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

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Abstract A key comparison has been made between the air-kerma standards of the NRC 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 3.2 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 Research Council (NRC), Canada and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 23 kV to 50 kV using mammography beams produced by a tungsten-anode tube and molybdenum filter combination (Kessler 2006). Four parallel-plate ionization chambers were used as transfer instruments. The measurements at the BIPM took place in February 2018 but the results were analysed in September 2019 after the re-characterization of the beam qualities at the distance of 1 m. Final results were received from the NRC in February 2020. Note that this comparison was carried out before the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at either laboratory. Subsequent implementation of the recommendations at both laboratories will have no significant effect on the comparison results.

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 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]

[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 a humidity correction $k_{\mathrm{h}} = 0.9980$. At both laboratories, the 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 measuring volume V is defined by the diameter of the chamber aperture and the length of the collecting region. The BIPM air-kerma standard is described in Boutillon *et al* (1969) and the changes made to certain correction factors in October 2003 and September 2009 given in Burns (2004), Burns *et al* (2009) and the references therein. Details of the NRC standard are also given in Boutillon *et al* (1969). The standard was most recently compared with the BIPM standard in an indirect comparison carried out in 2007, the results of which are reported in Kessler *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] (BIPM)	1.2930 kg m^{-3}	0.000 1
ρ_{air} [c] (NRC)	1.2045 kg m^{-3}	0.000 1
W_{air} / e	33.97 J C^{-1}	0.001 5

[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 used at the BIPM.
[c] Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa used at the NRC.

Table 2. Main characteristics of the standards

Standard	BIPM	NRC
Aperture diameter / mm	9.941	5.0089
Air path length / mm	100.0	98.98
Collecting length / mm	15.466	46.010
Electrode separation / mm	70	60.96
Collector width / mm	71	69
Measuring volume / mm^3	1 200.4	906.62
Polarizing voltage / V	1 500	1 200

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 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 $N_{K,\text{BIPM}}$ and $N_{K,\text{NMI}}$, 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 $k_{\text{Q,NMI}}$ 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

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

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

4.2 Details of the transfer instruments

Four thin-window parallel-plate ionization chambers belonging to the NRC were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The reference point for each chamber was taken to be on the axis defined by the entrance window. The reference plane for the PTW chambers was taken to be that defined by the front surface of the casing, while for the Radcal chambers it was taken to be defined by the red line around the casing.

Table 3. Main characteristics of the transfer chambers

Chamber type	Radcal 10X5-6M	Radcal 10X5-6M	PTW 23344	PTW 23344
Serial number	9646	9642	0948	0949
Window / mg cm^{-2}	0.7	0.7	2.8	2.8
Collector diameter / mm	30	30	13	13
Cavity height / mm	9 [b]	9 [b]	1.5	1.5
Nominal volume / cm^3	6	6	0.2	0.2
Polarizing potential [a] / V	300	300	300	300

[a] At the NRC, a negative polarizing potential is applied to the collector. At the BIPM, the collector must remain at virtual ground potential and a positive polarizing potential was applied to the chamber window.

[b] The Radcal cavity dimensions are not stated by the manufacturer. From radiographic measurements, the collector diameter is known to be around 30 mm, and ionometric measurements confirm the cavity volume of around 6 cm^3 stated by the manufacturer. From these, the cavity height is deduced to be around 9 mm.

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 tungsten-anode x-ray tube with an inherent filtration of 1 mm beryllium. 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 BIPM air-kerma rate determination shows a long-term standard deviation of less than 3 parts in 10^4. The BIPM tungsten-anode radiation qualities for mammography in the range from 23 kV to 50 kV are given in Table 4 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters.

Note that the reference distance at the NRC is 1000 mm and so for the present comparison the BIPM measurements were also made at a distance of 1000 mm rather than at the usual reference distance of 500 mm. The BIPM values for HVL and $(\mu/\rho)_{air}$ given in Table 4 were measured at 1000 mm.

