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Comparison of the air-kerma standards of the OMH 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 OMH and the BIPM in the low-energy x-ray range. The results at the different radiation qualities show the standards to be in close agreement with respect to the combined relative standard uncertainty of the comparison of 2.5×10^{-3}.

1. Introduction

A direct comparison has been made between the air-kerma standards of the Országos Mérésügyi Hivatal (OMH), Hungary, 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 $\Pi\, k_{\text{i}}$ 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 OMH XE-3 standard was previously compared with the BIPM standard in a direct comparison carried out at the BIPM in 1988, the results of which are reported in [4]. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

[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 $k_{\text{h}} = 0.9980$, 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	OMH XE-3
Aperture diameter / mm	4.9992	4.9995
Air path length / mm	100.0	63.7
Collecting length / mm	15.466	40.94
Electrode separation / mm	70	60.0
Collector width / mm	71	60.4
Measuring volume / mm^3	303.58	803.69
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 when the same aluminium filter is used. 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 OMH 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 OMH 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
μ_{air}† / 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 4	1.000 4	1.000 4	1.000 4	1.000 4	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 OMH 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 OMH.

Table 5. Correction factors for the OMH standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	u_{iA}	u_{iB}
Air attenuation k_a †	1.1189	1.0281	1.0199	1.0057	1.0029	0.0002	0.0001
Scattered radiation k_{sc}	0.9968	0.9977	0.9977	0.9982	0.9984	-	0.0015
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0002	-	0.0005
Ion recombination k_s	1.0005	1.0005	1.0005	1.0005	1.0005	0.0004	0.0001
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0005
Aperture edge transmission k_l	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	0.0001	0.0001
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.0002

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

3.3 Chamber positioning and measurement procedure

The OMH 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 for all qualities.

The air temperature for the OMH 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 the BIPM chamber the leakage current, relative to the ionization current, was less than 2×10^{-4} and for the OMH chamber around 3×10^{-4}. The relative standard uncertainty of the mean of a series of seven measurements for the OMH standard at each polarity was less than 2×10^{-4}, with no polarity difference measurable at this level. 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 OMH 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 Radcal 10X5-6M, serial number 8626, was calibrated at the BIPM. This chamber had previously been calibrated at the

OMH and subsequent to the BIPM measurements was recalibrated at the OMH. No build-up cap was used for the calibrations at either laboratory.

The calibration conditions at the two laboratories differ somewhat. The OMH calibrations were carried out at a distance of 500 mm with field diameter 60 mm, whereas the BIPM calibrations were at 500 mm with field diameter 95 mm. The characteristics of the OMH radiation qualities are given in Table 6 and those for the BIPM in Table 3. A second BIPM calibration for the 50 kVb quality at 4.6 mGy s^{-1} (instead of the standard 1.0 mGy s^{-1}) gave a calibration coefficient higher by the factor 1.001 1 (0.000 2). From this one can deduce a set of correction factors for the differences in the OMH and BIPM air-kerma rates, as given in the table.

The calibration coefficients at 20 °C and 101.325 kPa and for a polarizing voltage of 250 V (positive polarity) are given in Table 6. The OMH value at each radiation quality is the result of a single calibration before and after the BIPM measurements. For all qualities other than 10 kV a decrease is evident, indicating a change in the chamber response. The statistical relative standard uncertainty of the OMH mean value at each quality (other than 10 kV) is estimated to be 2.6×10^{-3}. The 10 kV results at the OMH have a larger uncertainty arising from air attenuation. 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. The results at 10 kV and 30 kV are corrected for the aperture effect noted in Section 4.2.

Table 6. Calibration coefficients for transfer chamber Radcal / 8626

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
OMH Al filtration / mm	0	0.235	0.455	1.13	4.24
OMH Al HVL / mm	0.034	0.17	0.25	1.03	2.25
OMH $\mu_{air}^{\dagger}$ / 10^{-3} mm^{-1}	1.90	0.402	0.264	0.081	0.046
$\dot{K}_{OMH}$ / mGy s^{-1}	0.9	4.2	1.9	2.7	0.8
$N_{K,OMH}$ (pre-comp) / Gy μC^{-1}	4.800	4.812	4.812	4.865	4.915
$N_{K,BIPM}$ / Gy μC^{-1}	4.890	4.820	4.811	4.822	4.876
$N_{K,OMH}$ (post-comp) / Gy μC^{-1}	4.822	4.790	4.806	4.842	4.897
Recombination corr to $N_{K,OMH}$	1.000 0	0.999 1	0.999 7	0.999 5	1.000 0
$N_{K,OMH}$ / $N_{K,BIPM}$	0.985 2	0.995 9	0.999 3	1.006 1	1.006 3

† Air attenuation coefficient at 293.15 K and 100 kPa, measured at the OMH for an air path length of 63.7 mm.

