Rapport BIPM-99/05

Bureau International des Poids et Mesures

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August 1999

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Comparison of the air-kerma standards of the NIST 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 NIST and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement to around 0.5 % at reference beam qualities up to 50 kV and at 100 kV. Agreement at the 80 kV quality is less satisfactory, which may be attributed to an incorrect value for the electron-loss correction for the NIST standard at this quality.

1. Introduction

A direct comparison has been made between the air-kerma standards of the National Institute of Standards and Technology (NIST) and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 100 kV. The comparison took place at the BIPM in July 1998 using the reference conditions recommended by the CCEMRI [1]. Two NIST primary-standard free-air ionization chambers were used for the comparison. The Lamperti chamber operates in the range from 10 kV to 60 kV and is the national standard for beam qualities of 15 kV and below. The Ritz chamber operates in the range from 20 kV to 100 kV and is the national standard for beam qualities in this range.

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

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

where

$I / \rho_{\mathrm{air}} V$ is the mass ionization current measured by the standard,
W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in dry air,
g_{air} is the 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 for the physical constants used in the determination of the air-kerma rate are given in Table 1.

3. Details of the standards

All three 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 plate. The BIPM air-kerma standard is described in [2] and [3]. The Lamperti standard of the NIST was previously compared with the BIPM standard in a direct comparison carried out at the BIPM in 1966, the results of which are reported in [2]. Details of the Lamperti chamber are given in [2] and [4]. Details concerning the Ritz standard, which has not previously been compared with the BIPM standard, can be found in [5]. The main dimensions, the measuring volume and the polarizing voltage for all three chambers are shown in Table 2.

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	$s^{\dagger}$ x 10^2
ρ_{air} ‡	1.293 kg m^{-3}	0.01
W_{air} / e	33.97 J C^{-1}	0.15
$1 - g_{air}$	1.000 0	0.01

† Here, s is the relative standard uncertainty.

‡ Density of dry air at 273.15 K and 101 325 Pa.

Table 2. Main characteristics of the standards

Chamber	BIPM	Lamperti	Ritz
Air-path length / mm	100.0	39.2	127.4
Plate separation / mm	70	40	90
Collecting plate length / mm	15.466	10.135	70.03
Aperture diameter / mm	4.999 2†	4.994 3	10.001 7
Measuring volume / mm^3	303.58†	198.55	5 502.0
Polarizing voltage / V	1 500	1 500	5 000

† For comparison with the Ritz standard an aperture of diameter 9.941 mm was used in the BIPM standard, which gives a measuring volume of 1200.4 mm^3.

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 (maximum usable generating potential 100 kV) and a tungsten-anode x-ray tube with an inherent filtration of 2.9 mm beryllium. Both the generating potential and the tube current are stabilized using feedback systems constructed at the BIPM; this results in a very high stability and obviates the need for a transmission current monitor. The variation in the measured ionization current over the duration of a comparison introduces a relative standard uncertainty of 4 x 10^{-4}. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCEMRI [1] and are given in Table 3 in ascending half-value layer (HVL) from left to right. For the Ritz standard, measurements were also made at the 80 kV and 100 kV qualities indicated in the table.

Table 3. Characteristics of the BIPM reference radiation qualities

Generating potential / kV	10	30	25	50(b)	50(a)	80	100
Al filtration / mm	0	0.208 2	0.373 4	1.008 2	3.989	3.041	3.451
Al HVL / mm	0.036	0.176	0.250	1.021	2.257	3.01	4.00
μ_{air}† / 10^{-3} mm^{-1}	1.757	0.415	0.304	0.091	0.046	0.042	0.035
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.56	3.31	1.13	1.57	0.34	0.61	0.84

† Air attenuation coefficient at 293.15 K and 100 000 Pa, measured at the BIPM for an air-path length of 100 mm.

3.2 Correction factors

The correction factors applied to each chamber at each radiation quality, together with their associated uncertainties, are given in Table 4 for the BIPM standard and in Tables 5 and 6 for the Lamperti and Ritz standards, respectively.

