Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the VNIIM, Russian Federation, 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 VNIIM and the BIPM in the medium-energy x-ray range. The results show the standards to be in agreement at the level of the standard uncertainty of the comparison of 1.9 parts in 10^3. 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 D. I. Mendeleyev Institute for Metrology (VNIIM), Russian Federation, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 100 kV to 250 kV. Two cavity ionization chambers were used as transfer instruments. The measurements at the BIPM took place in August 2020 using the reference conditions recommended by the CCRI (CCEMRI 1972). The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

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

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

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 fraction of the initial electron energy lost through radiative processes in air, and $\Pi\, k_{\text{i}}$ is the product of the correction factors to be applied to the standard.

The value used for ρ_{air} at each laboratory is 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]. The value used for W_{air}/e is that recommended in ICRU Report 90 (ICRU 2016), also given in Table 1.

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. The BIPM air-kerma standard is described in Boutillon (1978) and the changes made to certain correction

[1] For an air temperature $T \sim 293$ K, pressure P and relative humidity ~50 % in the measuring volume, the correction for air density involves a temperature correction T / T_0, a pressure correction P_0 / P, a humidity correction $k_{\text{h}} = 0.9980$. At the BIPM, the factor 1.0002 is also included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

factors are given in Burns (2004) and Burns *et al.* (2009). The changes made to the standard following the recommendations of ICRU Report 90 (ICRU 2016) are given in Burns (2018). The VNIIM standard is described in Oborin *et al.* (2012) and the changes made to the standard following the recommendations of ICRU Report 90 (ICRU 2016) are given in Oborin *et al.* (2019) and Oborin *et al.* (2020). The VNIIM standard was previously compared with the BIPM standard in an indirect comparison carried out in 2010, the results of which are reported in Burns *et al.* (2011). 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 [a]
ρ_{air} [b]	1.2930 kg m^{-3}	0.0001
W_{air} / e	33.97 J C^{-1}	0.0035

[a] u_i is the relative standard uncertainty.
[b] 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 M-01	VNIIM
Aperture diameter / mm	9.939	16.007
Air path length / mm	281.5	448.7
Collecting length / mm	60.004	100.233
Electrode separation / mm	180	300
Collector width / mm	200	300
Measuring volume / mm^3	4655.4	20171
Polarizing voltage / V	4000	4000

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 and pressure chosen for the comparison (T = 293.15 K, P = 101.325 kPa). No humidity correction has been applied to the current measured using the transfer instruments, on the basis that the BIPM laboratory is maintained with a relative humidity in the range from 40 % to 55 % and the VNIIM laboratory in the range from 35 % to 55 %.

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

$$R_{K,\text{NMI}} = \frac{k_\text{Q} N_{K,\text{NMI}}}{N_{K,\text{BIPM}}} \qquad (3)$$

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 cavity ionization chambers belonging to the VNIIM, a thimble-type PTW TM30010 and a spherical Standard Imaging Exradin A3, were used as transfer instruments for the comparison. The same PTW TM30010 chamber was also used during the 2010 comparison. The main characteristics of the chambers are given in Table 3. Each chamber, without build-up cap, was positioned with the stem perpendicular to the beam direction and with the line on the stem facing the source. The reference point for the PTW TM30010 chamber is located 13 mm from the thimble tip and that for the Exradin A3 chamber 9.71 mm from the top of the sphere.

Table 3. Main characteristics of the transfer chambers

Chamber type	PTW TM30010	SI Exradin A3
Serial number	0526	XR172515
Geometry	thimble	spherical
External diameter / mm	7.0	19.5
Wall material	graphite + PMMA	Shonka air-equivalent plastic C552
Wall thickness / mm	0.425	0.25
Nominal volume / cm^3	0.6	3.6
Polarizing potential / V	+400 [a]	+300 [a]

[a] At both laboratories the potential is applied to the outer wall of the chamber.

