Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the KRISS, Republic of Korea, and the BIPM in medium-energy x-rays

D T Burns[1], C Kessler[1], Chul-Young Yi[2], Yun Ho Kim[2]

[1] Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92310 Sèvres
[2] Korea Research Institute of Standards and Science, Daejeon, Republic of Korea

Abstract A key comparison has been made between the air-kerma standards of the KRISS, Republic of Korea, and the BIPM in the medium-energy x-ray range. The results show the standards to be in agreement at the limit of the expanded uncertainty of the comparison of 4.4 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 Korea Research Institute of Standards and Science (KRISS), Republic of Korea, 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 February 2017 using the reference conditions recommended by the CCRI (CCEMRI 1972). Final results for the calibration of the transfer chambers at the KRISS were supplied in November 2021 following a long delay while the KRISS verified certain dimensional aspects of their standard. During this period, the recommendations of ICRU Report 90 (ICRU 2016) were implemented 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

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

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 $\Pi\, k_{\mathrm{i}}$ 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.

[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 and the dry-air humidity correction $k_{\mathrm{h}} = 0.9980$. At the BIPM, a factor 1.0002 is included to account for the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

3. Details of the standards

Both free-air chamber standards are of the conventional parallel-plate design. The BIPM air-kerma standard M-01 is described in Boutillon (1978) and the changes made to certain correction factors are given in Burns (2004), Burns and Kessler (2009) and Burns *et al*. (2009). The changes made to the standard following the recommendations of ICRU Report 90 given in Burns and Kessler (2018). The KRISS took part in the 2003 comparison APMP.RI(I)-K3 (Lee *et al.* 2008) using a secondary standard traceable to the BIPM. More recently the KRISS developed a free-air chamber standard M1, details of which are given in the present report (as yet no written report exists for the new standard). 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] (BIPM)	1.2930 kg m^{-3}	0.0001
ρ_{air} [c] (KRISS)	1.2048 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.
[c] Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa.

Table 2. Main characteristics of the standards

Standard	BIPM M-01	KRISS M1
Aperture diameter / mm	9.939	10.0006
Air path length / mm	281.5	369.9
Collecting length / mm	60.004	99.883
Electrode separation / mm	180	244
Collector width / mm	200	250
Measuring volume / mm^3	4655.4	7845.7
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

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

where $\dot{K}$ is the air-kerma rate determined by the standard using Equation (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, RH = 50 %). 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 KRISS laboratory in the range from 30 % to 70 %.

To derive a comparison result from the calibration coefficients $N_{K,\mathrm{BIPM}}$ and $N_{K,\mathrm{NMI}}$ 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 and similar filtration at each institute, but the half-value layers (HVLs) can differ appreciably. A radiation quality correction factor k_Q is derived for each comparison quality Q. This corrects the calibration coefficient $N_{K,\mathrm{NMI}}$ determined at the NMI into one that applies at the 'equivalent' BIPM quality and is derived by interpolation of the $N_{K,\mathrm{NMI}}$ values in terms of log(HVL). The comparison result at each quality is then taken as

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

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 KRISS were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The Exradin A3 chamber incorporates a C552 shell serving as build-up. The PTW 30013 chamber was used without its build-up cap. Each chamber 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 30013 chamber was taken to be 13 mm from the thimble tip and that for the Exradin A3 chamber at the centre of the sphere.

Table 3. Main characteristics of the transfer chambers

Chamber type	Exradin A3	PTW 30013
Serial number	110	8979
Geometry	spherical	thimble
External diameter / mm	23.53	6.95
Wall material	C552	PMMA with inner graphite coating
Nominal volume / cm^3	3.6	0.6
Polarizing potential / V	–300[a]	–400[a]

[a] At both laboratories the stated potential was 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. In addition to the aluminium filter of thickness 1.203 mm used for the 100 kV quality, an aluminium filter of thickness 2.228 mm is added for all radiation qualities to compensate for the decrease in filtration 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 deviation of repeat air-kerma rate determinations over many months is typically 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 is 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 mass attenuation coefficients for air $(\mu/\rho)_{air}$ 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.

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 and Kessler (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.

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. Lateral alignment on the beam axis was 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 below 1 part in 10^4.