Table 4. Characteristics of the BIPM reference radiation qualities

Radiation quality	W/Mo 23	W/Mo 30	W/Mo 50
Generating potential / kV	23	30	50
Additional Mo filtration / mm		0.060	
Al HVL / mm (1000 mm)	0.343	0.376	0.513
$(\mu/\rho)_{air}{}^{a}$ / cm^2 g^{-1} (1000 mm)	1.74	1.61	1.35
$\dot{K}_{BIPM}$ / mGy s^{-1} (1000 mm)		0.23	

a Measured for an air path length of 100 mm.

The irradiation area is temperature controlled between 20 °C and 22 °C and is stable over the duration of a calibration to better than 0.1 °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 40 % to 50 % and consequently no humidity correction is applied to the current measured using transfer instruments.

5.2 The BIPM standard and correction factors

As noted above, for the present comparison the reference plane for the BIPM standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.03 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. Using an additional lead collimator positioned at the filter holder, the beam diameter in the reference plane was 88 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 1.0005 was applied to correct for the known polarity effect in the standard. The leakage current for the BIPM 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 BIPM standard, together with their associated uncertainties, are given in Table 5.

The correction factor k_a is evaluated for the distance of 1000 mm using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ 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 at the time of the measurements. Ionization 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.

Table 5. Correction factors for the BIPM standard and their associated uncertainties

Radiation quality	W/Mo 23	W/Mo 30	W/Mo 50	$u_{i\text{A}}$	$u_{i\text{B}}$
Air attenuation k_a[a] (1 m)	1.0212	1.0196	1.0163	0.0002	0.0001
Scattered radiation k_{sc}	0.9974	0.9974	0.9975	-	0.0003
Fluorescence k_{fl}	0.9972	0.9972	0.9975	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	-	0.0001
Ion recombination k_s	1.0004	1.0004	1.0004	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia}	0.9995	0.9995	0.9994	-	0.0003
Wall transmission k_p	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	-	0.0001

$u_{i\text{A}}$ represents the relative standard uncertainty estimated by statistical methods, type A

$u_{i\text{B}}$ represents the relative standard uncertainty estimated by other means, type B

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

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.03 mm. Each transfer 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 leakage current for the Radcal transfer chambers was always less than 1 part in 10^4. For the PTW chambers, a typical leakage current of 2 fA was measured corresponding in relative terms to around 7 parts in 10^4.

For each of the four transfer chambers and at each radiation quality, two sets of seven measurements were made, each measurement with integration time 30 s and 60 s for the Radcal and PTW chambers, respectively. The relative standard uncertainty of the mean ionization current for each set was always below 3 parts in 10^4. An additional relative standard uncertainty component of 5 parts in 10^4 is included (Table 11) to account for the typical reproducibility of calibrations in low-energy x-rays at the BIPM.

6. Calibration at the NRC

6.1 The NRC irradiation facility and reference radiation qualities

The low-energy x-ray facility at the NRC comprises a constant-potential low-ripple generator (Glassman PS/PK080N050Y31) and a 100 kV Philips MCN 101 tungsten-anode x-ray tube with an inherent filtration of 1.0 mm beryllium, a focal spot size of 1.5 mm by 1.5 mm and an anode angle of 22^{o}. The generating potential is measured at 3 s intervals using a Park divider calibrated to 3 parts in 10^5, which is constant for a given radiation quality to better than 5 V. The x-ray tube current is stabilized over a wide dynamic range (μA to mA) using a feedback system developed at the NRC that controls the beam current. In relative terms, stability over the short term is approximately 5 parts in 10^5 and long-term stability (0.5 year) around 1 part in 10^3.

A parallel-plate transmission ionization chamber is employed as the primary beam monitor. This monitor chamber is located 34 cm from the focal spot and consists of five layers of aluminized Mylar, totalling 5.6 mg cm^{-2} of Mylar and 0.21 mg cm^{-2} of aluminum. The air temperature for this monitor chamber is measured by a sensor mounted inside the chamber. The x-ray output is switched on and off using a mechanical shutter with a timing uncertainty of approximately 15 ms. The combination of tube current and shutter time serves as an independent secondary beam monitor. The two beam monitors typically agree at the level of 2 parts in 10^4. The characteristics of the NRC realization of the W/Mo qualities used in the present comparison are given in Table 6.