Table 4. Correction factors for the BIPM standard

Generating potential / kV	10	30	25	50(b)	50(a)	80	100	s x 10^2	
								type A	type B
Air attenuation k_a†	1.192 1	1.042 4	1.030 9	1.009 1	1.004 6	1.004 2	1.003 5	0.03	0.01
Scattered radiation k_{sc}	0.994 4	0.995 6	0.995 7	0.996 6	0.997 1	0.997 4	0.997 4	-	0.07
Electron loss k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.010 0	1.020 7	-	0.01‡
Ion recombination k_s§	1.000 5	1.000 7	1.000 5	1.000 6	1.000 5	-	-	0.02	0.01
Ion recombination k_s¶	1.000 7	1.001 9	1.001 0	1.001 1	1.000 6	1.000 6	1.000 8	0.02	0.01
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.07
Aperture transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.999 7	0.999 7	-	0.01
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.01	-
Humidity k_h	0.998	0.998	0.998	0.998	0.998	0.998	0.998	-	0.03

† These are nominal values for 293.15 K and 100 000 Pa; each measurement is corrected using the air temperature and pressure measured at the time.
‡ For qualities above 50 kV, the value is 0.15 x 10^{-2}.
§ For an aperture of diameter 4.999 2 mm.
¶ For an aperture of diameter 9.941 mm.

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 calculated using the measured air attenuation coefficients μ_{air} given in Table 3 (in units of inverse length). In practice, the values used deviate slightly from those given in the tables. This is because the attenuation varies with the temperature and pressure of the air in the chamber and the values for k_a used are corrected for this effect. The value for k_a for the Lamperti chamber at 10 kV has been increased by the factor 1.000 9 to account for the larger mean air attenuation coefficient for an air path of 39.2 mm (the values given in Table 3 were measured at the BIPM for an air path of 100 mm). This effect is negligible at the other beam qualities. All ionization measurements are also corrected for the temperature and pressure of the ambient air between the radiation source and the reference plane using the air attenuation coefficients given in Table 3.

Table 5. Correction factors for the Lamperti standard

Generating potential / kV	10	30	25	50(b)	50(a)	$s \times 10^2$	
						type A	type B
Air attenuation k_a†	1.072 1	1.016 4	1.012 0	1.003 6	1.001 8	0.03	0.01
Scattered radiation k_{sc}	0.996 0	0.996 7	0.996 9	0.997 5	0.997 9	-	0.20
Electron loss k_e	1.000	1.000	1.000	1.001	1.005	-	0.10
Ion recombination k_s	1.000 0	1.000 1	1.000 0	1.000 0	1.000 0	0.04	-
Field distortion k_d	1.000	1.000	1.000	1.000	1.000	-	0.20
Aperture transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 2	-	0.01
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.01
Humidity k_h	0.998	0.998	0.998	0.998	0.998	-	0.10

† These are nominal values for 293.15 K and 100 000 Pa; each measurement is corrected using the air temperature and pressure measured at the time.

Table 6. Correction factors for the Ritz standard

Generating potential / kV	30	25	50(b)	50(a)	80	100	$s \times 10^2$	
							type A	type B
Air attenuation k_a†	1.054 3	1.039 5	1.011 7	1.005 9	1.005 4	1.004 5	0.03	0.01
Scattered radiation k_{sc}	0.994 1	0.994 4	0.995 6	0.996 3	0.996 6	0.996 8	-	0.20
Electron loss k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.001 2	1.007 4	-	0.10
Ion recombination k_s	1.000 4	1.000 1	1.000 1	1.000 0	1.000 0	1.000 2	0.04	-
Field distortion k_d	1.000	1.000	1.000	1.000	1.000	1.000	-	0.20
Aperture transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.04
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.01
Humidity k_h	0.998	0.998	0.998	0.998	0.998	0.998	-	0.10

† These are nominal values for 293.15 K and 100 000 Pa; each measurement is corrected using the air temperature and pressure measured at the time.

All measured ionization currents are corrected for ion recombination. For comparison with the Ritz standard, the usual BIPM aperture of diameter 4.999 2 mm was replaced by an aperture of diameter 9.941 mm; values for the ion recombination correction k_s for each BIPM aperture diameter are given in Table 4. For the NIST chambers, the values for k_s given in Tables 5 and 6 are derived from measurements at the NIST using the BIPM air-kerma rates given in Table 3.

3.3 Chamber positioning and measurement procedure

For each comparison, the appropriate NIST chamber was positioned close to the BIPM chamber and both chambers remained fixed throughout a comparison; alternating 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. A movement of 0.1 mm off-axis changes the measured current by around 0.03 % at 10 kV and at 50 kV. No correction is applied for the radial non-uniformity of the beam since the aperture diameters are closely matched. The reference plane for each chamber was positioned at 500 mm from the radiation source for all qualities up to 50 kV and at 750 mm for the 80 kV and 100 kV 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 up to 50 kV, 68 mm for the 80 kV quality and 135 mm for the 100 kV quality.

