Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the NIM 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 NIM and the BIPM in the medium-energy x-ray range. The results show the standards to be in general agreement at the level of twice the stated relative standard uncertainty of 3.1×10^{-3}, although there is evidence of a trend in the results at different radiation 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 National Institute of Metrology (NIM), China, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Two cylindrical cavity ionization chambers were used as transfer instruments. The measurements at the BIPM took place in December 2001 and those at the NIM in October and November 2001, 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

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

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 mean fraction of the initial electron energy lost by bremsstrahlung production 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 defining 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, this 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.

correction factors in October 2003 given in [3] and the references therein. Details of the NIM standard, which has not previously been compared with the BIPM 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 [#]
ρ_{air} [*]	1.293 0 kg m^{-3}	0.000 1
W_{air} / e	33.97 J C^{-1}	0.001 5

\# u_i is the relative standard uncertainty.

* 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	NIM
Aperture diameter / mm	9.939	10.0397
Air path length / mm	281.5	365.9
Collecting length / mm	60.004	100.847
Electrode separation / mm	180	209
Collector width / mm	200	280
Measuring volume / mm^3	4 655.4	7 983.5
Polarizing voltage / V	4 000	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

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

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 standard conditions of 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

Two cylindrical cavity ionization chambers belonging to the NIM 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 cylindrical axis, 13 mm from the chamber tip for the NIM 0.6 Farmer-type chamber and 5 mm for the NE 2561. The NIM 0.6 chamber was oriented with the line on the chamber stem facing the source and similarly for the NE 2561 using the text inscribed on the stem.

Table 3. Main characteristics of the transfer chambers

Chamber type	NIM 0.6	NE 2561
Serial number	1999	159
Geometry	cylindrical	cylindrical
External diameter / mm	6.78	8.4
Wall material	graphite	graphite
Nominal volume / cm^3	0.6	0.3
Polarizing voltage / V	– 400 #	– 250 #

At the BIPM, the stated polarizing voltage is applied to the chamber cap, the collector remaining close to ground potential. For the NE 2561, the same arrangement was used at the NIM. However, the NIM 0.6 was calibrated at the NIM with + 400 V applied to the collector, the chamber cap remaining at ground potential.

5. Calibration at the BIPM

5.1 BIPM irradiation facility and reference radiation qualities

The following describes the BIPM medium-energy x-ray facility at the time of the comparison; the x-ray tube, collimator and high-voltage generators have since been changed. The BIPM laboratory housed a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 2.3 mm aluminium. Both the generating potential and the tube current were stabilized using feedback systems constructed at the BIPM; this resulted in a very high stability and obviated the need for a transmission current monitor. 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 0.2 °C. Two thermistors, calibrated to a few mK, 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
Additional Al filtration / mm	1.2032	-	-	-
Additional Cu filtration / mm	-	0.2321	0.4847	1.5701
Al HVL / mm	4.027	-	-	-
Cu HVL / mm	0.148	0.494	0.990	2.500
μ_{air}^{*} / m^{-1}	0.0360	0.0238	0.0201	0.0174
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.21	0.20	0.29	0.38

* Air attenuation coefficient at 293.15 K and 101.325 kPa, 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 was 83 mm for all radiation qualities; an off-axis displacement of 0.1 mm produces a relative change in the measured current of no more than 3×10^{-4} at 100 kV.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using one 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 typically 2×10^{-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 μ_{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. 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.

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 transfer chambers was up to 1×10^{-3}.

For each transfer chamber and at each radiation quality, two sets of seven measurements were made, each measurement with integration time 60 s for the NIM 0.6 chamber and 100 s for the

NE 2561. The relative standard uncertainty of the mean ionization current for each set was typically below 2×10^{-4}. An uncertainty component of 3×10^{-4} in relative value is introduced to account for the typical short-term reproducibility of BIPM calibration coefficients for cylindrical chamber types in medium-energy x-rays.

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#	1.0102	1.0067	1.0057	1.0049	0.0003	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	1.0005	1.0005	1.0005	1.0005	0.0002	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.