The irradiation area is temperature controlled at around 22 °C and is stable over the duration of a calibration to better than 0.1 K. A calibrated temperature sensor measures the temperature at the position of the instrument being calibrated, and this temperature generally follows the ambient air temperature to within 0.05 K. The air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. During the comparison the relative humidity was controlled within the range 20% to 50%. A humidity correction of nominally 0.998 is calculated, based on Fig. 5.14 of ICRU Report 31 (ICRU 1979), and applied to the calibration measurements.

Table 6. Characteristics of the NRC reference radiation qualities

Radiation quality	W/Mo-23	W/Mo-30	W/Mo-50
Generating potential / kV	23	30	50
Additional Mo filtration / mm	0.064		
Al HVL / mm	0.350	0.381	0.517
$(\mu/\rho)_{air}$[a] / cm^2 g^{-1} (1.0 m)	1.747	1.548	1.291
$\dot{K}_{NRC}$ / mGy s^{-1} (Radcal)	0.14	0.19	0.26
$\dot{K}_{NRC}$ / mGy s^{-1} (PTW)	0.34	0.60	1.33

[a] Measured for an air path length of 98.98 mm and for the reference distance of nominally 1000 mm.

6.2 The NRC standard and correction factors

The reference plane for the NRC standard was positioned at 1 000 mm from the radiation source, with a reproducibility of 0.1 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.2 mm. The beam diameter in the reference plane is approximately 90 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the NRC standard were made using positive polarity only. No polarity correction factor was applied as the polarity effect in the standard measured for each radiation quality was negligible.

The correction factors applied to the ionization current measured at each radiation quality using the NRC 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 NRC

The reference point for each chamber was positioned in the reference plane with a reproducibility of 0.1 mm. Alignment on the beam axis was to an estimated uncertainty of 0.2 mm.

After each series of measurements, the leakage current was measured with and without load and a leakage correction made using the mean value. The relative leakage current for the Radcal chambers was always less than 4 parts in 10^4 and for the PTW chambers less than 6 parts in 10^4.

For each of the four transfer chambers and at each radiation quality, three or four sets of measurements were made, each measurement with integration time 30 s to 60 s for the Radcal chambers and 60 s to 120 s for the PTW chambers, depending on beam quality. The relative standard uncertainty of the mean ionization current for each set was less than 4 parts in 10^4. The results for $N_{K,\mathrm{NRC}}$ are given in Table 8.

Table 7. Correction factors for the NRC standard [a]

Radiation quality	W/Mo-23	W/Mo-30	W/Mo-50	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a [b] (1 m)	1.0209	1.0185	1.0154	0.0002	0.0007
Scattered radiation k_{sc}	0.9959	0.9960	0.9962	-	0.0010
Electron loss k_e	1.0000	1.0000	1.0000	-	0.0007
Ion recombination k_s	1.0007	1.0007	1.0007	0.0001	0.0002
Polarity k_{pol}	1.0000	1.0000	1.0000	0.0001	-
Field distortion k_d	1.0000	1.0000	1.0000	-	0.0015
Wall transmission k_p	1.0000	1.0000	1.0000	-	0.0002
Humidity k_h [c]	0.9975	0.9975	0.9975	0.0001	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	-	0.0001

[a] The NRC standard does not presently incorporate corrections for fluorescence or aperture transmission.

[b] Values for 295.15 K and 101.325 kPa; each measurement is corrected using the air density measured at the time.

[c] Nominal values. The actual value of the humidity correction applied to each measurement is based on the humidity measured at the time and the data given in ICRU Report 31 (ICRU 1979).

7. Additional considerations for transfer chamber calibrations

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

Ion recombination: As can be seen from Tables 4 and 6, the air-kerma rates for the calibration of the Radcal chamber are similar at the two laboratories. However, for the PTW chamber calibrations at the NRC the air-kerma rate was higher than at the BIPM by up to a factor of 5. From experience with this chamber type, the effect of this increase in the ion recombination is not likely to be more than 5 parts in 10^4 and a corresponding uncertainty is included in Table 12.

