Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the KRISS, Republic of Korea, and the BIPM in mammography x-rays

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Abstract

A first key comparison has been made between the air-kerma standards of the KRISS, Republic of Korea, and the BIPM in mammography x-ray beams. The results show the standards to be in agreement at the level of the expanded uncertainty for 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

A direct 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 Mo/Mo mammography beams in the x-ray range from 25 kV to 35 kV. The comparison took place at the BIPM in February 2017 using the reference conditions recommended by the CCRI and described by Kessler *et al.* (2010). Final results for the KRISS were supplied in March 2022 following a determination of the electric-field distortion based on finite-element calculations and capacitance measurements. 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

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

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, 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.

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[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 $k_{\text{h}} = 0.9980$.

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.

3. Details of the primary standards

Both free-air chamber standards 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 L-02 is described in Kessler *et al.* (2010). The changes made to the standard following the recommendations of ICRU Report 90 given in Burns and Kessler (2018). Details of the KRISS standard L1, which has not previously been compared with the BIPM standard, are given in Yi *et al.* (2022) and in the present report. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

Table 2. Main characteristics of the standards

Standard	BIPM L-02	KRISS L1
Aperture diameter / mm	9.998	10.002
Air path length / mm	100.0	77.0
Collecting length / mm	15.537	15.800
Electrode separation / mm	70	69.5
Collector width / mm	70	70
Measuring volume / mm^3	1219.8	1241.5
Polarizing voltage / V	1500	2000

4. Comparison procedure

4.1 The BIPM irradiation facility and reference radiation qualities

The comparison was carried out in the BIPM low-energy x-ray laboratory, which houses a constant-potential generator and a molybdenum-anode x-ray tube with an inherent filtration of 0.8 mm beryllium. A molybdenum filter of thickness 0.030 mm is added for all radiation qualities. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system of the BIPM. Rather than use a transmission monitor, which might introduce its own variability, the anode current is measured and the ionization chamber current normalized for any deviation from the reference anode current. For a given radiation quality, the standard deviation of repeat air-kerma rate determinations over the past few years is below 3 parts in 10^4. The radiation qualities used in the range from 25 kV to 35 kV are given in Table 3 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.2 °C. Two calibrated thermistors measure the temperature of the ambient air and the air inside the BIPM standard; the KRISS standard does not contain an internal temperature sensor. Air pressure is measured by means of a calibrated barometer. The relative humidity is controlled within the range 40 % to 55 %.

Table 3. Characteristics of the BIPM mammography radiation qualities

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	0.030 mm Mo			
Al HVL / mm	0.277	0.310	0.329	0.365
$(\mu/\rho)_{\mathrm{air}}$ / cm^2 g^{-1}	2.20	1.99	1.91	1.74
Reference distance / mm	600			
Beam diameter / mm	100			
$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	2.00			

4.2 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 KRISS standard.

The correction factor k_a for the BIPM standard is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{\mathrm{air}}$ 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. Ionization current measurements are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the source and the reference plane. The correction factor k_a is evaluated for both standards using the BIPM $(\mu/\rho)_{\mathrm{air}}$ values given in Table 3.

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 $k_{\mathrm{ii}}k_W$ 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.

Measurements using the BIPM standard were made using positive polarity only as the polarity effect in the standard is less than 1 part in 10^4. The leakage current for the BIPM standard, relative to the ionization current, was measured to be less than 1 part in 10^4. Measurements using the KRISS standard were made using negative polarity only and a polarity correction of 1.0009 was applied (see Table 5).

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 KRISS 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 coefficients made at the KRISS.