6. Calibration at the NIM

6.1 NIM irradiation facility and reference radiation qualities

The medium-energy x-ray facility of the NIM consists of a Philips MG 324 x-ray system that can be operated from 16 kV to 320 kV, and a tube housing including collimator and filters. The anode material is tungsten and the inherent filtration is a combination of the filtration of the x-ray tube and an additional 3.0 mm aluminium. With this additional filtration, the characteristics of the NIM realization of the CCRI comparison qualities [1] are given in Table 6. Note the use of an additional quality at 60 kV. This was of use when interpolating the NIM results in terms of HVL to derive values for the factors k_Q defined in relation (3).

The irradiation area at the NIM is temperature controlled in the range from 20 °C to 23 °C and is stable over the duration of a calibration to around 0.2 °C. A calibrated quartz thermometer with a resolution of 0.01 °C is used to measure the temperature inside the free-air chamber and that of the air to the side of the transfer chamber. Air pressure is measured by means of a calibrated barometer with a relative uncertainty of 2×10^{-4}. The relative humidity of the laboratory is controlled within the range from 40 % to 65 % and measurements are made only when it is below 55 %. Consequently no humidity correction is applied to the current measured using transfer instruments.

Table 6. Characteristics of the NIM reference radiation qualities

Radiation quality	60 kV	100 kV	130 kV	180 kV	250 kV
Generating potential / kV	60	100	130	180	250
Additional Al filtration / mm	-	1.4	1.0	1.0	1.0
Additional Cu filtration / mm	-	-	0.230	0.500	1.585
Cu HVL / mm	0.066	0.164	0.506	1.000	2.480
μ_{air}^{*} / m^{-1}	0.0547	0.0356	0.0223	0.0185	0.0169
$\dot{K}_{NIM}$ / mGy s^{-1}	0.39	0.40	0.39	0.42	0.40

* Air attenuation coefficient at 293.15 K and 101.325 kPa, measured at the NIM for air path lengths of 200 mm to 500 mm.

6.2 NIM standard and correction factors

The distance from the reference plane of the NIM standard to the focal spot is around 1200 mm (the exact value is not well defined because of the uncertainty of the size and position of the focal spot). The positioning of the standard at this distance (by different persons) is reproducible to better than 0.05 mm; no measurable change in the air-kerma rate was observed as a result of this variation. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm, and with an angular uncertainty of 0.005 degrees.

Measurements of the beam diameter and uniformity at the NIM yield quite different results for different detectors and methods. The results reported here are based on experiments carried out in March 2002 using the NE2561 chamber with the chamber tip pointed toward the focus. The diameter of the beam in the reference plane, as defined by the 50 % isodose curve, is around 76 mm. Regarding beam uniformity, the diameter of the field defined by a dose level not less than 98 % of the dose on the central axis is about 55 mm. No correction factors have been applied for this non-uniformity; consideration is given to this effect when estimating the uncertainty.

During the calibration of the transfer chambers, measurements using the NIM standard were made at both polarities to correct for any polarity effect in the standard. The measured difference was typically 4.5×10^{-4} in relative value. The relative leakage current was typically not more than 2×10^{-4}.

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

6.3 Transfer chamber positioning and calibration at the NIM

The reference point for each transfer chamber was positioned at the reference distance (1 200 mm at the NIM). Alignment on the beam axis was to an estimated uncertainty of 0.2 mm. Each chamber was set-up and removed several times and the positioning reproducibility results in a relative standard uncertainty component of 3×10^{-4}.

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 transfer chambers was typically 1×10^{-3}.

For each transfer chamber and at each radiation quality, 10 sets of 10 measurements were made. The integration time for each measurement was in the range from 100 s to 300 s, depending on the measuring device. The relative standard uncertainty of the mean ionization current for each set was typically 3×10^{-4}. The relative standard uncertainty of the mean ionization current for each chamber was at most 1.8×10^{-4} for the NE2561 and 1.6×10^{-4} for the NIM 0.6 chamber. Measurements after the return of the transfer chambers to the NIM showed no significant change in the response of the transfer chambers.

