

Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the BEV, Austria 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 BEV, Austria 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 Bundesamt für Eich- und Vermessungswesen (BEV), Austria, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Two spherical cavity ionization chambers were used as transfer instruments. The measurements at the BIPM took place in April 2002 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

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

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 $\prod k_i$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air} , the ionization current I must be corrected for humidity and for the difference between the density of the air of the measuring volume at the time of measurement and the value given in the table¹.

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 given in [3] and the references therein. The BEV standard was previously compared with the BIPM standard in an indirect comparison carried out in 1982.

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

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
$\rho_{\text{air}}^\ddagger$	1.2930 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	BEV
Aperture diameter / mm	9.939	9.7060
Air path length / mm	281.5	465.4
Collecting length / mm	60.004	99.94
Electrode separation / mm	180	326
Collector width / mm	200	320
Measuring volume / mm ³	4 655.4	7394.5
Polarizing voltage / V	4 000	6 000

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

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

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 $N_{K,\text{BIPM}}$ and $N_{K,\text{NMI}}$ 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 $N_{K,\text{NMI}}$ determined at the NMI into one which applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\text{NMI}}$ values in terms of $\log(\text{HVL})$. The comparison result at each quality is then taken as

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

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 spherical cavity ionization chambers belonging to the BEV were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. A third Shonka chamber, serial number 510, was also measured at both laboratories, but on return to the BEV its response was measured to have changed by over 2 parts in 10^3 and it was therefore not used to derive a comparison result.

Table 3. Main characteristics of the transfer chambers

Chamber type	Shonka	Shonka
Serial number	1019	520
Geometry	spherical	spherical
External diameter / mm	19.30	19.20
Polarizing potential [†] / V	+ 300	+ 300

[†] At both laboratories, the polarizing potential of + 300 V was applied to the chamber wall, the collecting electrode remaining at virtual ground potential. At the BIPM, measurements were made for both polarities, but only those for +300 V were used for the comparison results.

5. Calibration at the BIPM

5.1 BIPM irradiation facility and reference radiation qualities

The BIPM high-voltage generator and x-ray tube for medium-energy x-rays were changed in June 2004. At the time of the comparison in 2002, the 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, resulting in a very high stability and obviating 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 0.1 °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.

5.2 BIPM standard and correction factors

The reference plane for the BIPM standard was positioned at 1200 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.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using positive polarity only. A correction factor of 1.000 15 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 at most 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.

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	1.203	-	-	-
Additional Cu filtration / mm	-	0.232	0.485	1.570
Al HVL / mm	4.027	-	-	-
Cu HVL / mm	0.148	0.494	0.990	2.500
$\mu_{\text{air}}^{\dagger} / \text{m}^{-1}$	0.0360	0.023 8	0.020 1	0.017 4
$\dot{K}_{\text{BIPM}} / \text{mGy s}^{-1}$	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.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each chamber was positioned in the reference plane (1200 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 both transfer chambers was below 1×10^{-4} .

For each transfer chamber and at each radiation quality, a set of seven measurements was made, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each set was around 1×10^{-4} . Based on experience with other chambers of

this type, an uncertainty component of 3×10^{-4} in relative value is introduced to account for the typical short-term reproducibility of chamber calibration coefficients for medium-energy x-rays at the BIPM.

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^\dagger	1.0102	1.0067	1.0057	1.0049	0.0003	0.0001
Scattered radiation k_{sc}^\ddagger	0.9952	0.9959	0.9964	0.9974	-	0.0003
Fluorescence k_{fl}^\ddagger	0.9985	0.9992	0.9994	0.9999	-	0.0003
Electron loss k_e^\ddagger	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
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.

6. Calibration at the BEV

6.1 BEV irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the BEV comprises a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 2.5 mm beryllium. The tube voltage is measured by the internal potential divider of the generator (accuracy 1 %, stability 0.2 %, reproducibility 0.2 kV). The x-ray output is monitored by means of a transmission ionization chamber whose windows introduce a filtration of around 10 mg cm^{-2} . The characteristics of the BEV realization of the CCRI comparison qualities [1] are given in Table 6.

6.2 BEV standard and correction factors

The reference plane for the BEV standard was positioned at 800 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 100 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the BEV standard were made using positive polarity only. A correction factor was applied for the polarity effect in the standard. The relative leakage current was 1×10^{-4} .

