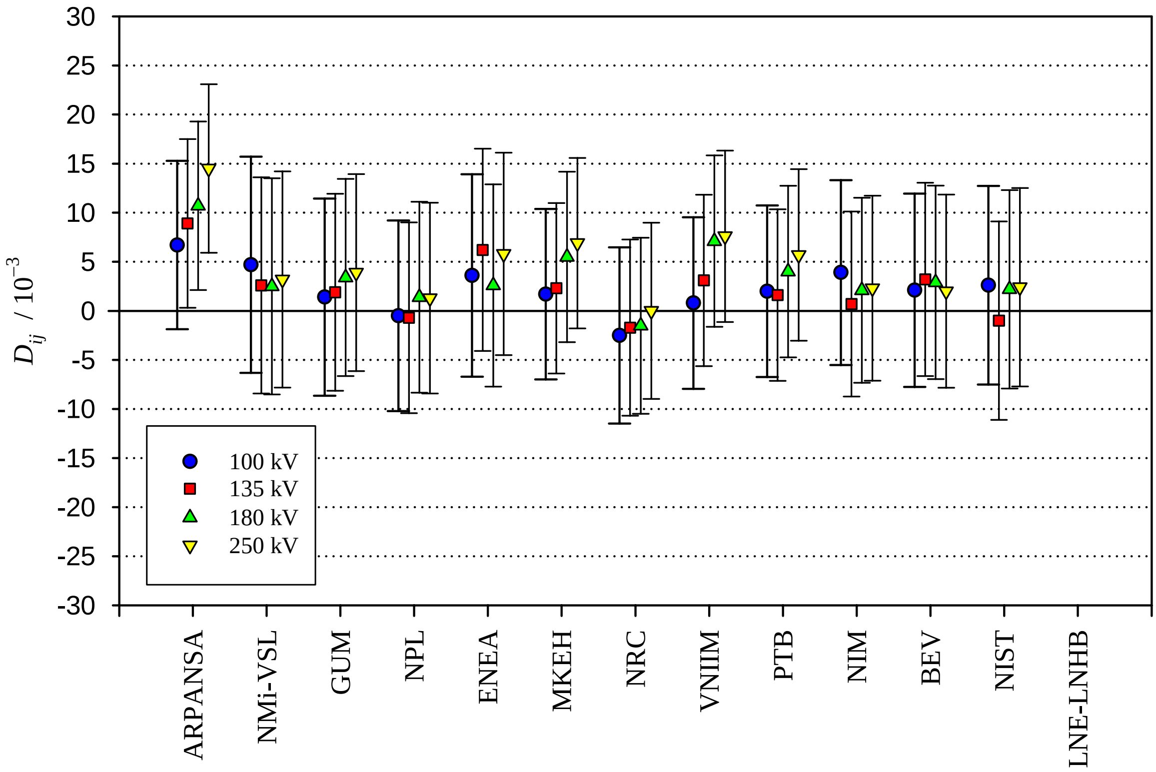

Figure 2. Degrees of equivalence for each laboratory *i* with respect to the LNE-LNHB

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