The combined relative standard uncertainty for OMH calibrations is 6×10^{-3}, except for the 10 kV quality where it is 1×10^{-2} (the higher value due to the air-attenuation correction). For the BIPM the value is 2.0×10^{-3}. Given these uncertainties, the indirect comparison shows the standards to be in reasonable agreement, except for the 10 kV quality. Agreement with the results of the direct comparison is poorer than one might expect from the statistical uncertainties. This may be due to problems associated with the x-ray tube set-up and beam profile at the OMH.

4.2 Comparison of apertures

Using an appropriate adaptor, the OMH aperture of diameter 4.999 5 mm was alternated in the BIPM chamber with the BIPM aperture of diameter 4.999 2 mm. The parameter of interest, i_a, is the ionization current per unit aperture area and the ratio $i_{a,OMH} / i_{a,BIPM}$ was measured as a function of radiation quality. The results are given in Table 7.

The spread of the results for the three higher qualities is consistent with the statistical standard uncertainty of 0.000 3 for each measured value, with mean value 0.999 8. However, the results show a decrease towards the lower qualities. This effect was also evident when the same two apertures were compared in 1988. These results are also given in the table, revised from the published value [4] to account for the new estimate of the OMH aperture diameter (the 1998 value being 5.004 mm). Recent measurements at the BIPM suggest that the trend with energy appears to be related to the use of the small BIPM aperture; measurements with the larger BIPM aperture (diameter 0.9941 mm) do not show this trend. To account for this effect, data from various aperture comparisons have been used to derive the correction factors 1.001 4 (0.000 4) and 1.000 6 (0.000 3) for the use of the small BIPM aperture at the 10 kV and 30 kV qualities, respectively.

Table 7. Results of aperture comparisons

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$i_{a,OMH} / i_{a,BIPM}$ (present)	0.998 2	0.999 1	0.999 6	1.000 1	0.999 7
1988 (revised)	0.998 9	-	0.999 5	1.000 4	1.000 5

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		OMH	
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	0.000 5
Positioning	0.000 1	0.000 1	0.000 1	0.000 1
Correction factors (excl. k_h)	0.000 3	0.001 0	0.000 5	0.001 7
Humidity k_h	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}_{\text{Standard}}$	0.000 6	0.001 9	0.001 2	0.002 3
	0.002 0		0.002 6	
$\dot{K}_{\text{OMH}} / \dot{K}_{\text{BIPM}}$	$u_c = 0.002\,5^{\dagger}$			

† 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 OMH. In particular, the air-attenuation correction at the OMH has a larger uncertainty.

The relative combined standard uncertainty u_c of the ratio $\dot{K}_{OMH}/\dot{K}_{BIPM}$ takes into account correlations in the type B uncertainties associated with the determination of the ionization current, the humidity correction and the physical constants.

6. Results and discussion

The comparison results are given in bold in Table 9. General agreement at around 1×10^{-3} is observed, which is well within the combined standard uncertainty. There is evidence of a slight trend with radiation quality.

Table 9. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa
$\dot{K}_{OMH}/\dot{K}_{BIPM}$	**0.998 2**	**0.998 7**	**0.999 1**	**0.999 8**	**0.999 6**
Previous result (1988)	0.997 3	-	0.999 4	1.001 0	1.002 0
Present using Burns [5]	0.997 0	0.997 4	0.998 0	0.999 0	0.999 1

The present results are within around 1×10^{-3} of those obtained in the comparison of 1988 [4], also given in the table. Since that time, there have been changes in the OMH values for k_{sc} and the OMH estimate of the aperture diameter (the same aperture was used but estimated at that time to be 5.004 mm in diameter). The recombination corrections used by both laboratories are also changed. However, these changes do not explain the small difference between the present results and those of 1988.