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

The correction factor k_a is evaluated using the measured air-attenuation coefficients μ_{air} 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.

Table 6. Characteristics of the BEV reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.62	4.02	4.02	4.02
Additional Cu filtration / mm	-	0.20	0.46	1.60
Al HVL / mm	3.99	-	-	-
Cu HVL / mm	-	0.49	0.99	2.51
$\mu_{\text{air}}^\dagger / \text{m}^{-1}$	0.0343	0.0254	0.0214	0.0184
$\dot{K}_{\text{BEV}} / \text{mGy s}^{-1}$	1.1	1.0	1.1	1.1

† Air attenuation coefficient at 293.15 K and 101.325 kPa, measured at the BEV for an air path length of 465.4 mm.

Table 7. Correction factors for the BEV standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a^\dagger	1.0161	1.0119	1.0100	1.0086	0.0002	0.0010
Scattered radiation k_{sc}	0.9935	0.9941	0.9944	0.9946	-	0.0010
Electron loss k_e	1.0000	1.0005	1.0010	1.0015	-	0.0005
Ion recombination k_s	1.0017	1.0017	1.0017	1.0017	0.0003	0.0006
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0002	0.0005
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0010
Aperture edge transmission k_l	0.9997	0.9996	0.9996	0.9995	-	0.0002
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0002	0.0002
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0005
$1 - g_{\text{air}}$	0.9997	0.9997	0.9997	0.9997	-	0.0002

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

6.3 Transfer chamber positioning and calibration at the BEV

The reference point for each transfer chamber was positioned at the reference distance (at the BEV 800 mm from the radiation source), with a reproducibility of 0.03 mm. Alignment on the beam axis was to an estimated uncertainty of 0.1 mm.

A calibrated platinum resistance thermometer was used to measure the air temperature inside the BEV standard and the monitor. Air pressure was measured using a calibrated barometer positioned approximately at the height of the transfer chambers. The relative humidity is recorded to verify that it does not lie outside acceptable limits. No humidity correction is applied to the current measured using transfer instruments.

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 both transfer chambers was below 1×10^{-4} . The short-term reproducibility of the mean current at each quality is estimated to be 1×10^{-3} .

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 BEV are up to five times those at the BIPM. Thus volume recombination effects will be greater for the transfer chamber calibrations at the BEV, although no recombination corrections have been applied at either laboratory. Measurements at the BIPM for a Shonka chamber of the same dimensions show a relative change in the calibration coefficient of perhaps 5×10^{-4} over this range. Based on this, a relative uncertainty component of 5×10^{-4} is introduced. Each transfer chamber was used with the same polarity at each institute and so no correction is applied for polarity effects in the transfer chambers. Nevertheless, the polarity effect, that is, $I(-ve) / I(+ve)$, was measured at the BIPM; for the Shonka 1019, the mean of the values measured at all four qualities was 1.0026(3), and for the Shonka 520, the mean was 1.0079(3)

No correction is applied at either laboratory for the radial non-uniformity of the radiation field, which should be small for the transfer chambers used. However, there is a difference in the field diameters at the BEV and the BIPM (100 mm and 83 mm, respectively). 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. The magnitude of such an effect for small spherical 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 BEV 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 standard uncertainty of 1×10^{-4} .

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 $R_{K, BEV}$ in Table 10. 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. No correlation is assumed in the BIPM and BEV values for k_e and k_{sc} as these are derived at the BIPM from Monte Carlo calculations and at the BEV from measurement.

Table 8. Uncertainties associated with the standards

Standard	BIPM		BEV	
	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Relative standard uncertainty				
Ionization current	0.000 3	0.000 2	0.000 2	0.000 5
Volume	0.000 1	0.000 5	-	0.001 0
Positioning	0.000 1	0.000 1	0.000 2	0.000 5
Correction factors (excl. k_h)	0.000 4	0.001 2	0.000 4	0.002 0
Humidity k_h	-	0.000 3	-	0.000 5
Physical constants	-	0.001 5	-	0.001 5
\dot{K}	0.000 5	0.002 0	0.000 5	0.002 8

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

Institute	BIPM		BEV	
	u_{iA}	u_{iB}	u_{iA}	u_{iB}
\dot{K}	0.000 5	0.002 0	0.000 5	0.002 8
Positioning of transfer chamber	0.000 1	0.000 1	0.000 2	0.000 5
I_{tr}	0.000 2	0.000 2	0.000 2	0.001 0
Short-term reproducibility	0.000 3	-	0.001 0	-
N_K	0.000 6	0.002 0	0.001 2	0.003 0

9. Results and discussion

The calibration coefficients determined at the BIPM and at the BEV are given in Table 11. The results obtained for the two transfer chambers are in agreement at the level of around 5×10^{-4} , which is consistent with the statistical uncertainty associated with current measurements, chamber positioning and short-term reproducibility at the two laboratories.

