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

C Kessler[1], D T Burns[1], P Roger[1], Wu Jinjie[2] and Wang Peiwei[2]

[1]Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex

[2]National Institute of Metrology, 18 Bei San Huan Dong Lu, Beijing 100029

Abstract

A first key comparison has been made between the air-kerma standards of the NIM, Republic of China and the BIPM in mammography x-ray beams. The results show the standards to be in agreement at the level of the combined standard uncertainty of 2.8 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 National Institute of Metrology (NIM), Republic of China 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 April 2018 using the reference conditions recommended by the CCRI and described by Kessler and Burns (2018). The final results were supplied by the NIM in September 2018.

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

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

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost through radiative processes in air, and $\Pi\, k_{\mathrm{i}}$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air}, the ionization current I must be corrected for humidity and for the difference between the density of the air of the measuring volume at the time of measurement and the value given in the table.[1]

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}	0.0015

[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.

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). Details of the NIM standard are given in the present report. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2. Note that, as the comparison was carried out during 2018, changes to the standards made in 2019 as the result of the implementation of the recommendations of ICRU Report 90 (ICRU 2016) are not included.

Table 2. Main characteristics of the standards

Standard	BIPM L-02	MPFAC-NIM-01
Aperture diameter / mm	9.998	8.025
Air path length / mm	100.0	61.91
Collecting length / mm	15.537	40.598
Electrode separation / mm	70	60
Collector width / mm	70	60
Measuring volume / mm^3	1219.8	2053.5
Polarizing voltage / V	1500	1600

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

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

$$N_K = \frac{\dot{K}}{I_{\mathrm{tr}}} \tag{2}$$

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 reference conditions of ambient air temperature, pressure and relative humidity chosen for the comparison (T = 293.15 K, P = 101.325 kPa and h = 50 %).

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 measurement 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) might differ. A radiation quality correction factor $k_{\mathrm{Q,NMI}}$ 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

$$R_{K,\mathrm{NMI}} = \frac{k_{\mathrm{Q,NMI}} N_{K,\mathrm{NMI}}}{N_{K,\mathrm{BIPM}}} \tag{3}$$

In practice, the half-value layers normally differ by only a small amount and $k_{\mathrm{Q,NMI}}$ is close to unity.

4.2 Details of the transfer instruments

Two thin-window parallel-plate ionization chambers belonging to the NIM, type Radcal RC6M, were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The chambers were positioned with the entrance window centred on the beam axis and with the red line around the chamber casing positioned in the reference plane.

Table 3. Main characteristics of the transfer chambers

Chamber type	Radcal RC6M	Radcal RC6M
Serial number	10112	10167
Window material	metallized polyester	
Window thickness / mg cm^{-2}	0.7	
Nominal volume / cm^3	6	
Collector diameter / mm	30 [a]	
Cavity height / mm	8 [a]	
Polarizing potential [b] / V	300	300

[a] The Radcal RC6M cavity dimensions are not clearly stated by the manufacturer. From radiographic measurements, the collector diameter is known to be close to 30 mm, and ionometric measurements are consistent with a cavity volume of about 5.8 cm^3, consistent with the value 6 cm^3 stated by the manufacturer. From these, the cavity height is deduced to be around 8.2 mm, which would position the collector close to the red line around the chamber casing.

[b] At both laboratories, a positive polarizing potential was applied to the chamber window.

5. Calibration at the BIPM

5.1 The BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory 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, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. The resulting variation in the BIPM FAC-L-02 free-air chamber current over the duration of a comparison is normally not more than 3×10^{-4} in relative terms. The radiation qualities used in the range from 25 kV to 35 kV are given in Table 4 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters.

The irradiation area is temperature controlled at 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. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 47 % to 53 % and consequently no humidity correction is applied to the current measured using transfer instruments.

Table 4. 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
$(\mu/\rho)_{\text{air}}$ / cm^2 g^{-1}	2.20	1.99	1.91	1.74
Reference distance / mm	600			
Beam diameter / mm	100			
$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	2.00			

5.2 Correction factors

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 correction factor k_a for the BIPM standard is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{\text{air}}$ 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 at the time of the measurements. Ionization measurements are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane.