Table 4. Correction factors for the BIPM FAC-L-02 standard

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_{a}[a]	1.0269	1.0243	1.0233	1.0212	0.0002	0.0001
Scattered radiation k_{sc}	0.9977	0.9977	0.9978	0.9978	−	0.0003
Fluorescence k_{fl}	0.9975	0.9976	0.9976	0.9977	−	0.0005
Electron loss k_{e}	1.0000	1.0000	1.0000	1.0000	−	0.0001
Initial ionization k_{ii}	0.9968	0.9968	0.9969	0.9969	-	0.0012
Energy dependence of W_{air} k_W						
Ion recombination k_{s}	1.0015	1.0015	1.0015	1.0015	0.0001	0.0001
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0001	−
Wall transmission k_{p}	1.0000	1.0000	1.0000	1.0000	0.0001	−
Field distortion k_{d}	1.0000	1.0000	1.0000	1.0000	−	0.0007
Diaphragm correction k_{dia}	0.9996	0.9995	0.9995	0.9995	−	0.0003
Humidity k_{h}	0.9980	0.9980	0.9980	0.9980	−	0.0003
$1 - g_{\mathrm{air}}$	1.0000	1.0000	1.0000	1.0000	−	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
$u_{i\mathrm{A}}$ represents the relative standard uncertainty estimated by statistical methods, type A
$u_{i\mathrm{B}}$ represents the relative standard uncertainty estimated by other means, type B

Table 5. Correction factors for the KRISS FAC L1 standard used at the BIPM

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_{a}[a]	1.0206	1.0187	1.0179	1.0163	0.0002[b]	0.0001[b]
Scattered radiation k_{sc}	0.9981	0.9982	0.9982	0.9982	−	0.0003
Fluorescence k_{fl}	0.9976	0.9977	0.9977	0.9978	−	0.0005
Electron loss k_{e}	1.0002	1.0002	1.0002	1.0002	−	0.0001
Initial ionization k_{ii}	0.9969	0.9970	0.9971	0.9971	−	0.0012
Energy dependence of W_{air} k_W						
Ion recombination k_{s}	1.0016	1.0016	1.0016	1.0016	0.0002	0.0001
Polarity k_{pol}	1.0009	1.0009	1.0009	1.0009	0.0003	
Wall transmission k_{p}	1.0000	1.0000	1.0000	1.0000	0.0001	
Field distortion k_{d} [c]	0.9894	0.9894	0.9894	0.9894	0.0001	0.0015
Diaphragm correction k_{dia}	0.9999	0.9999	0.9999	0.9998	−	0.0003
Humidity k_{h}	0.9980	0.9980	0.9980	0.9980	−	0.0003
$1 - g_{\mathrm{air}}$	1.0000	1.0000	1.0000	1.0000	−	0.0001

[a] Values for 293.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.
[b] For measurements at the KRISS, the uncertainties are $u_{i\mathrm{A}} = 0.0002$ and $u_{i\mathrm{B}} = 0.0002$.
[c] The field-distortion correction is discussed in Section 6.

4.3 Chamber positioning and measurement procedure

The reference plane for the BIPM and for the KRISS standard was positioned at 600 mm from the radiation source; this distance was measured to 0.03 mm and was reproducible to 0.01 mm. Lateral alignment on the beam axis was measured to around 0.1 mm and this position was reproducible to better than 0.01 mm The beam diameter in the reference plane is 100 mm for all radiation qualities. No correction is applied for the radial non-uniformity of the beam as the aperture diameters are very similar.

The KRISS chamber does not incorporate a sensor to measure the internal air temperature T_{KRISS}. A thermometer belonging to the BIPM was positioned in thermal contact with the side of the chamber, but this device was found to be unreliable. A series of temperature measurements inside the KRISS chamber were compared with the temperatures T_{BIPM} and T_{cap} measured inside the BIPM standard and in the nearby capacitor bank, respectively. These two temperatures are expected to provide approximate upper and lower limits, respectively, for T_{KRISS}. The result of this investigation was to adopt the value $T_{\mathrm{KRISS}} = T_{\mathrm{cap}} + 0.1$ °C. A corresponding standard uncertainty of 4 parts in 10^4 for the KRISS air-kerma rate determination is included in Table 6.

The leakage current was measured before and after each series of ionization current measurements and a correction made based on the mean of these leakage measurements. For both standards the leakage current, relative to the ionization current of around 90 pA, was below 1 part in 10^4.

For the KRISS chamber, the standard uncertainty of the mean of a series of seven measurements, each with integration time 40 s, was 1 part in 10^4. Two series were made for each comparison. For the BIPM standard, a similar series was made for each comparison with a standard uncertainty below 1 part in 10^4. Three qualities were repeated on subsequent days. The observed reproducibility of around 4 parts in 10^4 is included in Table 6 as an uncertainty for the short-term stability of the KRISS standard at the BIPM.