5. Calibration at the BIPM

5.1 The BIPM irradiation facility and reference radiation qualities

The BIPM medium-energy x-ray laboratory houses a high-stability generator and a tungsten-anode x-ray tube with a 3 mm beryllium window. An aluminium filter of thickness 2.228 mm is added (for all radiation qualities) to compensate for the decrease in attenuation that occurred when the original BIPM x-ray tube (with an aluminium window of approximately 3 mm) was replaced in June 2004. Two voltage dividers monitor the tube voltage and a voltage-to-frequency converter combined with data transfer by optical fibre measures the anode current. No transmission monitor is used. For a given radiation quality, the standard uncertainty of the distribution of repeat air-kerma rate determinations over many months is better than 3 parts in 10^4. The radiation qualities used in the range from 100 kV to 250 kV are those recommended by the CCRI (CCEMRI 1972) 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 typically 0.2 °C. Two calibrated thermistors 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.

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
Inherent Be filtration / mm	3	3	3	3
Additional Al filtration / mm	3.431	2.228	2.228	2.228
Additional Cu filtration / mm	-	0.232	0.485	1.570
Al HVL / mm	4.030	-	-	-
Cu HVL / mm	0.149	0.489	0.977	2.484
$(\mu/\rho)_{air}$ [a] / $cm^2\ g^{-1}$	0.290	0.190	0.162	0.137
$\dot{K}_{BIPM}$ / $mGy\ s^{-1}$	0.50	0.50	0.50	0.50

[a] Measured at the BIPM using an evacuated tube of length 280 mm.

5.2 The 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 laterally on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is 98 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 1.00015 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 measured to be around 1 part in 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 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.

Two new correction factors, k_{ii} and k_W, are implemented following the recommendations of ICRU Report 90 (ICRU 2016) and presented as the product $k_{ii}k_W$ by Burns (2018). Both correction factors are related to the mean energy expended in dry air per ion pair formed, W_{air}. The initial ionization correction factor k_{ii} accounts for the fact that the definition of W_{air} does not include the charge of the initial charged particle, while the correction factor k_W accounts for the rapid increase in the value of W_{air} at electron energies below around 10 keV.

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 [a]	1.0099	1.0065	1.0055	1.0047	0.0002	0.0001
Photon scatter 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	1.0015	1.0047	1.0085	-	0.0005
Initial ionization k_{ii} / Energy dependence of W_{air} k_W	0.9980	0.9980	0.9981	0.9986	-	0.0005
Ion recombination k_s	1.0010	1.0010	1.0010	1.0010	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
Diaphragm correction k_{dia}	0.9995	0.9993	0.9991	0.9980	-	0.0003
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

[a] Values for the BIPM reference conditions of 293.15 K and 101.325 kPa; each measurement is corrected using the air temperature and pressure measured at the time.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each transfer chamber was positioned in the reference plane (1200 mm from the radiation source), with a reproducibility of 0.03 mm. Each 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 each chamber was typically below 1 part in 10^4.

For each transfer chamber and at each radiation quality, two or more sets of seven measurements were made, each measurement with integration time in the range from 40 s to 60 s. For each set the standard uncertainty of the mean ionization current was typically 1 part in 10^4. Repeat calibrations including repositioning were made for each chamber at several qualities. An uncertainty component of 3 parts in 10^4 is included in Table 11 for the short-term reproducibility of the calibration coefficients determined at the BIPM.

6. Calibration at the VNIIM

6.1 The VNIIM irradiation facility and reference radiation qualities

The medium-energy x-ray facility of the VNIIM comprises an ISOVOLT 320 HS industrial unit and a tungsten-anode x-ray tube with an inherent filtration of 3 mm beryllium. The short-term stability of the generating potential is about 1 part in 10^4. The x-ray output is monitored by means of a transmission ionization chamber whose aluminized Mylar windows introduce a filtration of 2.1 mg cm^{-2}. Short-term stability of the air-kerma rate relative to the transmission monitor is better than 2 parts in 10^4. The characteristics of the VNIIM realization of the CCRI comparison qualities (CCEMRI 1972) are given in Table 6.

Two calibrated platinum resistance thermometers are used to measure the air temperature, one positioned close to the measurement volume of the standard or transfer chamber under calibration and the second close to the transmission monitor. Over the duration of a calibration the temperature was stable to around 2 °C. Air pressure is measured by means of a calibrated barometer.