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

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 radius 15 mm (Radcal type), $k_{rn,tr}$ for the BIPM reference fields at 1000 mm is around 1.001 and the effect is likely to be similar for the radiation fields at the NRC. A relative standard uncertainty of 3 parts in 10^4 is introduced for this effect in Table 12.

Field size: As the field diameter is similar at the two laboratories (close to 88 mm) no correction is applied.

7.2 HVL considerations

As noted in Section 4.1, slight differences in radiation qualities must be taken into account to evaluate a comparison result. From Tables 4 and 6 it can be seen that a slight difference exists between the HVL values measured at each laboratory. To derive a comparison result for the BIPM HVL values, a quadratic fit was made to each of the NRC data sets. From the fit, a set of $k_{Q,\mathrm{NRC}}$ factors was derived and are given in Table 8. The uncertainty of these values is taken to be 2 parts in 10^4 and included in Table 12.

8. Comparison results

The calibration coefficients $N_{K,\mathrm{NRC}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 8 along with the correction factors $k_{Q,\mathrm{NRC}}$ evaluated as described in Section 7.2. The values $N_{K,\mathrm{NRC}}$ measured before and after the measurements at the BIPM give rise to the relative standard uncertainties $s_{tr,1}$, $s_{tr,2}$, $s_{tr,3}$ and $s_{tr,4}$ for the four chambers, which are taken to represent the uncertainty in N_K arising from transfer chamber stability (although this is not distinguishable from the reproducibility of calibrations at the NRC).

Table 8. Ratios of calibration coefficients $N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$ for the transfer chambers

Radiation quality	W/Mo-23	W/Mo-30	W/Mo-50
Radcal 9642			
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	4.7504	4.7473	4.7720
$N_{K,\mathrm{NRC}}$ (post-BIPM)	4.7503	4.7448	4.7753
$s_{tr,1}$ (relative) [a]	0.00001	0.0004	0.0005
$N_{K,\mathrm{BIPM}}$	4.7530	4.7500	4.780
$k_{Q,\mathrm{NRC}}$	1.0004	1.0001	0.9997
Radcal 9646			
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	4.7529	4.7476	4.7551
$N_{K,\mathrm{NRC}}$ (post-BIPM)	4.7352	4.7332	4.749
$s_{tr,2}$ (relative) [a]	0.0024	0.0020	0.0008
$N_{K,\mathrm{BIPM}}$	4.7429	4.7437	4.7623
$k_{Q,\mathrm{NRC}}$	1.0003	1.0001	0.9998

Radiation quality	W/Mo-23	W/Mo-30	W/Mo-50
PTW 0948			
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	75.249	74.851	74.262
$N_{K,\mathrm{NRC}}$ (post-BIPM)	75.213	74.941	74.233
$s_{\mathrm{tr},3}$ (relative) [a]	0.0003	0.0008	0.0003
$N_{K,\mathrm{BIPM}}$	75.455	75.121	74.469
$k_{Q,\mathrm{NRC}}$	1.0012	1.0006	1.0001
PTW 0949			
$N_{K,\mathrm{NRC}}$ (pre-BIPM)	75.638	75.439	74.909
$N_{K,\mathrm{NRC}}$ (post-BIPM)	75.653	75.458	74.944
$s_{\mathrm{tr},4}$ (relative) [a]	0.0001	0.0002	0.0003
$N_{K,\mathrm{BIPM}}$	75.795	75.599	75.057
$k_{Q,\mathrm{NRC}}$	1.0007	1.0003	1.0001

[a] For each pre-post pair of $N_{K,\mathrm{NRC}}$ values with half-difference d, the standard uncertainty of the mean is taken to be $s_{\mathrm{tr},i} = d / \sqrt{(n–1.4)}$, where the term ($n$–1.4) is found empirically to be a better choice than (n–1) to estimate the standard uncertainty for low values of n. For $n = 2$, $s_{\mathrm{tr},i} = 1.3\ d$.