The comparison results are summarized in Table 12. It is clear from the final results for $R_{K, BEV}$ (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 aperture introduces significant scatter into the standard. This effect has been now measured for the four radiation qualities, giving correction factors to the BIPM standard of 0.9984(2), 0.9964(2), 0.9950(2) and 0.9935(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 change (see Section 10).

When correcting for this effect, the trend with radiation quality is largely removed as seen in the second from last row of Table 12. The deviations from unity are consistent with the stated comparison uncertainty of 3.4×10^{-3} (Table 10).

Table 10. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	U_{iB}
$N_{K, BEV} / N_{K, BIPM}$	0.001 3	0.002 9 [†]
Ion recombination	-	0.000 5
Field size	-	0.001 0
k_Q	-	0.000 1
$R_{K, BEV}$	0.001 3	0.003 1
	$u_c = 0.003 4$	

[†] Takes account of correlations in type B uncertainties.

Table 11. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
<i>Transfer chamber Shonka 1019</i>				
$N_{K, BEV} / \text{Gy } \mu\text{C}^{-1}$ (pre-comp)	8.465	8.450	8.491	8.543
$N_{K, BIPM} / \text{Gy } \mu\text{C}^{-1}$	8.460	8.444	8.508	8.603
$N_{K, BEV} / \text{Gy } \mu\text{C}^{-1}$ (post-comp)	8.467	8.445	8.484	8.540
$N_{K, BEV} / N_{K, BIPM}$	1.0007	1.0004	0.9976	0.9928
<i>Transfer chamber Shonka 520</i>				
$N_{K, BEV} / \text{Gy } \mu\text{C}^{-1}$ (pre-comp)	8.482	8.520	8.591	8.666
$N_{K, BIPM} / \text{Gy } \mu\text{C}^{-1}$	8.481	8.521	8.614	8.729
$N_{K, BEV} / \text{Gy } \mu\text{C}^{-1}$ (post-comp)	8.478	8.514	8.582	8.660
$N_{K, BEV} / N_{K, BIPM}$	1.0000	0.9995	0.9968	0.9925

The final row of the table shows the results of the comparison made in 1982, taking account of the changes made to the BIPM standard in October 2003 documented in [3], as well as changes (of at most 1×10^{-3}) in the correction factors for the BEV standard and the effect of the BIPM

aperture support. While the results for 100 kV are consistent, the two data sets diverge progressively as energy increases. The reason for this divergence is not known.

Table 12. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$R_{K, \text{BEV}}$	1.0003	0.9999	0.9972	0.9926
New result corrected for aperture support	1.0019	1.0035	1.0022	0.9991
Previous result (1982) [†]	1.0015	1.0045	1.0042	1.0022

[†] The results from 1982 are corrected for the changes made to the BIPM standard in October 2003, as documented in [3], for small changes made to the BEV standard, and for the aperture support.

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 [4]. 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 and k_{sc} . 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 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 BEV, 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 for all laboratories are those appearing in the BIPM key comparison database.

References

- [1] BIPM, Qualités de rayonnement, CCEMRI(I), 1972, R15.
- [2] BOUTILLON M., Mesure de l'exposition au BIPM dans le domaine des rayons X de 100 à 250 kV, 1978, [Rapport BIPM-78/3](#).
- [3] BURNS D.T., Changes to the BIPM primary air-kerma standards for x-rays, 2004, [Metrologia 41, L3](#).
- [4] 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](#).