4.4 Additional measurements

At the same time as running the BIPM.RI(I)-K7 comparison in the Mo/Mo beams, a direct comparison BIPM.RI(I)-K2 was made using the KRISS primary standard in the W-anode radiation qualities (Burns *et al.* 2022). During this comparison, an additional test of the measurement volumes was made using a third aperture belonging to the BIPM in both standards, for the 30 kV quality only. The result was within 5 parts in 10^4 of the 30 kV comparison result from the main comparison, which is consistent with the associated uncertainties and confirms that there is no significant difference in the standards arising from the apertures. A check measurement was also made at 25 kV of the KRISS polarity correction. The result was 1.0010, consistent with the value 1.0009 determined by the KRISS.

5. Uncertainties

The uncertainties associated with the primary standards and with the results of the direct comparison are listed in Table 6. The uncertainties associated with air attenuation, measurement of the ionization current, air temperature and chamber positioning are those that apply to measurements at the BIPM.

The combined standard uncertainty u_{c} of the comparison result $R_{K,\mathrm{KRISS}} = \dot{K}_{\mathrm{KRISS}} / \dot{K}_{\mathrm{BIPM}}$ 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} is taken into account in an approximate way by assuming half of the uncertainty value for each factor at each laboratory.

Table 6. Uncertainties associated with the direct comparison

Standard	BIPM		KRISS	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Ionization current	0.0002	0.0002	0.0002[a]	0.0002[a]
Positioning	0.0001	0.0001	0.0001	0.0001
Volume	0.0003	0.0005	0.0001	0.0005
Correction factors (excl. k_h)	0.0003	0.0015	0.0004	0.0020
Humidity k_h	-	0.0003	-	0.0003
Air temperature	-		-	0.0004[b]
Reproducibility	-	-	0.0004	-
Physical constants	-	0.0035	-	0.0035
$\dot{K}_\mathrm{Standard}$	0.0005	0.0039	0.0006	0.0041
	0.0039		0.0041[c]	
$\dot{K}_\mathrm{KRISS}/\dot{K}_\mathrm{BIPM}$	u_c = 0.0022[d]			

[a] Similar uncertainty components for measurements at the KRISS.

[b] This additional component arises because the KRISS standard does not have an internal thermometer. See Section 4.3.

[c] The uncertainty of the air-kerma rate determination at the KRISS is also 0.0041 and appears as $u_{\mathrm{Lab}\,i}$ in the KCDB.

[d] Takes account of correlation in the type B uncertainties.

6. Results and discussion

The comparison results are given in Table 7. Agreement at the level of around 3.5 parts in 10^3 is observed, which is within the expanded uncertainty of the comparison of 4.4 parts in 10^3 derived from Table 6. No significant trend with energy is observed in the comparison results.

Table 7. Comparison results

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
$\dot{K}_\mathrm{KRISS}/\dot{K}_\mathrm{BIPM}$	**0.9965**	**0.9964**	**0.9968**	**0.9963**

In the interest of transparency, it is noted that at the time of the comparison in 2017 the preliminary results were not satisfactory. The two KRISS staff members present at the BIPM were made aware of this, but were not informed of the magnitude or sign of the discrepancy. Following discussions of correction factors, and noting that aperture effects had been eliminated (see Section 4.4), the KRISS decided to re-determine the effective collecting length for their standard. In March 2022, following finite-element electric-field calculations and capacitance measurements, the KRISS reported a field distortion correction factor of 0.9894 with an uncertainty of 1.5 parts in 10^3. This significant reduction in the KRISS air-kerma rate determination results in better agreement between the standards as presented in this report.

7. Degrees of Equivalence

The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described by Burns (2003) and a similar analysis is adopted for comparisons in mammography x-ray beams. 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 $D_i = (\dot{K}_i - \dot{K}_{\mathrm{BIPM},i}) / \dot{K}_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$. The results for D_i and U_i expressed in mGy/Gy, are shown in Table 8. These data are presented graphically in Figure 1.