The calibration procedure involves measurements with a transfer chamber and with the standard at a given radiation quality before proceeding to the next quality, with a period of typically 10 minutes following a change of quality to allow the generator and tube to stabilize (longer for the 250 kV quality). For each transfer chamber and at each radiation quality, one or two sets of seven measurements were made, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each set was typically below 1 part in 10^4. Based on the results of repeat calibrations including chamber repositioning, an uncertainty component of 3 parts in 10^4 is included (Table 11) for the short-term reproducibility of the calibration coefficients determined at the BIPM.

Table 5. Correction factors for the BIPM M-01 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
Radiative loss $1 - g_{air}$	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.

6. Calibration at the KRISS

6.1 The KRISS irradiation facility and reference radiation qualities

The medium-energy x-ray facility at the KRISS comprises a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 3 mm beryllium. No transmission monitor is used. The high-voltage is monitored using a voltage divider for each polarity and regulated within 5 V. The standard deviation of repeat air-kerma rate determinations over a period of one year is typically 2 parts in 10^3. The characteristics of the KRISS realization of the CCRI comparison qualities (CCEMRI 1972) are given in Table 6.

The irradiation area is temperature controlled, normally remaining between 23 °C and 25 °C, and is stable over the duration of a calibration to typically 0.05 °C. Platinum resistance thermometers measure the temperature of the ambient air and the air inside the KRISS standard. Air pressure is measured by means of a calibrated barometer.

Table 6. Characteristics of the KRISS reference radiation qualities

Radiation quality	100 kV	135 kV	180 kV	250 kV
Generating potential / kV	100	135	180	250
Additional Al filtration / mm	3.45	2.24	2.24	2.24
Additional Cu filtration / mm	-	0.23	0.48	1.57
Al HVL / mm	4.025	-	-	-
Cu HVL / mm	-	0.497	1.004	2.535
$(\mu/\rho)_{air}$ [a]/ $cm^2\ g^{-1}$	0.301	0.187	0.176	0.140
$\dot{K}_{KRISS}$ / $mGy\ s^{-1}$	0.096	0.095	0.140	0.090

[a] Measured at the KRISS using an evacuated tube of length 369.37 mm.

6.2 The KRISS standard and correction factors

The reference plane for the KRISS standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.05 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 96 mm for all radiation qualities. During the calibration of the transfer chambers, measurements using the KRISS standard were made using negative polarity only. A correction factor of 1.0001 is applied to correct for the known polarity effect in the standard. The relative leakage current was measured to be around 4 parts in 10^4.

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

6.3 Transfer chamber positioning and calibration at the KRISS

The reference point for each transfer chamber was positioned at the KRISS reference distance of 1000 mm from the radiation source, with a reproducibility of 0.5 mm. Lateral alignment on the beam axis was to an estimated uncertainty of 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 standard uncertainty of the mean ionization current for each series was typically 2 parts in 10^4. Repeatability was around 5 parts in 10^4 (after repositioning the chamber).

Table 7. Correction factors for the KRISS M1 standard

Radiation quality	100 kV	135 kV	180 kV	250 kV	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a [a]	1.0135	1.0084	1.0079	1.0063	0.0002	0.0002
Photon scatter k_{sc}	0.9943	0.9950	0.9955	0.9964	-	0.0003
Fluorescence k_{fl}	0.9986	0.9993	0.9996	0.9999	-	0.0001
Electron loss k_e	1.0000	1.0002	1.0016	1.0039	-	0.0005
Initial ionization k_{ii} Energy dependence of W_{air} k_W	0.9981	0.9980	0.9979	0.9985	-	0.0005
Ion recombination k_s	1.0011	1.0011	1.0011	1.0011	0.0002	0.0001
Polarity k_{pol}	1.0001	1.0001	1.0001	1.0001	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm contribution k_{dc}	0.9998	0.9996	0.9994	0.9990	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	0.9998	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
Radiative loss $1 - g_{air}$	0.9998	0.9998	0.9997	0.9997	-	0.0001

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

7. Additional corrections to transfer chamber measurements

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

As can be seen from Tables 4 and 6, the air-kerma rates at the BIPM are up to five times higher than those at the KRISS. Thus volume recombination effects will be greater for the transfer chamber calibrations at the BIPM. For the PTW 30013 chamber this effect should be negligible and no recombination corrections have been applied at either laboratory. For the Exradin A3 chamber, the KRISS measured the recombination effect and applied a correction based on the equation $k_s = 1.0018 + 0.0016\,I$, where I is the measured current in nA. For this reason, the N_K values determined at the BIPM are also corrected, but as the measured current is 0.06 nA at the BIPM (and five times less at the KRISS) the correction for initial recombination (1.0018) dominates and consequently k_s largely cancels at the two laboratories.