Table 7. Correction factors for the NIM standard

Radiation quality	60 kV	100 kV	130 kV	180 kV	250 kV	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a*	1.0202	1.0131	1.0082	1.0068	1.0062	0.0006	-
Scattered radiation k_{sc}	0.9926	0.9939	0.9947	0.9956	0.9960	-	0.0007
Electron loss k_e	1.0000	1.0000	1.0006	1.0020	1.0041	-	0.0007
Ion recombination k_s	1.0010	1.0009	1.0010	1.0010	1.0012	0.0002	0.0003
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0007
Aperture edge transmission k_l	1.0000	0.9999	0.9997	0.9997	0.9995	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.9996	-	0.0001
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0002
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0002

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

7. Additional corrections to transfer chamber measurements

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

As can be seen from Tables 4 and 6, the air-kerma rates at the NIM are up to two times higher than those at the BIPM. Thus volume recombination effects will be greater for the transfer chamber calibrations at the NIM, although no recombination corrections $k_{s,tr}$ have been applied at either laboratory. Based on previous measurements of recombination corrections for the NE 2561 and NE 2571 chamber types, this effect is very small and is accounted for by introducing a component of uncertainty of 2×10^{-4} in relative value.

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. For small cylindrical transfer chambers the effect of the radial non-uniformity of the radiation field is very small and no corrections are applied.

The effect of radiation field size on chamber calibration coefficients has not been well studied but could be significant. The field diameter at the NIM is 76 mm and at the BIPM is 83 mm. Noting the comments in Section 6.2 regarding the radiation fields at the NIM, a relative standard uncertainty of 2×10^{-3} is introduced to account for the effect of this difference.

7.2 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities may require a correction factor k_Q. From Tables 4 and 6 it is evident that the 180 kV and 250 kV qualities are closely matched in terms of HVL and so the correction factor k_Q is taken to be unity for these qualities. The 135 kV quality at the BIPM is reasonably matched in HVL with the 130 kV quality at the NIM. The difference in generating potential should not have a significant effect on the calibration coefficient and again k_Q is taken to be unity. For the 100 kV quality the difference in HVL is not negligible. In order to permit interpolation, the calibration coefficient $N_{K,\mathrm{NIM}}$ was also determined at the NIM 60 kV quality noted in Table 6. The results for $N_{K,\mathrm{NIM}}$ were plotted as a function of log(HVL) for each transfer chamber and used to derive the correction factor $k_Q = 1.0005$ for the NIM 0.6 chamber at 100 kV and $k_Q = 0.9994$ for the NE 2561 chamber at this quality.

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 in Table 10. The combined standard uncertainty u_c of the comparison result takes into account correlations in the type B uncertainties associated with the physical constants and the humidity correction. As the BIPM values for k_e and k_{sc} are derived from Monte Carlo calculations, they are assumed to be uncorrelated with the NIM values.

Table 8. Uncertainties associated with the standards

Standard	BIPM		NIM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0003	0.0002	0.0003	0.0007
Volume	0.0001	0.0005	-	0.0002
Positioning	0.0001	0.0001	0.0001	0.0001
Correction factors (excl. k_h)	0.0004	0.0012	0.0006	0.0013
Humidity k_h	-	0.0003	-	0.0002
Physical constants	-	0.0015	-	0.0015
$\dot{K}_{\mathrm{std}}$	0.0005	0.0020	0.0007	0.0021

9. Results and discussion

The calibration coefficients determined at the BIPM and at the NIM are given in Table 11. In this table, the NIM values at 100 kV are corrected by the factors k_Q given in Section 7.2.

The comparison results are summarized in Table 12. General agreement is observed, the mean ratio $N_{K,\mathrm{NIM}}/N_{K,\mathrm{BIPM}}$ for all eight comparisons (two chambers at four qualities) being 0.9972 (standard uncertainty of the distribution 3.8×10^{-3}). The deviation from unity of this mean value is consistent with the stated standard uncertainty of the comparison of 3.1×10^{-3} (Table 10).

There is a systematic difference in the results for the two transfer chambers of 1 or 2 parts in 10^3 (larger at 100 kV). Although the reason for this is not known, one possibility is the effect of the different fields at the two laboratories, both in size and uniformity, which might affect each chamber differently. Furthermore, there is a significant trend with radiation quality, the comparison result decreasing by around 9 parts in 10^3. A similar trend has been seen in previous comparisons with the BIPM standard. Recent calculations and measurements at the BIPM indicate that scatter from the aperture support for the BIPM standard is likely to be responsible for most of the observed effect, but more work remains to be done before correction factors can be adopted for the combined effects of the aperture and its support. Recent measurements at the NIM show unexplained effects related to chamber area and focal spot size and further work is required.