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 1×10^{-4}.

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 5.

Table 5. Correction factors for the BIPM FAC-L-02 standard

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35	u_{iA}	u_{iB}
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
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
$1 - g_{air}$	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_{iA} represents the relative standard uncertainty estimated by statistical methods, type A
u_{iB} represents the relative standard uncertainty estimated by other means, type B

5.3 Transfer chamber positioning and calibration at the BIPM

The reference plane for each chamber was positioned at 600 mm from the radiation source; this distance was measured to 0.03 mm and was reproducible to 0.01 mm. 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.

The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The leakage current for the Radcal transfer chambers was always less than 1 part in 10^4.

For each of the transfer chambers and at each radiation quality, two sets of seven measurements were made, each measurement with integration time 30 s. The relative standard uncertainty of the mean ionization current for each set was typically below 1 part in 10^4. Repeat measurements for each chamber at several qualities showed a typical reproducibility of 2 parts in 10^4. Despite this good agreement, an additional relative standard uncertainty component of 5 parts in 10^4 is included in Table 11 to account for the typical reproducibility of calibrations in low-energy x-rays at the BIPM.

6. Calibration at the NIM

6.1 NIM irradiation facility and reference radiation qualities

The mammography x-ray facility at the NIM consists of of a constant-potential generator and a Mo-anode x-ray tube with an inherent filtration of 0.8 mm beryllium. The x-ray output is monitored using a transmission ionization chamber PTW-34014. The radiation qualities established in the range from 25 kV to 35 kV are those recommended by the IEC 61267 and are given in Table 6, in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters

Table 6. Characteristics of the NIM reference radiation qualities

Radiation quality	Mo/Mo-25	Mo/Mo-28	Mo/Mo-30	Mo/Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	0.030 mm Mo			
Al HVL / mm	0.274	0.306	0.324	0.364
$(\mu/\rho)_{air}$ [a] / $cm^2\ g^{-1}$	2.28	2.03	1.94	1.75
Reference distance / mm	600			
Beam diameter / mm	80			
$\dot{K}_{NIM}$ / $mGy\ s^{-1}$	1.52			

[a] Values measured using an evacuation tube

The irradiation area is temperature controlled between 17.5 °C and 18 °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 standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range 20% to 60 %; no humidity correction is applied to the current measured using transfer instruments.

6.2 NIM standard and correction factors

The reference plane for the NIM standard was positioned at 600 mm from the radiation source, with a reproducibility of 0.2 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.5 mm. The beam diameter in the reference plane is approximately 80 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the NIM standard were made using positive polarity only. No polarity correction factor was applied as the polarity effect in the standard is negligible at the level of the stated uncertainty of 5 parts in 10^4. The leakage current for the NIM standard was measured to be less than 1 part in 10^4.

The correction factors applied to the ionization current measured at each radiation quality using the NIM standard, together with their associated uncertainties, are given in Table 7.

The correction factors k_a are 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 the measurements. Ionization 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.

6.3 Transfer chamber positioning and calibration at the NIM

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.2 mm. Alignment on the beam axis was to an estimated uncertainty of 0.5 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 the Radcal chambers was 2 parts in 10^4.

For each transfer chamber and at each radiation quality, 10 measurements were made, each measurement with integration time 60 s. The relative standard uncertainty of the mean ionization current for each set was 1 part in 10^3.

Table 7. Correction factors for the NIM MPFAC-01 standard

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35	u_{iA}	u_{iB}
Air attenuation k_a [a]	1.0171	1.0153	1.0146	1.0132	-	0.0015
Scattered radiation k_{sc} Fluorescence k_{fl}	0.9940	0.9942	0.9943	0.9943	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.0002
Ion recombination k_s	1.0004	1.0004	1.0004	1.0004	0.0002	0.0001
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0001	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	-	0.0001
Diaphragm correction k_{dia}	1.0000	1.0000	1.0000	1.0000	0.0002	0.0003
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	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_{iA} represents the relative standard uncertainty estimated by statistical methods, type A
u_{iB} represents the relative standard uncertainty estimated by other means, type B

7. Additional considerations for transfer chamber calibrations

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

Ion recombination: No correction for ion recombination $k_{s,tr}$ is applied. Based on previous measurements at the BIPM for this chamber type at different air kerma rates, a relative standard uncertainty of 5 parts in 10^4 is introduced to account for this effect as the kerma rates are different at the two laboratories.