More recent values for the correction factors k_{sc} and k_e have been calculated by Burns [5] using the Monte Carlo code EGSnrc [6], both for the OMH and BIPM standards. 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 OMH and BIPM standards is smaller, as indicated in the final row of Table 9, and arises mainly from the revised values for k_{sc} for the BIPM standard. Inclusion of the Monte Carlo values for these correction factors does not explain the slight trend with radiation quality. It should be noted that the BIPM has not yet adopted Monte Carlo values, nor has the OMH in the case of k_{fl}.

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
OMH XE-3 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.

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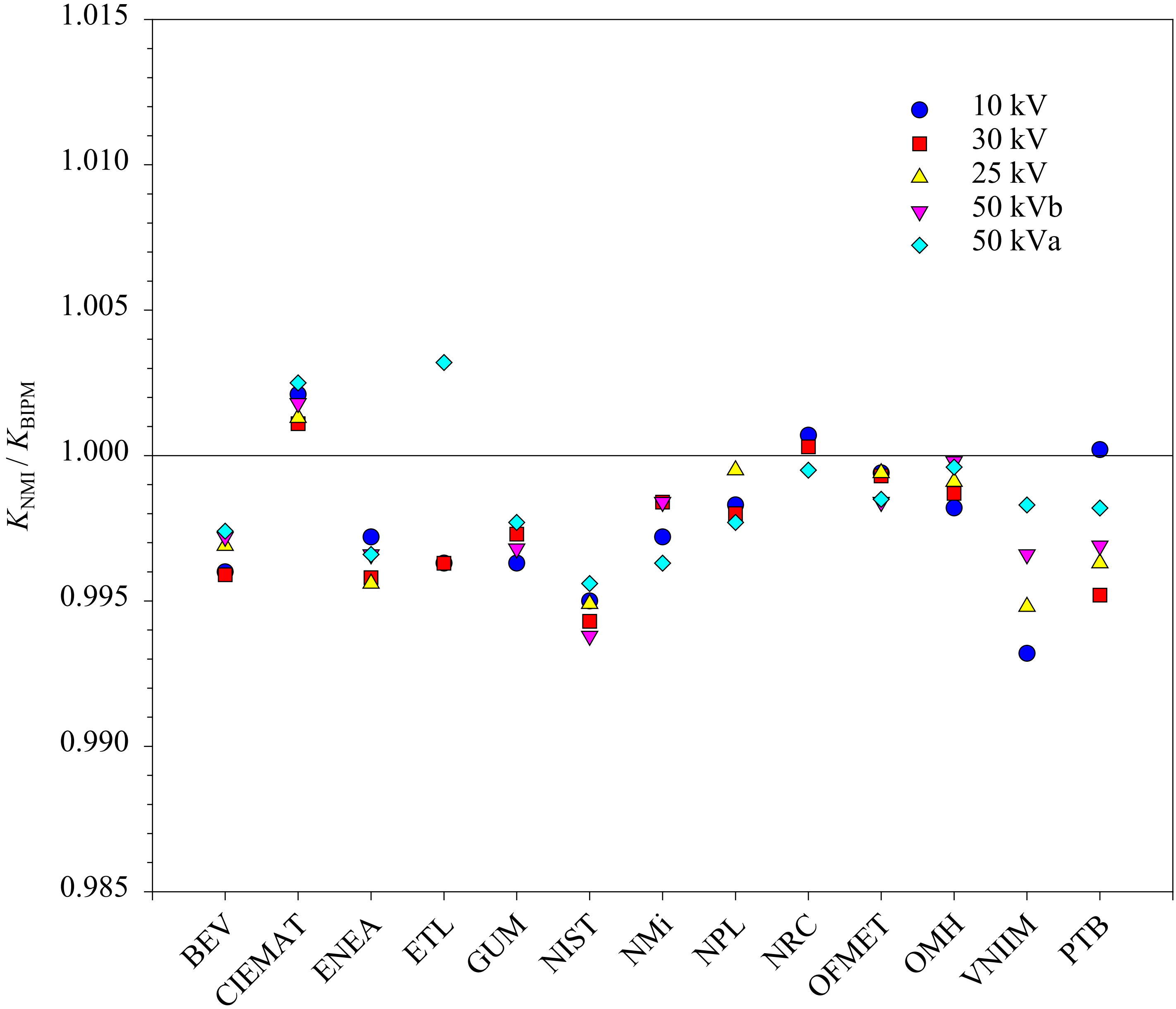

Figure 1. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once at the BIPM, only the results of the most recent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