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Comparison of the air-kerma standards of the BEV and the BIPM in the low-energy x-ray range

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Abstract A direct comparison has been made between the air-kerma standards of the BEV and the BIPM in the low-energy x-ray range. The results at the different radiation qualities show the standards to be in reasonable agreement with respect to the combined relative standard uncertainty of the comparison of 2.4×10^{-3}.

1. Introduction

A direct 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 10 kV to 50 kV. The comparison took place at the BIPM in March 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

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

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost by bremsstrahlung production in air, and $\Pi\, k_i$ 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 table[1].

3. Details of the standards

Both free-air chamber standards used in the present comparison 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 [3]. The BEV-PKK standard has not previously been compared with the BIPM standard. Its main dimensions, the measuring volume and the polarizing voltage, and those of the BIPM standard, are shown in Table 2.

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[1] For an air temperature T, 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 change in 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 †
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	BEV
Aperture diameter / mm	9.941	8.024
Air path length / mm	100.0	63.64
Collecting length / mm	15.466	40.822
Electrode separation / mm	70	60
Collector width / mm	71	60
Measuring volume / mm^3	1 200.4	2 064.3
Polarizing voltage / V	1 500	1 600

3. Comparison procedure

3.1 BIPM irradiation facility and reference beam qualities

The comparison was carried out in the BIPM low-energy x-ray laboratory, which 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. The generating potential 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 normalized for any deviation from the reference anode current. The resulting variation in the BIPM free-air chamber current over the duration of a comparison is normally not more than 3×10^{-4} in relative value. 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 3 in ascending HVL from left to right.

3.2 Correction factors

The correction factors applied to the ionization current measured at each radiation quality, together with their associated uncertainties, are given in Table 4 for the BIPM standard and in Table 5 for the BEV standard.

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 using the measured air-attenuation coefficients μ_{air} given in Table 3. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard at the time of the measurements. The value for k_a for the BEV chamber at 10 kV has been increased by the factor 1.001 1 to account for the larger mean air-attenuation coefficient for an air path length of 64 mm (the values given in Table 3 were measured at the BIPM for an air path length of 100 mm). This effect is negligible at the other radiation qualities. Ionization measurements 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 3. 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
$\mu_{air}^{\dagger}$ / 10^{-3} mm^{-1}	1.764	0.435	0.310	0.090	0.045
$\dot{K}_{BIPM}$ / mGy s^{-1}	1.00	1.00	1.00	1.00	1.00

† Air attenuation coefficient at 293.15 K and 100 kPa, measured at the BIPM for an air path length of 100 mm.

Table 4. Correction factors for the BIPM standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a†	1.192 1	1.042 4	1.030 9	1.009 1	1.004 6	0.000 2	0.000 1
Scattered radiation k_{sc}	0.994 4	0.995 6	0.995 7	0.996 6	0.997 1	-	0.000 7
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
Aperture edge transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1
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
$1 - g_{air}$	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 1

† These are nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air temperature and pressure measured at the time.

All measured ionization currents are corrected for ion recombination. The measured values for the ion recombination correction k_s for the BIPM standard are given in Table 4. For the BEV standard, the values for k_s given in Table 5 for the BIPM air-kerma rates are derived from measurements of initial and volume recombination at the BEV.

Table 5. Correction factors for the BEV standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a †	1.1188	1.0281	1.0199	1.0057	1.0029	0.0002	0.0001
Scattered radiation k_{sc}	0.9950	0.9960	0.9960	0.9970	0.9970	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0010	-	0.0005
Ion recombination k_s	1.0008	1.0008	1.0008	1.0008	1.0008	0.0003	0.0006
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0010
Aperture edge transmission k_l	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0002
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0002	0.0002
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	0.9999	0.9998	0.9998	0.9998	0.9997	-	0.0002

† These are nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air temperature and pressure measured at the time.

3.3 Chamber positioning and measurement procedure

The BEV chamber was positioned close to the BIPM chamber and both remained fixed throughout the comparison; the alternation of measurements between chambers was carried out by displacement of the radiation source. Alignment on the beam axis was measured to around 0.1 mm and this position was reproducible to better than 0.01 mm. An off-axis displacement of 0.1 mm produces a relative change in the measured current of no more than 3×10^{-4} at 10 kV and at 50 kV. No correction is applied for the radial non-uniformity of the beam over the different aperture diameters. The reference plane for each chamber was positioned at 500 mm from the radiation source for all qualities. This distance was measured to 0.03 mm and was reproducible to better than 0.01 mm. The beam diameter in the reference plane is 45 mm.