Table 6. Characteristics of the VNIIM reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.210	2.450	2.720	0.761
Additional Cu filtration / mm	-	0.231	0.465	1.550
Al HVL / mm	4.003	-	-	-
Cu HVL / mm	-	0.496	0.993	2.496
$(\mu/\rho)_{air}$ / cm^2 g^{-1}	0.268	0.188	0.168	0.144
$\dot{K}_{VNIIM}$ / mGy s^{-1}	0.95	0.94	0.93	0.94

6.2 The VNIIM standard and correction factors

The reference plane for the VNIIM standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.01 mm. The standard was aligned laterally on the beam axis to an estimated uncertainty of 0.2 mm. The beam diameter in the reference plane is 95 mm for all radiation qualities.

During the calibration of the transfer chamber, measurements using the VNIIM standard were made at both polarities to correct for any polarity effect in the standard. The measured difference was typically 5 parts in 10^4. The relative leakage current was below 2 parts in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the VNIIM standard, together with their associated uncertainties, are given in Table 7. The correction factor k_a is evaluated using the measured air-attenuation coefficients 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 measurements. Ionization current 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.

The set of correction factors k_e, k_{sc}, k_{ap}, k_g and k_{CPE} is calculated using an EGSnrc application egs_fac (Mainegra-Hing *et al.* 2008). The correction k_g accounts for the actual geometry of the beam and takes into account any losses that arise from photons passing through the aperture with large angle, for example following scatter in the air path between the source and the aperture.

The correction factors k_{ii} and k_W are introduced following the recommendations of ICRU Report 90 (ICRU 2016) in the same way as at the BIPM. To obtain the product $k_{ii}k_W$ for the VNIIM radiation qualities the monoenergetic values for $k_{ii}k_w$ presented in the ICRU Report were interpolated to the effective energy for each quality. The stated uncertainty is that recommended by Burns (2018).

Table 7. Correction factors for the VNIIM standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0146	1.0102	1.0091	1.0078	0.0003	0.0001
Photon scatter and fluorescence k_{sc}	0.9909	0.9920	0.9933	0.9943	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0004	1.0015	-	0.0007
Initial ionization k_{ii} Energy-dependence of W_{air} k_W	0.9982	0.9978	0.9978	0.9984	-	0.0005
Ion recombination k_s	1.0020	1.0020	1.0020	1.0020	0.0002	0.0002
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0005
Aperture k_{ap}	0.9999	0.9995	0.9994	0.9993	-	0.0002
Beam geometry k_g	1.0000	1.0000	1.0000	1.0000	-	0.0002
Charged-particle equilibrium k_{CPE}	1.0000	1.0000	1.0000	1.0000	-	0.0001
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	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

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

6.3 Transfer chambers positioning and calibration at the VNIIM

The reference point for each transfer chamber was positioned at the reference distance (1000 mm from the radiation source), with a reproducibility of 0.01 mm. Alignment on the beam axis was to an estimated uncertainty of 0.1 mm.

The platinum resistance thermometer positioned close to the transfer chamber was used to measure the air temperature during the measurements. 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 each chamber was below 2 parts in 10^4.

For each transfer chamber and at each radiation quality, a set of eleven measurements was made, each measurement with integration time 100 s. For each set the standard uncertainty of the mean ionization current relative to the transmission monitor was below 2 parts in 10^4. Three such calibrations including repositioning were made for each chamber at each quality. In each case the standard uncertainty of the mean was below 4 parts in 10^4. An uncertainty component of 4 parts in 10^4 is included in Table 11 for the short-term reproducibility of the calibration coefficients determined at the VNIIM.

7. Additional considerations for transfer chambers calibrations

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

As can be seen from Tables 4 and 6, the air-kerma rates at the VNIIM are two times higher than those at the BIPM. However, even for the Exradin A3 chamber at the VNIIM air-kerma rates volume recombination is less than 2 parts in 10^4 and the difference in volume recombination at the two laboratories is less than 1 part in 10^4. Consequently, no corrections are applied for ion recombination. Each transfer chamber was used with the same polarity at each laboratory and so no corrections are applied for polarity effects in the transfer chambers.

No correction is applied at either laboratory for the radial non-uniformity of the radiation fields. For small chambers with cavity dimensions below 2 cm, the effect should be small and will cancel to some extent at the two laboratories. A relative standard uncertainty of 3 parts in 10^4 is introduced in Table 12 for this effect. There is no significant difference in the radiation field size at the two laboratories.