Field size: The beam diameter at the reference distance differs at the two laboratories. From previous BIPM measurements with different field sizes, the effect of this difference on the Radcal chamber type is known to be around 4 parts in 10^4. A corresponding uncertainty is included in Table 12.

Polarity: The transfer chamber was used with the same polarity at each laboratory and so no corrections are applied for polarity effects in the transfer chamber.

Radial non-uniformity: No correction $k_{rn,tr}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For a chamber with collector diameter 30 mm, the correction factor for the BIPM reference field (relative to the aperture diameter of 10 mm) is around 6×10^{-4} and this effect is likely to cancel to some extent at the two laboratories. A relative standard uncertainty of 2×10^{-4} is introduced for this effect.

HVL considerations: Tables 4 and 6 show that the radiation qualities at the BIPM and the NIM are well matched in terms of HVL; no radiation quality correction factor $k_{Q,NMI}$ is derived for the present comparison.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{NIM}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8. Note that because of temperature instability problems at the NIM during the post-comparison (summer) period, the $N_{K,\mathrm{NIM}}$ values supplied after the comparison (shown in italic in the table) are *not* used for the final comparison results. Nevertheless, they are used to provide an estimate of the stability of the transfer chambers, which might be considered an upper estimate. These stability estimates $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ for the two chambers are evaluated at each quality as the relative change in $N_{K,\mathrm{NIM}}$ before and after the comparison. The best estimates, $\bar{s}_{\mathrm{tr},1}$ and $\bar{s}_{\mathrm{tr},2}$, are then evaluated as the mean of the four qualities for each chamber.

Table 8. Calibration coefficients for the transfer chamber

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
Radcal 10112				
$N_{K,\mathrm{NIM}}$ (pre-BIPM) / Gy µC^{-1}	4.762	4.756	4.756	4.755
$N_{K,\mathrm{NIM}}$ (post-BIPM) [a] / Gy µC^{-1}	*4.753*	*4.750*	*4.749*	*4.747*
$s_{\mathrm{tr},1}$ (relative)	0.0019	0.0013	0.0015	0.0017
$\bar{s}_{\mathrm{tr},1}$	0.0016			
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	4.760	4.757	4.755	4.751
Radcal 10167				
$N_{K,\mathrm{NIM}}$ (pre-BIPM) / Gy µC^{-1}	4.743	4.738	4.738	4.735
$N_{K,\mathrm{NIM}}$ (post-BIPM) [a] / Gy µC^{-1}	*4.746*	*4.741*	*4.737*	*4.733*
$s_{\mathrm{tr},2}$ (relative)	0.0006	0.0006	0.0002	0.0004
$\bar{s}_{\mathrm{tr},2}$	0.0005			
$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	4.744	4.741	4.739	4.737

[a] As noted in the text, the $N_{K,\mathrm{NIM}}$ values supplied after the comparison (shown in italic) are *not* used for the final comparison results, but rather in the evaluation of the uncertainty estimates $s_{\mathrm{tr},i}$.