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 and Ritz chambers the leakage current was less than 0.03 % of the ionization current and for the Lamperti chamber less than 0.02 %. Each measurement series consisted of five measurements, the integration time for each measurement chosen between 20 s and 80 s. The relative standard uncertainty of the mean of a series of five measurements was typically less than 2×10^{-4}, in the worst case 4×10^{-4}. Taking into account the relative standard uncertainty of 4×10^{-4} arising from the variation in the measured ionization current over the duration of a comparison, a type A relative standard uncertainty of 5×10^{-4} is taken for all current measurements. For all chambers, measurements were made at both polarities to correct for any polarity effect. The measured difference was typically 0.11 % for the BIPM chamber, 0.02 % for the Lamperti chamber and around 0.06 % for the Ritz chamber.

Due to a failure of the NIST temperature probe, the air temperature for the Lamperti chamber was taken to be that measured by the thermistor positioned in the BIPM capacitor bank; a series of tests showed this procedure to be accurate to better than 0.05 K. For the Ritz chamber, the air temperature was measured using a BIPM mercury thermometer calibrated to 0.02 K and positioned in the holder of the Ritz chamber. For the Ritz chamber the polarizing voltage was applied for the duration of the comparison so as to maintain temperature equilibrium. All ionization measurements are corrected to a temperature of 273.15 K and a pressure of 101 325 Pa.

4. Comparison of apertures

The Lamperti aperture of diameter 4.994 3 mm was positioned in the BIPM chamber, replacing the BIPM aperture of diameter 4.999 2 mm. This moved the measurement plane towards the radiation source by 12.0 mm and the source was therefore moved back correspondingly. The current measured at 25 kV by the BIPM standard under these conditions was corrected for the 12.0 mm of additional attenuation and for the decrease in aperture diameter. The resulting air-kerma rate determination was 0.10 % less than the usual BIPM determination at 25 kV (measured with a relative standard uncertainty of 2×10^{-4}).

A similar procedure was used for the Ritz chamber at 25 kV, interchanging the BIPM 9.941 mm and the Ritz 10.001 7 mm apertures in both the BIPM and the Ritz chambers (a source movement of 3.0 mm was required between apertures). Agreement for these apertures was much better, within the relative standard uncertainty of the measurement (2 x 10^{-4}).

5. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 7. In general, the quoted uncertainties in the air-kerma rate determination are representative of those associated with routine air-kerma rate determinations at both institutions. The uncertainties associated with the measurement of the ionization current and with chamber positioning are those which apply to measurements at the BIPM and are different from those in routine use for air-kerma rate determinations at the NIST.

The uncertainties of the ratios $\dot{K}_{\text{NIST}}/\dot{K}_{\text{BIPM}}$ take 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 data set.

Table 7. Uncertainties associated with the comparison results

Standard	BIPM		Lamperti		Ritz	
s x 10^2	type A	type B	type A	type B	type A	type B
Ionization current	0.05	0.02	0.05	0.02	0.05	0.02
Volume	0.03	0.05	0.04	0.01	0.04	0.01
Positioning	0.01	0.01	0.01	0.03	0.01	0.03
Correction factors (excl. k_h)	0.04	0.10†	0.05	0.30	0.05	0.30
Humidity k_h	-	0.03	-	0.10	-	0.10
Physical constants	-	0.15	-	0.15	-	0.15
Quadratic summation	0.07	0.19†	0.08	0.35	0.08	0.35
s ($\dot{K}_{\text{LAB}}$) x 10^2	0.20†		0.36		0.36	
s ($\dot{K}_{\text{NIST}}/\dot{K}_{\text{BIPM}}$) x 10^2	-		0.34		0.34‡	

† Applies up to 50 kV only. The increase in the relative standard uncertainty of k_e for the BIPM standard from 1 x 10^{-4} to 1.5 x 10^{-3} at 80 kV and 100 kV increases the relative uncertainty of $\dot{K}_{\text{BIPM}}$ to 2.5 x 10^{-3} for these qualities.