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 BEV. 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	4.6	6.6
NMI-VSL	2.9	8.4	2.6	9.5
GUM	-0.4	7.1	-0.7	8.1
NPL	-2.3	6.6	-2.6	8.0
ENEA	1.8	7.5	1.5	8.7
MKEH	-0.1	5.1	-0.4	8.3
NRC	-4.3	5.5	-4.6	7.1
VNIIM	-1.0	5.1	-1.3	6.7
PTB	0.2	5.2	-0.1	7.8
NIM	2.1	6.2	1.8	7.8
BEV	0.3	6.8		
NIST	0.8	7.3	0.5	9.4

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	5.7	6.6
NMI-VSL	-0.7	8.4	-0.6	9.5
GUM	-1.4	7.1	-1.3	8.1
NPL	-4.0	6.6	-3.9	8.0
ENEA	2.9	7.5	3.0	8.7
MKEH	-1.0	5.1	-0.9	8.3
NRC	-5.0	5.5	-4.9	7.1
VNIIM	-0.2	5.1	-0.1	6.7
PTB	-1.7	5.2	-1.6	7.8
NIM	-2.6	6.2	-2.5	7.8
BEV	-0.1	6.8		
NIST	-4.3	7.3	-4.2	9.4

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	7.8	6.6
NMI-VSL	-3.2	8.4	-0.4	9.5
GUM	-2.3	7.1	0.5	8.1
NPL	-4.3	6.6	-1.5	8.0
ENEA	-3.1	7.5	-0.3	8.7
MKEH	-0.2	5.1	2.6	8.3
NRC	-7.2	5.5	-4.4	7.1
VNIIM	1.4	5.1	4.2	6.7
PTB	-1.7	5.2	1.1	7.8
NIM	-3.6	6.2	-0.8	7.8
BEV	-2.8	6.8		
NIST	-3.5	7.3	-0.7	9.4

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	12.5	6.6
NMI-VSL	-6.2	8.4	1.2	9.5
GUM	-5.5	7.1	1.9	8.1
NPL	-8.1	6.6	-0.7	8.0
ENEA	-3.6	7.5	3.8	8.7
MKEH	-2.5	5.1	4.9	8.3
NRC	-9.4	5.5	-2.0	7.1
VNIIM	-1.8	5.1	5.6	6.7
PTB	-3.7	5.2	3.7	7.8
NIM	-7.1	6.2	0.3	7.8
BEV	-7.4	6.8		
NIST	-7.0	7.3	0.4	9.4