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 VNIIM 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 negligible uncertainty.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{VNIIM}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are given in Table 8 and the comparison results $R_{K,\mathrm{VNIIM}}$ evaluated according to Equation (3) are presented in Table 9. For each quality, the final result in bold in Table 9 is evaluated as the unweighted mean for the two transfer chambers. The standard uncertainty u_{tr} arising from the difference in the results for the two chambers is also given. The r.m.s. value of u_{tr} for the four qualities $u_{\mathrm{tr,comp}} = 0.0006$ is included in Table 12.

Also given in Table 9 are the results of the previous comparison of the VNIIM and BIPM standards (Burns *et al.* 2011), revised for the changes made to both standards. These are equivalent to the results currently available in the BIPM key comparison database (KCDB 2020) corrected for small differences in the VNIIM and BIPM implementations of the factor $k_{\mathrm{ii}}k_W$.

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 10 and those for the transfer chamber calibrations in Table 11. The combined standard uncertainty u_{c} for the comparison results $R_{K,\mathrm{VNIIM}}$ is presented in Table 12. The uncertainty u_{c} takes into account correlation in the type B uncertainties associated with the physical constants, the humidity correction and the product of the correction factors $k_{\mathrm{ii}}k_W$. Correlation in the values for k_{e}, k_{sc} and k_{fl} at the BIPM with those for k_{e} and k_{sc} at the VNIIM, derived from Monte Carlo calculations in each laboratory, are taken into account in an approximate way by assuming half of the uncertainty value for each factor at each laboratory. This is consistent with the analysis of the results of the BIPM comparisons in medium-energy x-rays in terms of degrees of equivalence described in Burns (2003).

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Transfer chamber PTW TM30010-0526				
$N_{K,\mathrm{VNIIM}}$ (pre-comp) / Gy μC^{-1}	48.40	48.32	48.35	48.44
$N_{K,\mathrm{VNIIM}}$ (post-comp) / Gy μC^{-1}	48.43	48.33	48.35	48.44
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	48.44	48.30	48.29	48.35
Transfer chamber Exradin A3- XR172515				
$N_{K,\mathrm{VNIIM}}$ (pre-comp) / Gy μC^{-1}	- [a]	- [a]	- [a]	- [a]
$N_{K,\mathrm{VNIIM}}$ (post-comp) / Gy μC^{-1}	7.777	7.804	7.836	7.868
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	7.766	7.793	7.819	7.848

[a] The VNIIM pre-comparison measurements for the Exradin A3 chamber were made with an adaptor cable that applied the polarizing voltage to the guard. A set of post-comparison measurements was also made with this configuration and verified the chamber stability at the 0.1 % level.

Table 9. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$R_{K,\mathrm{VNIIM}}$ using PTW TM30010-0526	0.9995	1.0005	1.0012	1.0019
$R_{K,\mathrm{VNIIM}}$ using Exradin A3- XR172515	1.0014	1.0014	1.0022	1.0025
Standard uncertainty u_{tr}	0.0010	0.0005	0.0005	0.0003
Final $R_{K,\mathrm{VNIIM}}$	**1.0005**	**1.0010**	**1.0017**	**1.0022**
Revised results of 2010 comparison	*1.0016*	*1.0016*	*1.0023*	*1.0024*

10. Discussion

The comparison results presented in Table 9 show the VNIIM and the BIPM standards to be in agreement at the level of the standard uncertainty of the comparison of 1.9 parts in 10^3. The present results are in reasonable agreement with those obtained during the 2010 comparison, given in the final row of Table 9. The slight increase with HVL might arise from the fact that the correction factor k_{ap} for the VNIIM standard has a smaller variation with HVL than that of the corresponding correction factor k_{dia} for the BIPM standard, although this variation was less evident in the results from 2010 determined using the same correction factors for both standards (excluding $k_{\mathrm{ii}}k_W$).

11. 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 Burns (2003). Following a decision of the CCRI, the BIPM determination of the air-kerma rate is taken as 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 the relative difference $D_i = (K_i - K_{\text{BIPM},i}) / K_{\text{BIPM},i} = x_\text{i} - 1$ and its expanded uncertainty $U_i = 2\ u_i$. The results for D_i and U_i, expressed in mGy/Gy and including those of the present comparison, are shown in Table 13 and in Figure 1, which include the linked results of the corresponding regional key comparisons APMP.RI(I)-K3 (Lee *et al.* 2008) and SIM.RI(I)-K3 (O'Brien *et al.* 2015).