The air temperature for the BEV chamber was taken to be that of the ambient air, an assumption which is normally good to around 0.05 K. The leakage current was measured before and after each series of ionization current measurements and a correction made based on the mean of these leakage measurements. For both chambers the relative leakage current was less than 3×10^{-5}. The relative standard uncertainty of the mean of a series of seven measurements for the BEV standard at each polarity was typically 1×10^{-4}, the polarity difference being around 2×10^{-4}. Taking into account a relative standard uncertainty of 3×10^{-4} arising from the typical day-to-day repeatability of current measurements in the BIPM facility, a type A relative standard uncertainty of 4×10^{-4} is taken for current measurements using the BEV chamber. For the BIPM standard, two sets of seven current measurements were made (positive polarity only), the mean current being determined with a relative standard uncertainty of typically 2×10^{-4}.

4. Supporting measurements

4.1 Indirect comparison using transfer chamber

At the same time as the direct comparison, a transfer chamber type Exradin A11TW, serial number 118, was calibrated at the BIPM. This chamber had previously been calibrated a number of times at the BEV and subsequent to the BIPM measurements was recalibrated at the BEV. No build-up cap was used for the calibrations at either laboratory.

The calibration conditions at the two laboratories differ somewhat. The BEV calibrations were carried out at a distance of 600 mm with field diameter 100 mm, whereas the BIPM calibrations were at 500 mm with field diameter 95 mm. The BEV HVLs and air-kerma rates are given in Table 6 and those for the BIPM in Table 3. A small recombination correction (at most 5×10^{-4} in relative value) is applied to the BEV calibrations to account for the higher air-kerma rates than those at the BIPM.

The calibration coefficients at 20 °C and 101.325 kPa and for a polarizing voltage of 300 V (negative polarity) are given in Table 6. The BEV value at each radiation quality is the result of a single calibration before and after the BIPM measurements. A decrease is evident for all of the qualities, indicating a change in the chamber response. The statistical relative standard uncertainty of the BEV mean value at each quality is estimated to be 1.1×10^{-3}. The BIPM values are the results of a single calibration at each quality; a standard uncertainty of 5×10^{-4} is assumed which represents the typical short-term repeatability of BIPM calibrations for well-behaved ionization chambers.

Table 6. Calibration coefficients for transfer chamber A11TW / 118

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
BEV Al HVL / mm	0.034	0.170	0.244	1.000	2.232
BEV air-kerma rate / mGy s^{-1}	2.00	3.04	2.75	3.07	0.75
$N_{K,\mathrm{BEV}}$ (pre-comp) / Gy μC^{-1}	33.279	32.704	32.730	32.475	32.004
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	33.283	32.765	32.816	32.551	32.095
$N_{K,\mathrm{BEV}}$ (post-comp) / Gy μC^{-1}	33.255	32.648	32.677	32.406	31.963
$N_{K,\mathrm{BEV}} / N_{K,\mathrm{BIPM}}$	0.9995	0.9973	0.9966	0.9966	0.9965

Given these statistical uncertainties, the ratios of the BEV and BIPM calibration coefficients are consistent for the different radiation qualities, except for the result at 10 kV. This may be due to the correction for air attenuation and its dependence on air density, or to the effect on the response of the transfer chamber of differences in the BEV and BIPM 10 kV qualities. The combined relative standard uncertainty for BEV calibrations is 3.7×10^{-3}, except for the 10 kV quality where it is 6.1×10^{-3} (the higher value due to the air-attenuation correction). For the BIPM the value is 2.0×10^{-3}. The results of the indirect comparison are in close agreement with those of the direct comparison and confirm the calibration capability of each laboratory.

4.2 Comparison of apertures

Using an appropriate adaptor, the BEV aperture of diameter 8.024 mm was alternated in the BIPM chamber with the BIPM aperture of diameter 9.941 mm. The parameter of interest, i_a, is the ionization current per unit aperture area and the ratio $i_{a,\mathrm{BEV}} / i_{a,\mathrm{BIPM}}$ was measured as a function of radiation quality. The results are given in Table 7.

The spread of the results is consistent with the statistical standard uncertainty of 3×10^{-4} for each measured value. The mean value 0.999 1 differs from unity by an amount which is consistent with the stated volume uncertainties (Table 8).