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 around 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.

The reference distance is 1000 mm at the KRISS and 1200 mm at the BIPM, and the field diameter is 96 mm at the KRISS and 98 mm at the BIPM. Although thimble-type transfer chambers show some sensitivity to scattered radiation in a way that free-air chambers do not, the field size at the two laboratories is sufficiently close that field-size effects will be negligible.

7.2 Thermal response of Exradin A3 chamber

The KRISS has measured the effect of different ambient temperatures on the response of plastic-walled spherical chambers (Yi and Kim 2013), observing a temperature response coefficient of 4 parts in 10^4 per °C for three chambers with volumes 100 cm^3, 800 cm^3 and 1000 cm^3 (a fourth, graphite-walled chamber showed no significant effect). At the KRISS, the laboratory temperature for the Exradin A3 measurements was between 23.5 °C and 25 °C so that corrections of 1.5 to 2 parts in 10^3 were applied to the measured current (the reference temperature being 20 °C). The uncertainty of this correction is around 1 part in 10^4 and is neglected. At the BIPM, the laboratory temperature was around 20.5 °C and the corresponding correction factor 0.9998 was applied. No thermal response correction was applied for the PTW 30013 chamber.

7.3 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities might require a correction factor k_{Q}, depending on the energy response of the transfer chamber. From Tables 4 and 6 it is evident that the BIPM and KRISS radiation qualities are well matched in terms of HVL, and the energy dependence of the transfer chambers is sufficiently small, such that the required correction is at most 4 parts in 10^4 (for the Exradin A3 at 180 kV) with a mean value of 1 part in 10^4. Consequently, k_{Q} is taken to be unity for all chambers and qualities, with a standard uncertainty of 3 parts in 10^4 included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{KRISS}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8. The values $N_{K,\mathrm{KRISS}}$ measured before and after the measurements at the BIPM give rise to the relative standard uncertainties $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ for the two chambers, which represent the uncertainty in N_K arising from transfer chamber stability.

For each chamber at each radiation quality, the mean of the KRISS results before and after the BIPM measurements is used to evaluate the results $N_{K,\mathrm{KRISS}}$ / $N_{K,\mathrm{BIPM}}$ given in Table 9. The final comparison results $R_{K,\mathrm{KRISS}}$ in Table 9 are evaluated as the mean for the two transfer chambers. For each quality, the corresponding uncertainty s_{tr} is the standard uncertainty of this mean, or taken as

$$s_{\mathrm{tr}} = \sqrt{\left(s_{\mathrm{tr},1}^2 + s_{\mathrm{tr},2}^2\right)} / 2 \qquad (4)$$

if this is larger (on the basis that the agreement between the comparison results for different transfer chambers should not, on average, be better than their combined stability estimated using $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ from Table 8). The root mean square value of s_{tr} for the four qualities, $s_{\mathrm{tr,comp}} = 0.0007$, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 12.

Also given in the final row of Table 9 are the results for the KRISS obtained in the APMP.RI(I)-K3 comparison (Lee *et al.* 2008). It should be noted, however, that for the 2008 comparison the KRISS used a secondary standard traceable to the BIPM.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	100 kV	135 kV	180 kV	250 kV
Exradin A3				
$N_{K,\mathrm{KRISS}}$ (pre-comp) / Gy μC^{-1}	8.538	8.300	8.349	8.464
$N_{K,\mathrm{KRISS}}$ (post-comp) / Gy μC^{-1}	8.532	8.294	8.346	8.468
$s_{\mathrm{tr},1}$ (relative)	0.0005	0.0005	0.0003	0.0003
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	8.509	8.253	8.310	8.448
PTW 30013				
$N_{K,\mathrm{KRISS}}$ (pre-comp) / Gy μC^{-1}	47.808	47.708	47.691	47.761
$N_{K,\mathrm{KRISS}}$ (post-comp) / Gy μC^{-1}	47.825	47.739	47.757	47.818
$s_{\mathrm{tr},2}$ (relative)	0.0003	0.0005	0.0010	0.0008
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	47.576	47.495	47.534	47.629