When required, the degree of equivalence between two laboratories i and j can be evaluated as the difference $D_{ij} = D_i - D_j$ and its expanded uncertainty $U_{ij} = 2u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j (Burns 2003).

Table 10. Uncertainties associated with the standards

Standard	BIPM		VNIIM	
Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$	$u_{i\text{A}}$	$u_{i\text{B}}$
Ionization current	0.0002	0.0002	0.0002	0.0003
Volume	0.0001	0.0005	0.0002	0.0005
Positioning	0.0001	0.0001	0.0001	0.0001
Correction factors (excl. k_h)	0.0003	0.0011	0.0004	0.0015
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}$	0.0004	0.0037	0.0005	0.0039

Table 11. Uncertainties associated with the calibration of the transfer chambers

Laboratory	BIPM		VNIIM	
Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$	$u_{i\text{A}}$	$u_{i\text{B}}$
$\dot{K}$	0.0004	0.0037	0.0005	0.0039
Positioning of transfer chamber	0.0001	-	0.0001	0.0001
I_tr	0.0002	0.0002	0.0002	0.0003
Short-term reproducibility	0.0003	-	0.0004	-
N_K	0.0005	0.0037	0.0007	0.0039

12. Conclusions

The key comparison BIPM.RI(I)-K3 for the determination of air kerma in medium-energy x-rays shows the standards of the VNIIM and the BIPM to be in agreement at the level of the stated standard uncertainty of the comparison of 1.9 parts in 10^3. The results are in reasonable agreement with those of the 2010 comparison between the two standards.

Tables and graphs of degrees of equivalence, including those for the VNIIM, are presented for entry in the BIPM key comparison database. Note that the data presented in the tables, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database (KCDB 2020).

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{VNIIM}}/N_{K,\mathrm{BIPM}}$	0.0009	0.0015
$k_{\mathrm{rn,tr}}$	-	0.0003
Agreement between transfer chambers $u_{\mathrm{tr,comp}}$	0.0006	-
$R_{K,\mathrm{VNIIM}}$	0.0011	0.0015
	u_c = 0.0019	

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

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. Tables formatted as they appear in the BIPM key comparison database; red indicates participation in BIPM.RI(I)-K3, blue in APMP.RI(I)-K3 and green in SIM.RI(I)-K3.

	100 kV		135 kV		180 kV		250 kV	
Lab *i*	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i
GUM	0.9	5.6	3.8	5.6	3.5	5.6	4.5	5.6
ARPANSA	3.7	7.8	5.6	7.8	6.0	7.8	5.3	7.8
MKEH	-0.4	7.0	0.9	7.0	0.4	7.0	0.4	7.0
PTB	2.7	5.2	4.5	5.2	4.9	5.2	5.5	5.2
ENEA	3.9	6.2	4.2	6.2	7.3	6.2	5.6	6.2
BEV	3.2	6.4	4.7	6.4	4.1	6.4	1.1	6.4
NRC	3.1	6.6	2.3	6.6	1.3	6.6	0.4	6.6
NMIJ	-0.8	6.2	-1.4	6.2	-2.4	6.2	-3.7	6.2
VSL	-1.0	6.4	-0.4	6.4	0.0	6.4	-2.1	6.4
NIST	-2.2	7.8	-3.3	7.8	-2.7	7.8	-5.8	7.8
NIM	7.2	6.2	5.4	6.2	6.1	6.2	6.0	6.2
NPL	0.4	6.8	0.0	6.8	-2.5	6.8	-4.4	6.8
LNE-LNHB	0.5	7.6	-0.5	7.6	-1.0	7.6	-2.8	7.6
VNIIM	0.5	3.8	1.0	3.8	1.7	3.8	2.2	3.8
INER	3.7	4.6	4.3	4.6	6.0	4.6	5.5	4.6
Nuc. Malaysia	14.2	12.1	16.2	12.1	15.0	12.1	15.9	12.1
DMSc	-3.1	11.8	4.2	11.8	9.6	11.8	13.0	11.8
BARC	8.5	13.8					14.8	13.8
NMISA	4.5	5.6	2.0	5.6	4.8	5.6	7.5	5.6
KRISS	-8.4	5.2	1.1	5.2	6.6	5.2	7.6	5.2
IAEA	4.3	7.4	9.2	7.4	13.1	7.4	14.0	7.4
CNEA	-6.0	14.3	1.1	14.3	2.1	14.3	1.4	14.3
LMNRI/IRD	-9.5	12.1	-9.4	12.1	-8.0	12.1	-8.5	12.1
ININ	-9.3	16.1	-12.1	16.1	-11.1	16.1	-12.0	16.1