‡ The increased uncertainty of k_e for the BIPM standard at 80 kV and 100 kV increases the relative standard uncertainty of the ratio $\dot{K}_{\text{RITZ}}/\dot{K}_{\text{BIPM}}$ to 3.7 x 10^{-3} for these qualities.

6. Results and discussion

The comparison results are given in Table 8. For the Ritz and BIPM standards agreement at the 0.5 % level is observed (one and a half times the standard uncertainty), except for the 80 kV result. This result at 80 kV most likely arises from the value k_e = 1.0012 used for the Ritz standard at this quality, which is probably too low. Evidence for the underestimation of k_e values for small chambers used at higher beam qualities comes from measurements at the BIPM using the magnetic-field technique and from the comparison of the BIPM low- and medium-energy standards at energies up to 100 kV. More recent confirmation comes from Monte Carlo calculations by Burns [6] and by Grimbergen *et al* [7]. The values for the correction factors k_e and k_{sc} for the Ritz chamber are currently being re-evaluated at the NIST for some new reference radiation qualities under development and a change to the value for k_e at 80 kV is expected. In addition, Monte Carlo calculations of k_e and k_{sc} are in progress at the BIPM [6], including calculations for the Lamperti and Ritz chambers.

Table 8. Comparison results

Generating potential / kV	10	30	25	50(b)	50(a)	80	100
$\dot{K}_{LAMPERTI}/\dot{K}_{BIPM}$	0.9950	0.9961	0.9968	0.9948	0.9938	-	-
Previous result (1966)	0.9976	0.9989	-	0.9966	0.9948	-	-
$\dot{K}_{RITZ}/\dot{K}_{BIPM}$	-	0.9943	0.9949	0.9938	0.9956	0.9902	0.9947

It is also interesting to compare the measured values for the ratio $\dot{K}_{LAMPERTI}/\dot{K}_{RITZ}$ given in the table. At the 25 kV and 30 kV qualities this has the value 1.0018 (within 0.01 %), but at 50 kV(b) and 50 kV(a) decreases to 1.0010 and 0.9982, respectively. If these results are used as a *measure* of k_e for the Lamperti standard, one obtains the values k_e = 1.0018 and k_e = 1.0087, in comparison with the values k_e = 1.001 and k_e = 1.005 used at present. Note that at these qualities it is the Ritz chamber which is the national standard.

For the lower beam qualities the Lamperti and BIPM standards agree at around the 0.4 % level. The result of the aperture comparison explains 0.1 % of the difference between the two standards. The results are slightly further from unity than those of the previous comparison in 1966, particularly at the lower beam qualities. Small changes in the values adopted for k_{sc} and k_s for both standards account for around 0.05 % of the difference between the new and old results.

A summary of the results of BIPM comparisons of air-kerma standards for low-energy x-rays, including the present comparison, are presented in Annex A. For the NIST, the values quoted are those obtained using the Ritz standard, except the 10 kV result which is that obtained using the Lamperti standard.

References

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[7] GRIMBERGEN T.W.M., VAN DIJK E. and DE VRIES W., Correction factors for the NMi free-air ionization chamber for medium-energy x rays calculated with the Monte Carlo method, *Physics in Medicine and Biology*, 1998, 43, 3207-3224, and private communication.

Annex A

The results of BIPM comparisons of air-kerma standards for low-energy x-rays are presented in Table A.1. For laboratories which have compared more than once at the BIPM, only the results of the most recent comparison are included. The same data are presented in graphical form in Figure A.1.

Table A.1 Results of BIPM low-energy x-ray comparisons, expressed as $\dot{K}_{\mathrm{NMI}}/\dot{K}_{\mathrm{BIPM}}$.

NMI	Country	Date	Generating potential / kV				
			10 kV	30 kV	25 kV	50 kV(b)	50 kV(a)
NRC	Canada	1966	1.000 7	1.000 3	-	-	0.999 5
ETL	Japan	1972	0.996 3	0.996 3	-	-	1.003 2
CIEMAT	Spain	1979	1.002 1	1.001 1	1.001 3	1.001 8	1.002 5
OMH	Hungary	1988	0.997 3	-	0.999 4	1.001 0	1.002 0
GUM	Poland	1994	0.996 3	0.997 3	-	0.996 8	0.997 7
NMi	Netherlands	1996	0.997 2	0.998 4	-	0.998 4	0.996 3
NPL†	UK	1997	0.998 3	0.998 0	0.999 5	-	0.997 7
NIST	USA	1998	0.995 0	0.994 3	0.994 9	0.993 8	0.995 6
OFMET	Switzerland	1998	0.999 4	0.999 3	0.999 4	0.998 4	0.998 5
ENEA	Italy	1998	0.997 2	0.995 8	0.995 6	0.996 6	0.996 6

† The results for this laboratory are provisional; BIPM report still in preparation.