Table 9. Comparison results

Radiation quality	100 kV	135 kV	180 kV	250 kV
$N_{K,\mathrm{KRISS}}$ /$N_{K,\mathrm{BIPM}}$ using Exradin A3	1.0031	1.0053	1.0045	1.0021
$N_{K,\mathrm{KRISS}}$ /$N_{K,\mathrm{BIPM}}$ using PTW 30013	1.0051	1.0048	1.0040	1.0034
s_{tr}	0.0010	0.0003	0.0005	0.0006
$\boldsymbol{R_{K,\mathrm{KRISS}}}$	**1.0041**	**1.0051**	**1.0043**	**1.0028**
Results for KRISS in APMP.RI(I)-K3	*0.9894*	*0.9966*	*1.0010*	*1.0001*

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 $R_{K,\mathrm{KRISS}}$ is presented in Table 12. This combined uncertainty takes into account correlation in the type B uncertainties associated with the physical constants, the humidity correction and the factor $k_{\mathrm{ii}}k_W$. Correlation in the values for k_{e}, k_{sc} and k_{fl}, 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 BIPM comparisons in medium-energy x-rays in terms of degrees of equivalence described in Burns (2003).

Table 10. Uncertainties associated with the standards

Standard	BIPM		KRISS	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0007	0.0002
Positioning	0.0001	0.0001	-	-
Volume	0.0001	0.0005	0.0001	0.0010
Correction factors (excl. k_h)	0.0003	0.0011	0.0003	0.0011
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
$\dot{K}_{std}$	0.0004	0.0037	0.0008	0.0038

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

Institute	BIPM		KRISS	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}_{std}$	0.0004	0.0037	0.0008	0.0038
I_{tr}	0.0002	0.0002	0.0002	0.0002
Positioning of transfer chamber	0.0001	-	-	0.0006
Short-term reproducibility	0.0003	-	- [a]	-
$N_{K,std}$	0.0005	0.0037	0.0008	0.0039

[a] The reproducibility of the KRISS transfer chamber calibrations over the duration of the comparison is implicitly included in s_{tr} in Table 9 and consequently in $s_{tr,comp}$ in Table 12.

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,KRISS}$ / $N_{K,BIPM}$	0.0010	0.0018 [a]
Radial uniformity	-	0.0003
k_Q	-	0.0003
Transfer chambers $s_{tr,comp}$	-	0.0007
$R_{K,KRISS}$	u_c = 0.0022	

[a] Takes account of correlation in type B uncertainties as noted in Section 9.

10. Discussion

The comparison results presented in Table 9 show the KRISS and BIPM standards to be in agreement at the limit of the expanded uncertainty of the comparison of 4.4 parts in 10^3. No significant trend with radiation quality is observed.

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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_\mathrm{i} - 1$ 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.

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 KRISS and the BIPM to be in agreement at the limit of the expanded uncertainty of the comparison of 4.4 parts in 10^3.

Tables and a graph of degrees of equivalence, including those for the KRISS, are presented for entry in the BIPM key comparison database. Note that these data, 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 key comparison database (KCDB 2022).

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. Laboratory names in red indicate 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
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
KRISS	4.1	4.4	5.1	4.4	4.3	4.4	2.8	4.4
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
GUM	6.9	6.0	3.2	6.0	3.6	6.0	2.7	6.0
ARPANSA	3.8	8.2	5.2	8.2	5.4	8.2	4.5	8.2
INER	3.7	4.6	4.3	4.6	6.0	4.6	5.5	4.6
MNA	14.2	12.0	16.2	12.0	15.0	12.0	15.9	12.0
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
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