For each chamber at each radiation quality, the NIM result before the BIPM measurements are combined with $N_{K,\mathrm{BIPM}}$ to evaluate the comparison result $R_{K,\mathrm{NIM}}$ according to Equation (3) (k_Q is taken as unity, as explained in section 7.1). The results are given in Table 9. For each quality, the final result in bold in Table 9 is evaluated as the mean for the two transfer chambers. The corresponding uncertainty s_{tr} is the standard uncertainty of this mean[1] or taken as

$$s_{\mathrm{tr}} = \sqrt{\left(\bar{s}^2_{\mathrm{tr},1} + \bar{s}^2_{\mathrm{tr},2}\right)/2} = 0.0008 \qquad (4)$$

[1] The standard uncertainty is evaluated as the standard deviation of the population divided by (n–1.4), found empirically to be a better choice than (n–1) to estimate the standard uncertainty for low values of n.

if this is larger (on the basis that the agreement between transfer chambers should, on average, not be better than their combined stability estimated using $\bar{s}_{tr,1}$ and $\bar{s}_{tr,2}$ from Table 8). The mean value of s_{tr} for the four qualities, $s_{tr,comp}$ = 0.0008, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 12.

Table 9. Combined comparison results

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
$R_{K,NIM}$ using Radcal 10112	1.0004	0.9998	1.0002	1.0008
$R_{K,NIM}$ using Radcal 10167	0.9998	0.9994	0.9998	0.9996
s_{tr}	0.0008	0.0008	0.0008	0.0008
Final $R_{K,NIM}$	**1.0001**	**0.9996**	**1.0000**	**1.0002**

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 uncertainty for the comparison results $R_{K,NIM}$ is presented in Table 12. This combined uncertainty takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction.

Correlations in the values for the correction factors k_e, k_{sc}, k_{fl} and the diaphragm corrections are taken into account if the NMI has used values derived from Monte Carlo calculations. This is the case for the NIM standard and consequently this correlation has been assumed.

Table 10. Uncertainties associated with the standards

Standard	BIPM		NIM	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0002	0.0004
Positioning	0.0001	0.0001	-	0.0010
Volume	0.0003	0.0005	0.0001	0.0012
Correction factors (excl. k_h)	0.0003	0.0010	0.0003	0.0019
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0004	0.0029

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

Institute	BIPM		NIM	
Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$	$u_{i\text{A}}$	$u_{i\text{B}}$
$\dot{K}$	0.0005	0.0019	0.0004	0.0029
I_{tr}	0.0002	0.0002	0.0010	0.0004
Positioning of transfer chamber	0.0001	-	0.0001	0.0010
Short-term reproducibility	0.0005	-	-	0.0008
N_K	0.0007	0.0019	0.0011	0.0032

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\text{A}}$	$u_{i\text{B}}$
$N_{K,\text{NIM}}$ / $N_{K,\text{BIPM}}$	0.0013	0.0023[a]
Ion recombination	-	0.0005
Radial non-uniformity	-	0.0002
Field size	-	0.0004
Transfer chambers $s_{\text{tr,comp}}$	0.0008	-
$R_{K,\text{NIM}}$	0.0015	0.0024
	u_c = 0.0028	

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

The comparison results $R_{\text{K,NIM}}$ show the NIM and BIPM standards to agree at the level of the standard uncertainty of the comparison of 2.8 parts in 10^3.

10. 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 $D_i = (K_i - K_{\text{BIPM},i}) / K_{\text{BIPM},i} = x_i - 1$ 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 13. These data are presented graphically in Figure 1.