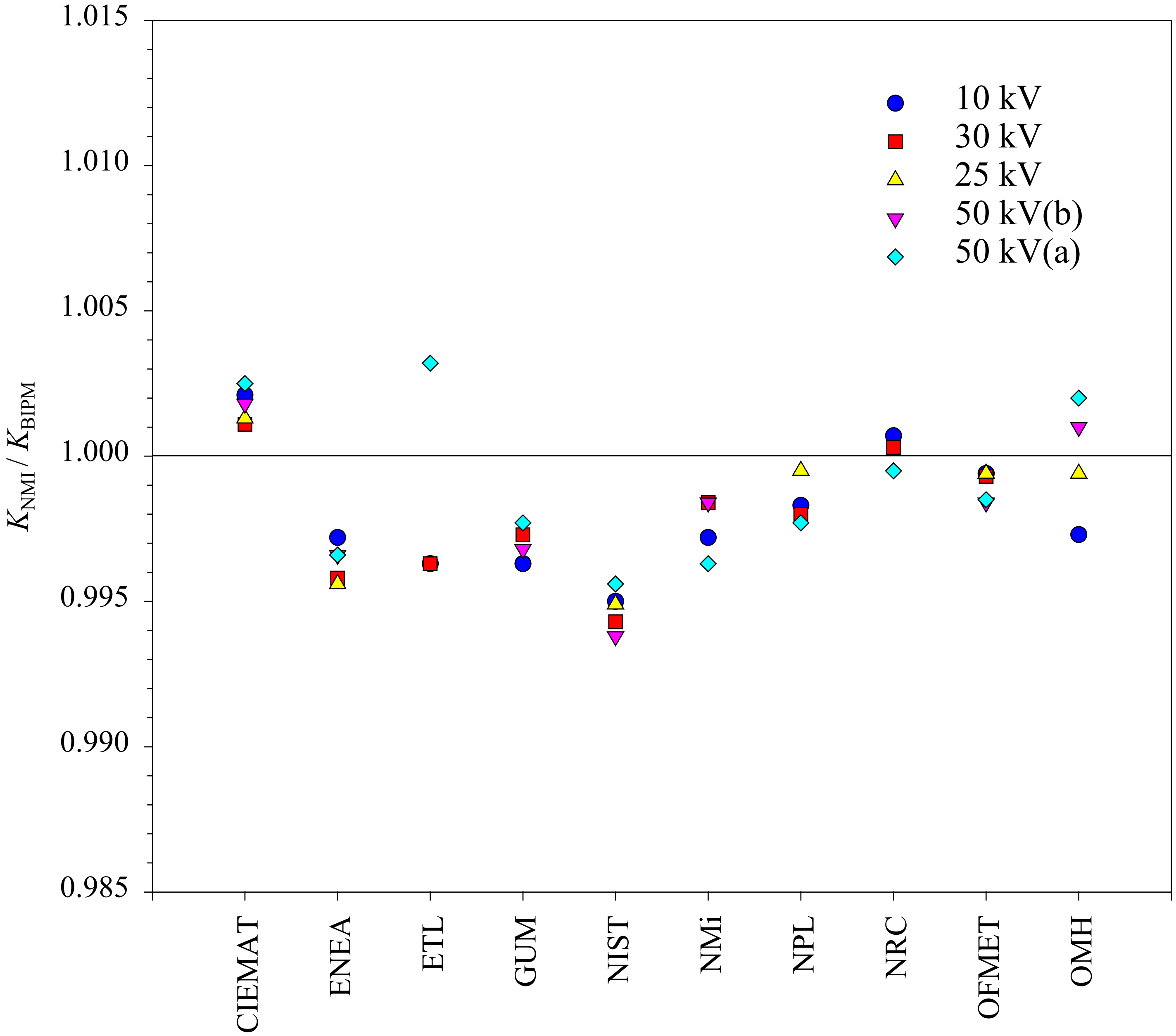

Figure A.1. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the NMI standard to that determined by the BIPM standard. The results for the NPL are provisional.