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

Institute	BIPM		NIM	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}_{\mathrm{std}}$	0.000 5	0.002 0	0.000 7	0.002 1
Positioning of transfer chamber	0.000 1	0.000 1	0.0003	-
I_{tr}	0.000 2	0.000 2	0.0003	0.0007
Short-term reproducibility	0.000 3	-	0.0002	-
$N_{K,\mathrm{std}}$	0.000 6	0.002 1	0.000 8	0.002 2

Table 10. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{NIM}}/N_{K,\mathrm{BIPM}}$	0.001 0	0.002 1[#]
$k_{\mathrm{s,tr}}$	-	0.000 2
Differences in field size / uniformity	-	0.002 0
$\dot{K}_{\mathrm{NIM}}/\dot{K}_{\mathrm{BIPM}}$	u_{c} = 0.003 1	

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

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 [5]. 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 x_{R}, for each of the CCRI radiation qualities. It follows that for each laboratory i with BIPM comparison result x_i, determined with combined standard uncertainty u_i, the degree of equivalence D_i with respect to x_{R} is simply $x_i - 1$. The expanded uncertainty of D_i is $U_i = 2\,u_i$. 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 D_{ij} of laboratory i with respect to each laboratory j that has taken part in a similar BIPM comparison is the difference $D_i - D_j$, which is therefore $x_i - x_j$. The expanded uncertainty of D_{ij} is $U_{ij} = 2\,u_{ij}$, where the combined standard uncertainty u_{ij} is mainly the combined uncertainty of the air-kerma rate determinations for the laboratories *i* and *j*. In evaluating each u_{ij}, correlation between the standards is removed, notably that for k_e, k_{sc} and k_{fl}. As described in [5], 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 laboratory. 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 NIM are given in Table 13 and in Figure 2. It should be noted, however, that these data might change when a given laboratory *i* makes a new comparison at the BIPM. The up-to-date results are always those appearing in the BIPM key comparison database.

Acknowledgements

The authors would like to thank Mr. Xu Mian for his involvement in the comparison and for his work on the NIM primary standard current measurement and data processing.

Table 11. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Transfer chamber NIM 0.6				
$N_{K,\mathrm{NIM}}$ / Gy μC^{-1}	43.23	43.11	43.08	43.08
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	43.045	43.184	43.210	43.351
Transfer chamber NE 2561				
$N_{K,\mathrm{NIM}}$ / Gy μC^{-1}	90.78	91.62	92.14	92.39
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	90.79	91.94	92.52	93.13

Table 12. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$N_{K,\mathrm{NIM}}/N_{K,\mathrm{BIPM}}$ using chamber NIM 0.6	1.004 4	0.998 3	0.997 0	0.993 8
$N_{K,\mathrm{NIM}}/N_{K,\mathrm{BIPM}}$ using chamber NE 2561	0.999 9	0.996 5	0.995 8	0.992 0
$\dot{K}_{\mathrm{NIM}}/\dot{K}_{\mathrm{BIPM}}$	**1.002 1**	**0.997 4**	**0.996 4**	**0.992 9**

Table 13. Degrees of equivalence and their uncertainties, for each radiation quality.
$D_i = x_i - x_R$ for each laboratory i with respect to the key comparison reference value x_R,
and $D_{ij} = x_i - x_j$ for each laboratory i with respect to laboratory j, where j is the NIM.
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	2.8	6.1
NMi-VSL	2.9	8.4	0.8	9.1
GUM	-0.4	7.1	-2.5	7.7
NPL	-2.3	6.6	-4.4	7.5
ENEA	1.8	7.5	-0.3	8.2
MKEH	-0.1	5.1	-2.2	7.7
NRC	-4.3	5.5	-6.4	6.6
VNIIM	-1.0	5.1	-3.1	6.2
PTB	0.2	5.2	-1.9	7.3
NIM	2.1	6.2		
NIST	0.8	7.3	-1.3	8.9