Table 8. Degrees of equivalence (W/Mo)

	W/Mo-23		W/Mo-28		W/Mo-30		W/Mo-50	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
NRC	**-0.7**	6.4	–	–	**-1.4**	6.4	**-2.1**	6.4
	W/Mo-23		W/Mo-28		W/Mo-30		W/Mo-35	
ENEA-INMRI	**-3.8**	9.6	**-3.2**	9.6	**-2.9**	9.6	**-2.8**	9.6

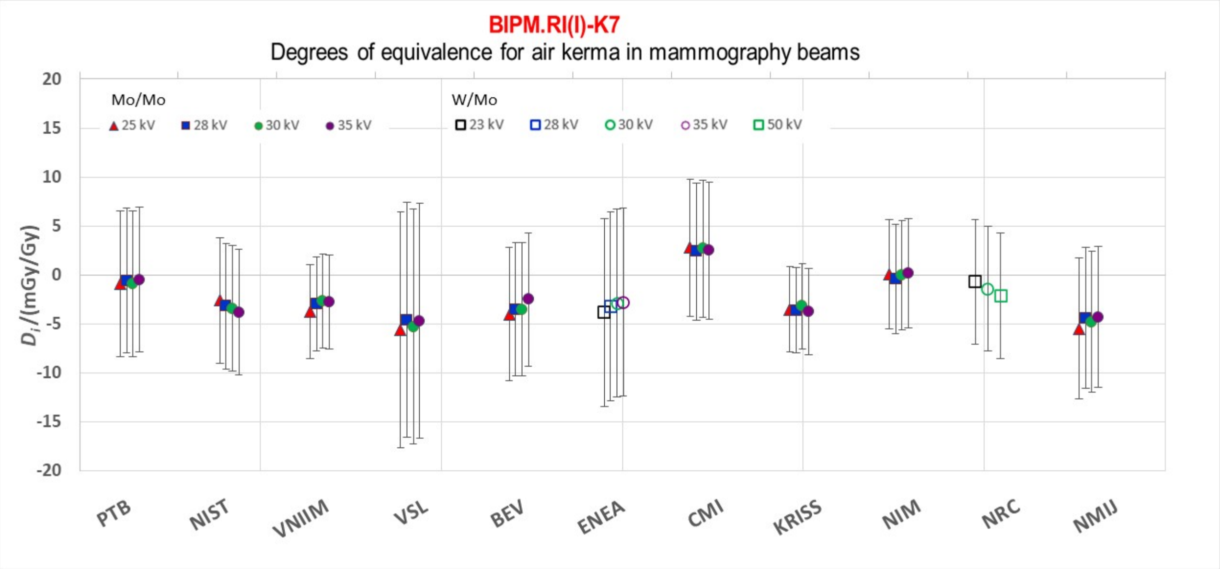
Degrees of equivalence (Mo/Mo)

	Mo/Mo-25		Mo/Mo-28		Mo/Mo-30		Mo/Mo-35	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
PTB	**-0.9**	7.4	**-0.6**	7.4	**-0.9**	7.4	**-0.5**	7.4
NIST	**-2.6**	6.4	**-3.2**	6.4	**-3.4**	6.4	**-3.8**	6.4
VNIIM	**-3.7**	4.8	**-3.0**	4.8	**-2.7**	4.8	**-2.8**	4.8
VSL	**-5.6**	12.0	**-4.6**	12.0	**-5.3**	12.0	**-4.7**	12.0
BEV	**-4.0**	6.8	**-3.5**	6.8	**-3.5**	6.8	**-2.5**	6.8
CMI	**2.8**	7.0	**2.4**	7.0	**2.7**	7.0	**2.5**	7.0
KRISS	**-3.5**	4.4	**-3.6**	4.4	**-3.2**	4.4	**-3.7**	4.4
NIM	**0.1**	5.6	**-0.4**	5.6	**0.0**	5.6	**0.2**	5.6
NMIJ	**-5.5**	7.2	**-4.4**	7.2	**-4.8**	7.2	**-4.3**	7.2

Note that the data presented in the table, while correct at the time of publication of the present report, will become out of date when a laboratory makes a new comparison with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

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

Figure 1. **Graph of degrees of equivalence with the KCRV**



8. Conclusion

The key comparison BIPM.RI(I)-K7 for the determination of air kerma in mammography x-ray beams shows the standards of the KRISS and the BIPM to be in agreement at the level of the expanded uncertainty for the comparison of 4.4 parts in 10^3. Degrees of equivalence, including those for the KRISS, are presented for entry in the BIPM key comparison database. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

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