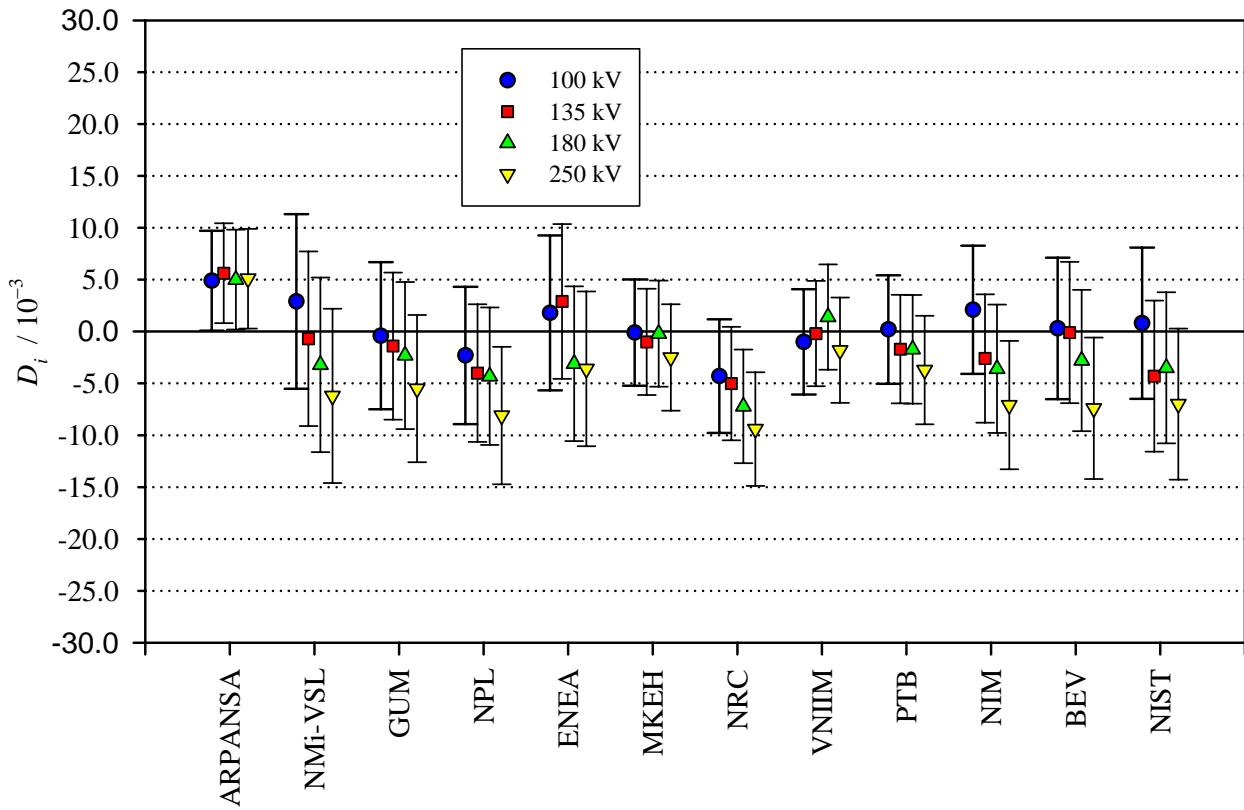


Figure 1. Degrees of equivalence for each laboratory i with respect to the key comparison reference value

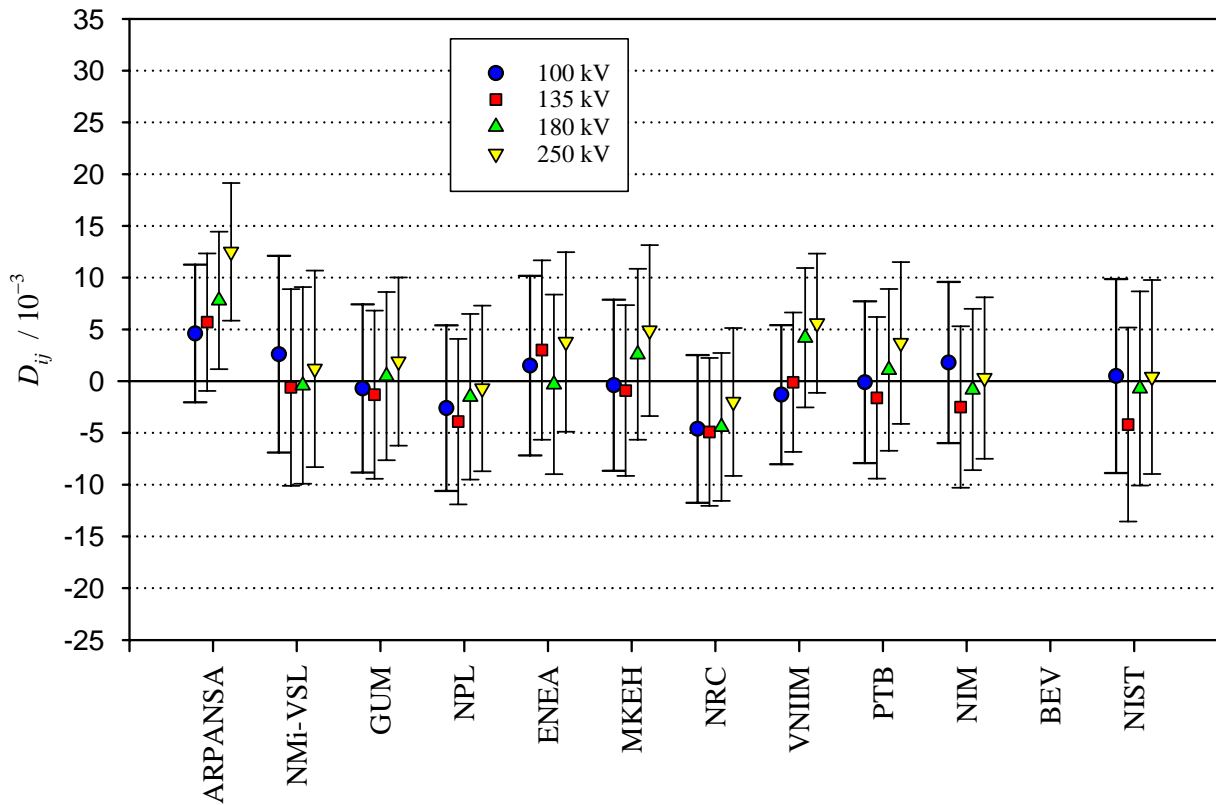


Figure 2. Degrees of equivalence for each laboratory i with respect to the BEV