Table 7. Results of aperture comparison

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$i_{a,BEV}$ / $i_{a,BIPM}$	0.999 0	0.999 5	0.999 4	0.998 8	0.998 8

4.3 Alternative treatment of air-attenuation correction

For the main comparison, the BEV and BIPM chambers were each positioned with the reference plane of the aperture positioned in the plane where the air-kerma rate is to be determined. For this standard method of operation, ionization current measurements are corrected for air attenuation between the aperture plane and the centre of the measurement volume using the air-attenuation coefficients μ_{air} measured at the BIPM, as given in Table 3.

An alternative series of measurements was made with the BEV standard moved away from the x-ray source by 36.36 mm so that the centres of the measurement volumes were aligned. Under these conditions the air-attenuation correction cancels and the ratio of the BEV and BIPM ionization currents per unit irradiated collecting volume (corrected for k_{sc}, k_e, k_s, k_d, k_l, k_p and k_{pol}) should be the same. Knowledge of the irradiated collecting volume requires the position of the focus to be known. This is uncertain at the level of perhaps 1 mm, which gives rise to an uncertainty in the comparison result (using this method) of 3×10^{-4}.

Two sets of measurements were made, yielding a comparison result BEV / BIPM of 0.996 2 for the 10 kV radiation quality and 0.996 7 for the 50 kVb quality. Given the statistical uncertainties and the 3×10^{-4} arising from the uncertainty of the position of the focus, these are in satisfactory agreement with the results of the main comparison and confirm the BIPM determination of μ_{air}.

5. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 8.

Table 8. Uncertainties associated with the comparison results

Standard	BIPM		BEV	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.000 2	0.000 2	0.000 4	0.000 2
Volume	0.000 3	0.000 5	-	0.001 0
Positioning	0.000 1	0.000 1	0.000 1	0.000 1
Correction factors (excl. k_h)	0.000 3	0.001 0	0.000 4	0.001 7
Humidity k_h	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}_{Standard}$	0.000 6	0.001 9	0.000 6	0.002 5
	0.002 0		0.002 6	
$\dot{K}_{BEV}/\dot{K}_{BIPM}$	u_c = 0.002 4 †			

† Takes account of correlations in Type B uncertainties.

The uncertainties associated with the measurement of the ionization current, with chamber positioning and with the attenuation and humidity corrections are those which apply to the measurements at the BIPM. These may be different from those in routine use for air-kerma rate determinations at the BEV. In particular, the air-attenuation correction at the BEV has a significantly larger uncertainty.

The relative combined standard uncertainty u_c of the ratio $\dot{K}_{BEV}/\dot{K}_{BIPM}$ takes into account correlations in the type B uncertainties associated with the determination of the ionization current, the humidity correction and the physical constants. Correlations between the values for k_{sc} are not taken into account, although these are derived from the same basic data.

6. Results and discussion

The comparison results are given in bold in Table 9. General agreement at around 3×10^{-3} is observed, or approximately 1.5 times the relative standard uncertainty. The results of the aperture comparisons (Table 7) explain around 1×10^{-3} of the difference between the standards. A slight trend with radiation quality is evident. Nevertheless, the standards can be considered to be in acceptable agreement.

Table 9. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$\dot{K}_{BEV}/\dot{K}_{BIPM}$	**0.9960**	**0.9959**	**0.9969**	**0.9972**	**0.9974**
Using Burns [5]	0.9966	0.9963	0.9975	0.9976	0.9975

More recent values for the correction factors k_{sc} and k_e have been calculated by Burns [4] using the Monte Carlo code EGSnrc [5], both for the BIPM standard and for the standard of the Országos Mérésügyi Hivatal (OMH), Hungary, which is of the same design as the BEV PKK standard. The results of these calculations are given in Table 10, which includes values for a new correction factor k_{fl} arising from the re-absorption of fluorescence radiation generated by the argon content of the air inside free-air chambers (this effect was to some extent included in the original measurement of k_{sc}). Differences between the new and old values can give rise to relative changes in the absolute air-kerma rate determination of up to 3×10^{-3}. The net effect on the ratio of the BEV and BIPM standards is much smaller, as indicated in the final row of Table 9. These revised results show less of a trend with radiation quality. It should be noted, however, that neither laboratory has as yet adopted these new values.

A summary of the results of BIPM comparisons of air-kerma standards for low-energy x-rays, including the present comparison, is presented in Figure 1.

Table 10. Values for correction factors calculated by Burns [5]†.