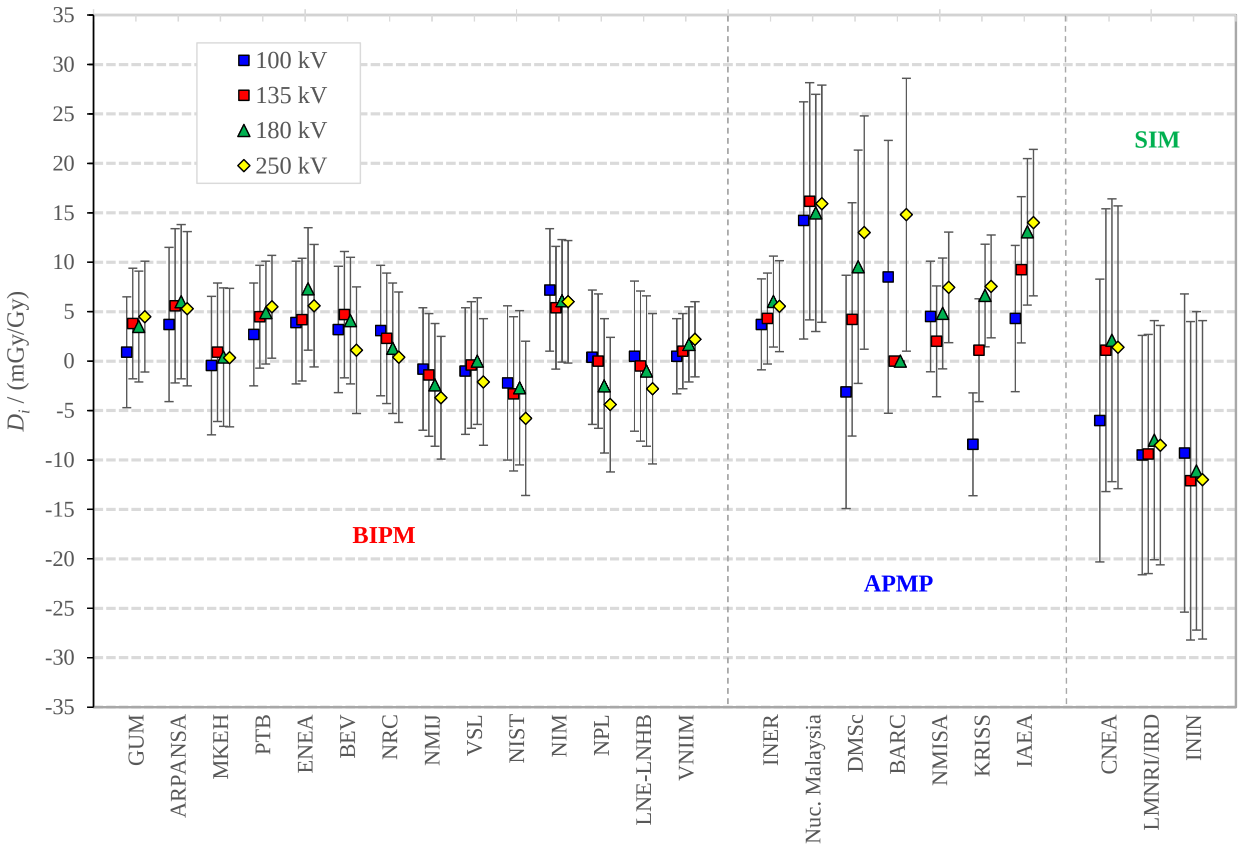

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K3, those in the middle section for the regional comparison APMP.RI(I)-K3 and those to the right for the regional comparison SIM.RI(I)-K3.

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