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	8.2	6.1
NMi-VSL	-0.7	8.4	1.9	9.1
GUM	-1.4	7.1	1.2	7.7
NPL	-4.0	6.6	-1.4	7.5
ENEA	2.9	7.5	5.5	8.2
MKEH	-1.0	5.1	1.6	7.7
NRC	-5.0	5.5	-2.4	6.6
VNIIM	-0.2	5.1	2.4	6.2
PTB	-1.7	5.2	0.9	7.3
NIM	-2.6	6.2		
NIST	-4.3	7.3	-1.7	8.9

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	8.6	6.1
NMi-VSL	-3.2	8.4	0.4	9.1
GUM	-2.3	7.1	1.3	7.7
NPL	-4.3	6.6	-0.7	7.5
ENEA	-3.1	7.5	0.5	8.2
MKEH	-0.2	5.1	3.4	7.7
NRC	-7.2	5.5	-3.6	6.6
VNIIM	1.4	5.1	5.0	6.2
PTB	-1.7	5.2	1.9	7.3
NIM	-3.6	6.2		
NIST	-3.5	7.3	0.1	8.9

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	12.2	6.1
NMi-VSL	-6.2	8.4	0.9	9.1
GUM	-5.5	7.1	1.6	7.7
NPL	-8.1	6.6	-1.0	7.5
ENEA	-3.6	7.5	3.5	8.2
MKEH	-2.5	5.1	4.6	7.7
NRC	-9.4	5.5	-2.3	6.6
VNIIM	-1.8	5.1	5.3	6.2
PTB	-3.7	5.2	3.4	7.3
NIM	-7.1	6.2		
NIST	-7.0	7.3	0.1	8.9

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[3] BURNS D.T., Changes to the BIPM primary air-kerma standards for x-rays, 2004, *Metrologia* **41**, L3.

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[5] BURNS D.T., Degrees of equivalence for the key comparison BIPM.RI(I)-K3 between national primary standards for medium-energy x-rays, 2003, *Metrologia* **40** *Technical Supplement*, 06036.