Table 13. Degrees of equivalence

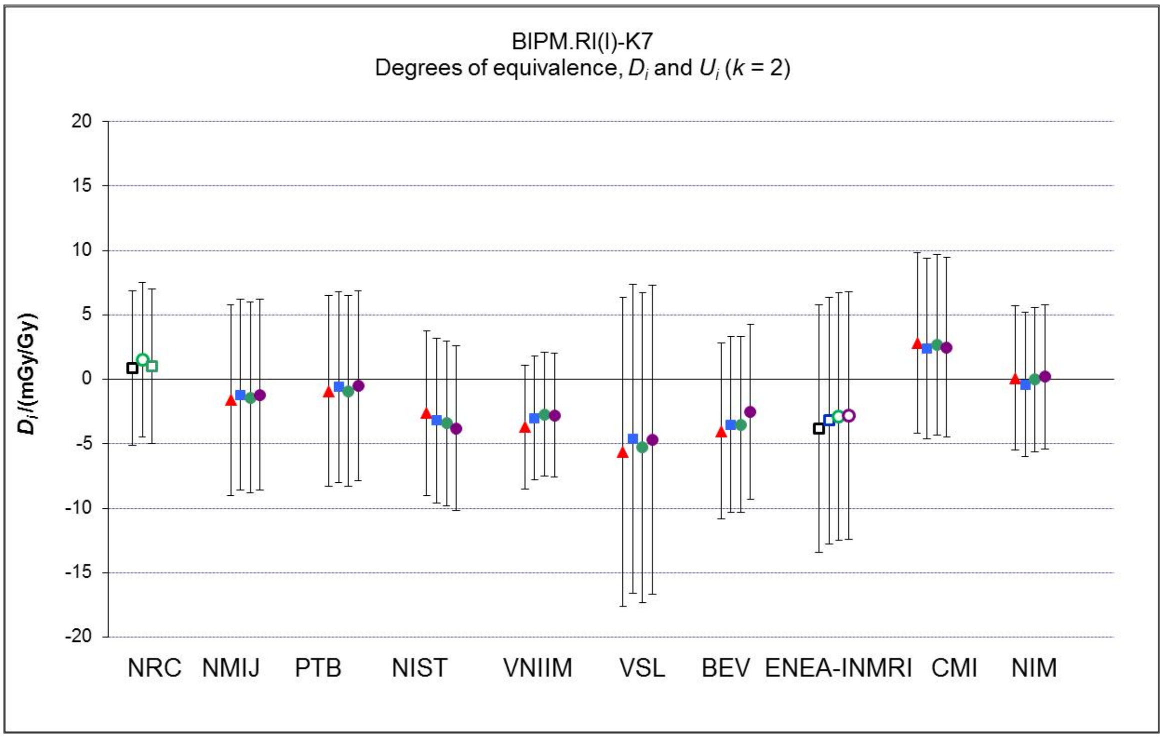
	Mo/Mo-25		Mo/Mo-28		Mo/Mo-30		Mo/Mo-35	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
NMIJ	**-1.6**	7.4	**-1.2**	7.4	**-1.4**	7.4	**-1.2**	7.4
PTB	**-0.9**	7.4	**-0.6**	7.4	**-0.9**	7.4	**-0.5**	7.4
NIST	**-2.6**	6.4	**-3.2**	6.4	**-3.4**	6.4	**-3.8**	6.4
VNIIM	**-3.7**	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
NIM	**0.1**	5.6	**-0.4**	5.6	**0.0**	5.6	**0.2**	5.6

	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	**0.9**	6.0	**–**	–	**1.5**	6.0	**1.0**	6.0
	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

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**



W/Mo qualities
Open black square: radiation quality W/Mo 23 kV
Open blue square: radiation quality W/Mo 28 kV
Open green circle: radiation quality W/Mo 30 kV
Open purple circle: radiation quality W/Mo 35 kV
Open green square: radiation quality W/Mo 50 kV

Mo/Mo qualities
Red triangle: radiation quality Mo/Mo 25 kV
Blue square: radiation quality Mo/Mo 28 kV
Green circle: radiation quality Mo/Mo 30 kV
Purple circle: radiation quality Mo/Mo 35 kV

11. Conclusion

The key comparison BIPM.RI(I)-K7 for the determination of air kerma in mammography x-ray beams shows the standards of the NIM and the BIPM to be in agreement at the level of the standard uncertainty for the comparison of 2.8 parts in 10^3.

Degrees of equivalence, including those for the NIM, 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.

References

Allisy P J, Burns D T and Kessler C 2011 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport BIPM-*2011/04

Burns D T 2003 Degrees of equivalence for the key comparison BIPM.RI(I)-K2 between national primary standards for low-energy x-rays *Metrologia **40** Technical Supplement 06031*

IEC 61267 Medical diagnostic X-ray equipment – Radiation conditions for use in the determination of characteristics International Electrotechnical Commission

KCDB 2019 The BIPM key comparison database is available online at http://kcdb.bipm.org/

Kessler C, Roger P and Burns D T 2010 Establishment of reference radiation qualities for mammography *Rapport BIPM*-2010/01