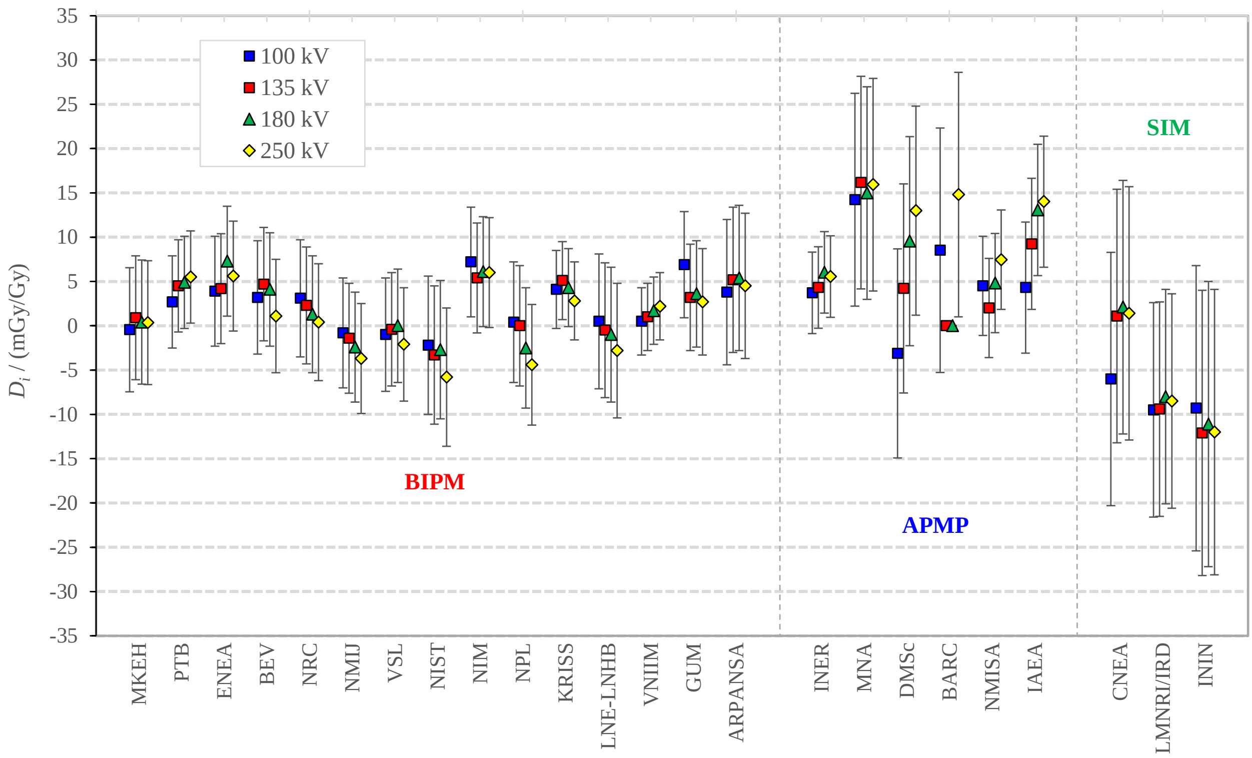

Figure 1. Degrees of equivalence for each laboratory *i* with respect to the key comparison reference value. Results to the left are for the ongoing international comparison BIPM.RI(I)-K3, those in the middle section are for the regional comparison APMP.RI(I)-K3 and those to the right are for the regional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

References

Boutillon M 1978 Mesure de l'exposition au BIPM dans le domaine des rayons X de 100 à 250 kV *Rapport BIPM*-78/3

Burns D T 2003 Degrees of equivalence for the key comparison BIPM.RI(I)-K3 between national primary standards for medium-energy x-rays *Metrologia* **40** *Tech. Suppl.* 06036

Burns D T 2004 Changes to the BIPM primary air-kerma standards for x-rays *Metrologia* **41** L3

Burns D T, Kessler C 2009 Diaphragm correction factors for free-air chamber standards for air kerma in x-rays *Phys. Med. Biol.* **54** 2737–45

Burns D T, Kessler C 2018 Re-evaluation of the BIPM international dosimetry standards on adoption of the recommendations of ICRU Report 90 *Metrologia* **55** R21

Burns D T, Kessler C, Allisy P J 2009 Re-evaluation of the BIPM international standards for air kerma in x-rays *Metrologia* **46** L21–23

CCEMRI 1972 Qualités de rayonnement *Comité Consultatif pour les Étalons de Mesures des Rayonnements Ionisants (Section I)* 2nd *meeting* R15–16

ICRU 2016 Key data for ionizing-radiation dosimetry: Measurement standards and applications J. ICRU **14** Report 90 (Oxford University Press)

KCDB 2022 The BIPM key comparison database is available online at http://kcdb.bipm.org/

Lee J H, Hwang W S, Kotler L H, Webb D V, Büermann L, Burns D T, Takeyeddin M, Shaha V V, Srimanoroth S, Meghzifene A, Hah S H, Chun K J, Kadni T B, Takata N and Msimang Z 2008 APMP/TCRI key comparison report of measurement of air kerma for medium-energy x-rays (APMP.RI(I)-K3) *Metrologia* **45** *Tech. Suppl.* 06012

Yi C-Y, Kim H-M 2013 Temperature dependence of cavity ionization chamber response *Metrologia* **50** 146–52