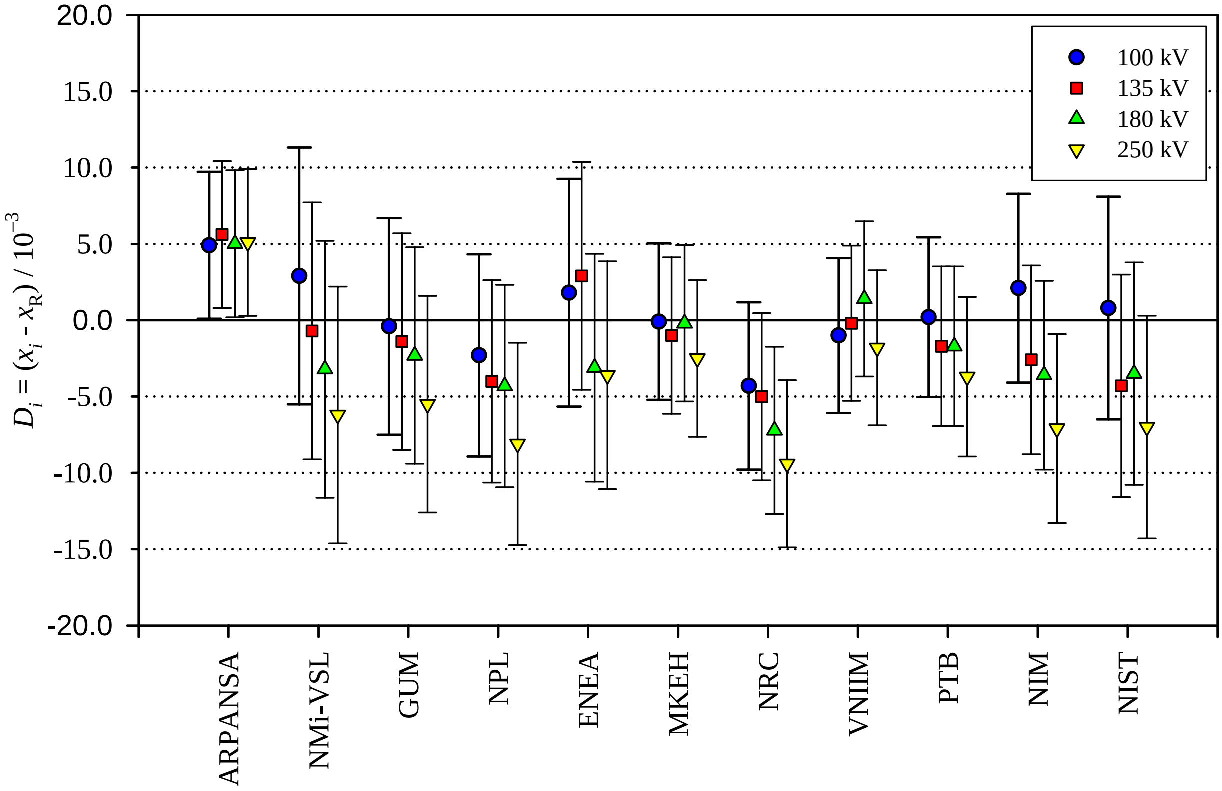

Figure 1. Degrees of equivalence D_i and their uncertainties U_i for each laboratory i with respect to the key comparison reference value

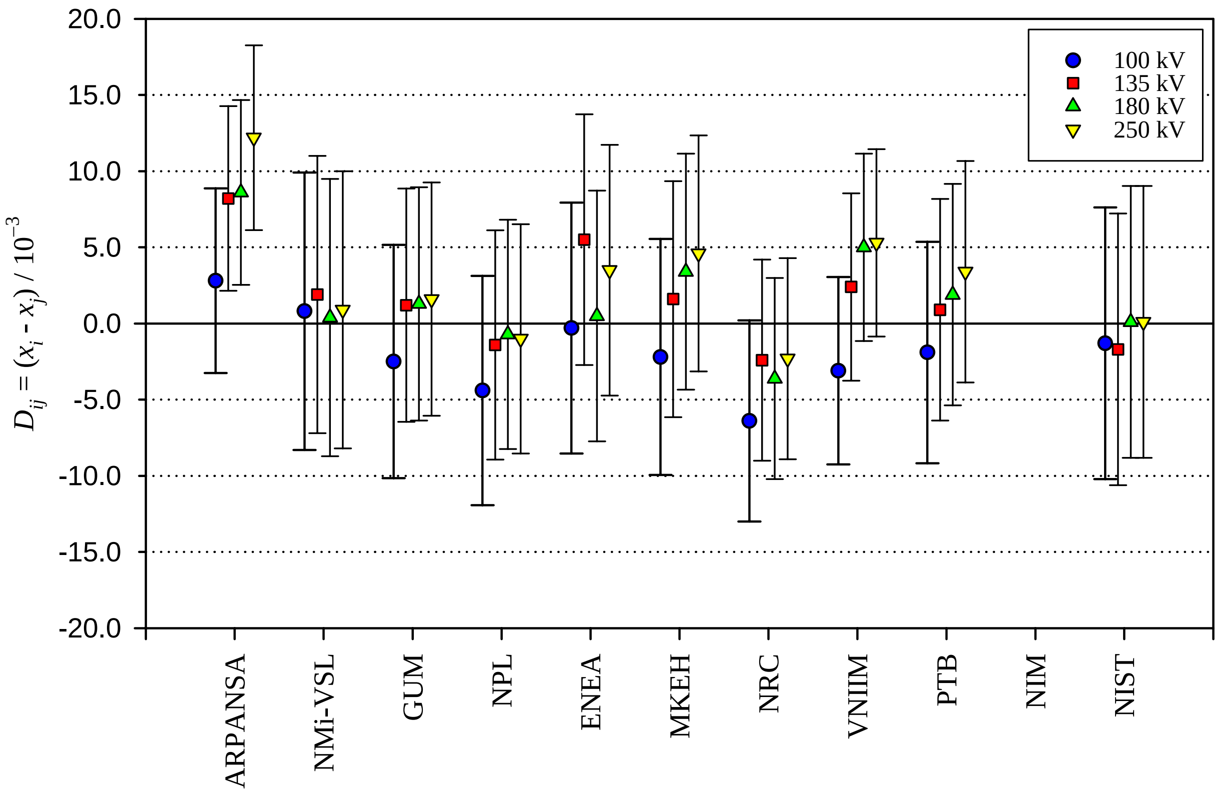

Figure 2. Degrees of equivalence D_{ij} and their uncertainties U_{ij} for each laboratory i with respect to laboratory j, where j is the NIM