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
BIPM standard					
k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0
k_{sc}	0.996 2	0.997 3	0.997 4	0.997 8	0.998 0
k_{fl}	0.994 7	0.996 6	0.996 7	0.997 8	0.998 3
BEV PKK standard					
k_e	1.000 0	1.000 0	1.000 0	1.000 1	1.000 3
k_{sc}	0.997 0	0.997 9	0.998 0	0.998 3	0.998 5
k_{fl}	0.995 1	0.996 8	0.997 0	0.998 0	0.998 5

† The type A uncertainties associated with the stated values are less than 1×10^{-4}. The type B uncertainties have yet to be evaluated rigorously, but approximate values are: 5×10^{-4} for k_{sc}, 7×10^{-4} for k_{fl} and less than 2×10^{-4} for k_e.

References

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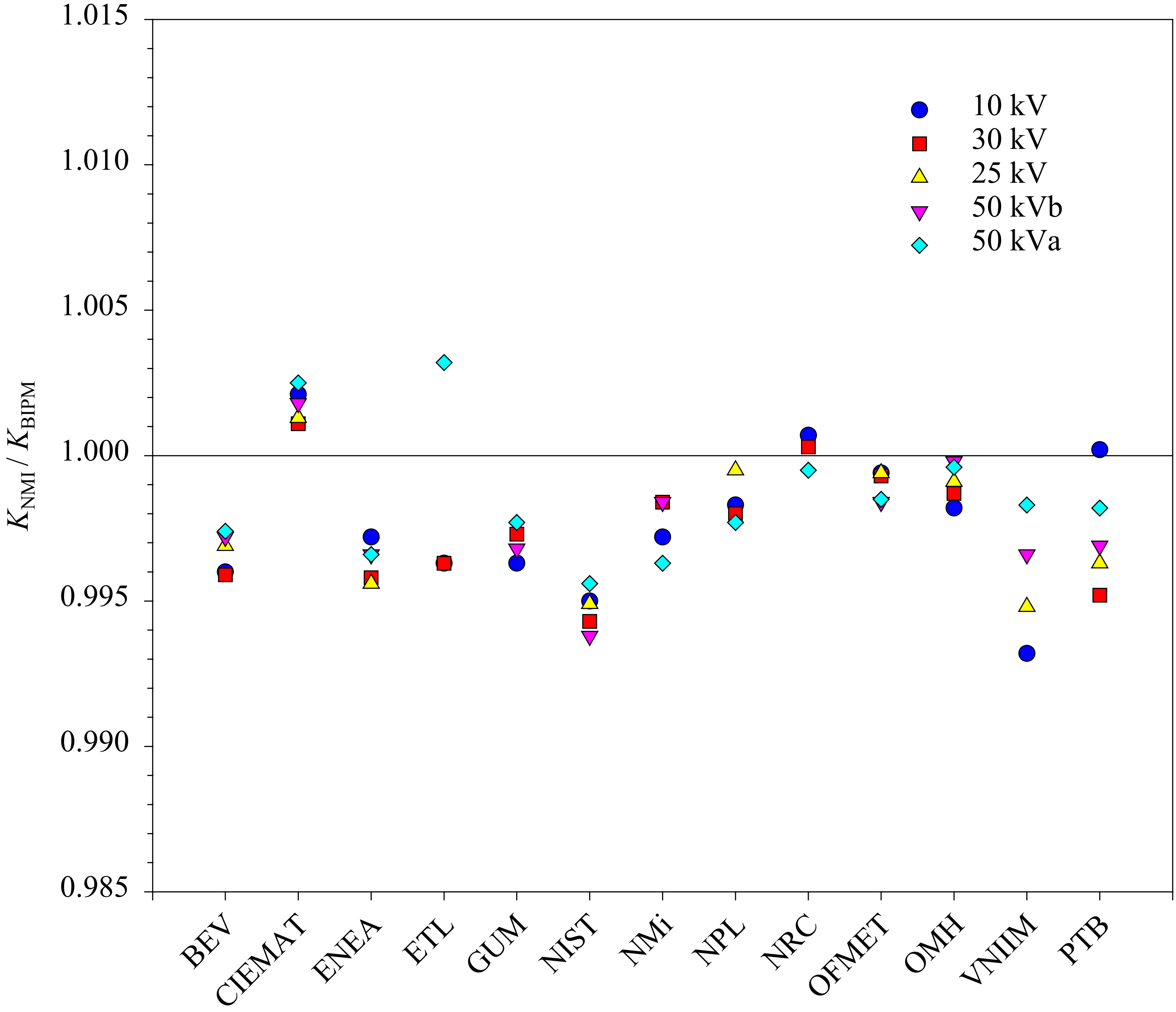

Figure 1. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once at the BIPM, only the results of the most recent comparison are included.