For each chamber at each radiation quality, the mean of the NRC results before and after the BIPM measurements and the corresponding value for $k_{Q,\mathrm{NRC}}$ are combined to evaluate the comparison result $R_{K,\mathrm{NRC}}$ according to Equation (3). The results are given in Table 9.

Table 9. Combined comparison results

Radiation quality	W/Mo-23	W/Mo-30	W/Mo-50
$R_{K,\mathrm{NRC}}$ using Radcal 9642	0.9998	0.9992	0.9983
$R_{K,\mathrm{NRC}}$ using Radcal 9646	1.0005	0.9994	0.9977
$R_{K,\mathrm{NRC}}$ using PTW 0948	0.9982	0.9976	0.9971
$R_{K,\mathrm{NRC}}$ using PTW 0949	0.9987	0.9984	0.9984
s_{tr}	0.0006	0.0005	0.0005
Final $R_{K,\mathrm{NRC}}$	**0.9993**	**0.9986**	**0.9979**

For each quality, the final result in bold in Table 9 is evaluated as the mean for the four transfer chambers. The corresponding uncertainty s_{tr} is the usual standard uncertainty of the mean (using again the choice (n–1.4) introduced in the footnote to Table 8), or taken as

$$s_{\mathrm{tr}} = \sqrt{\left(s_{\mathrm{tr},1}^2 + s_{\mathrm{tr},2}^2 + s_{\mathrm{tr},3}^2 + s_{\mathrm{tr},4}^2\right)} / 4 \qquad (4)$$

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 $s_{tr,1}$, $s_{tr,2}$, $s_{tr,3}$ and $s_{tr,4}$ from Table 8). The mean value of s_{tr} for the three qualities, $s_{tr,comp}$ = 0.0006, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 12.

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 $R_{K,\mathrm{NRC}}$, 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. In the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described in Burns *et al* (2003), correlation in the values for the correction factors k_e, k_{sc} and k_{fl} are taken into account if the NMI has used values derived from Monte Carlo calculations. This is not presently the case for the NRC standard and consequently no such correlation is assumed.

Table 10. Uncertainties associated with the standards

Standard	BIPM		NRC	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.0002	0.0002	0.0003	0.0003
Volume	0.0003	0.0005	0.0001	0.0004
Positioning	0.0001	0.0001	0.0002	0.0001
Correction factors (excl. k_h)	0.0003	0.0010	0.0002	0.0021
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0004	0.0026

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

Institute	BIPM		NRC	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
$\dot{K}$	0.0005	0.0019	0.0004	0.0026
Positioning of transfer chamber	0.0001	-	0.0002	0.0002
I_{tr}	0.0002	0.0002	0.0004	0.0015
Short-term reproducibility	0.0005	-	0.0010	-
N_K	0.0007	0.0019	0.0012	0.0030

Table 12. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,\mathrm{NRC}}$ / $N_{K,\mathrm{BIPM}}$	0.0014	0.0028[a]
$k_{\mathrm{rn,tr}}$	-	0.0003
$k_{\mathrm{s,tr}}$	-	0.0005
$k_{Q,\mathrm{NRC}}$		0.0002
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0006	
$R_{K,\mathrm{NRC}}$	0.0015	0.0029
	u_c = 0.0032	

a Takes account of correlation in type B uncertainties.

10. Discussion

The comparison results presented in Table 9 show general agreement at the level of the combined standard uncertainty of 3.2 parts in 10^3. While the use of transfer chambers might introduce more uncertainty than a direct comparison of the primary standards, useful information is gained on the reproducibility of calibration coefficients, particularly in the present work with the exceptional use of four transfer instruments.

11. Degrees of Equivalence

The analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence is described in 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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ 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 13 and in Figure 1.

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).

Table 13. Degrees of equivalence (W/Mo)

	W/Mo-23		W/Mo-28		W/Mo-30		W/Mo-50	
	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i	D_i /(mGy/Gy)	U_i
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)	
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

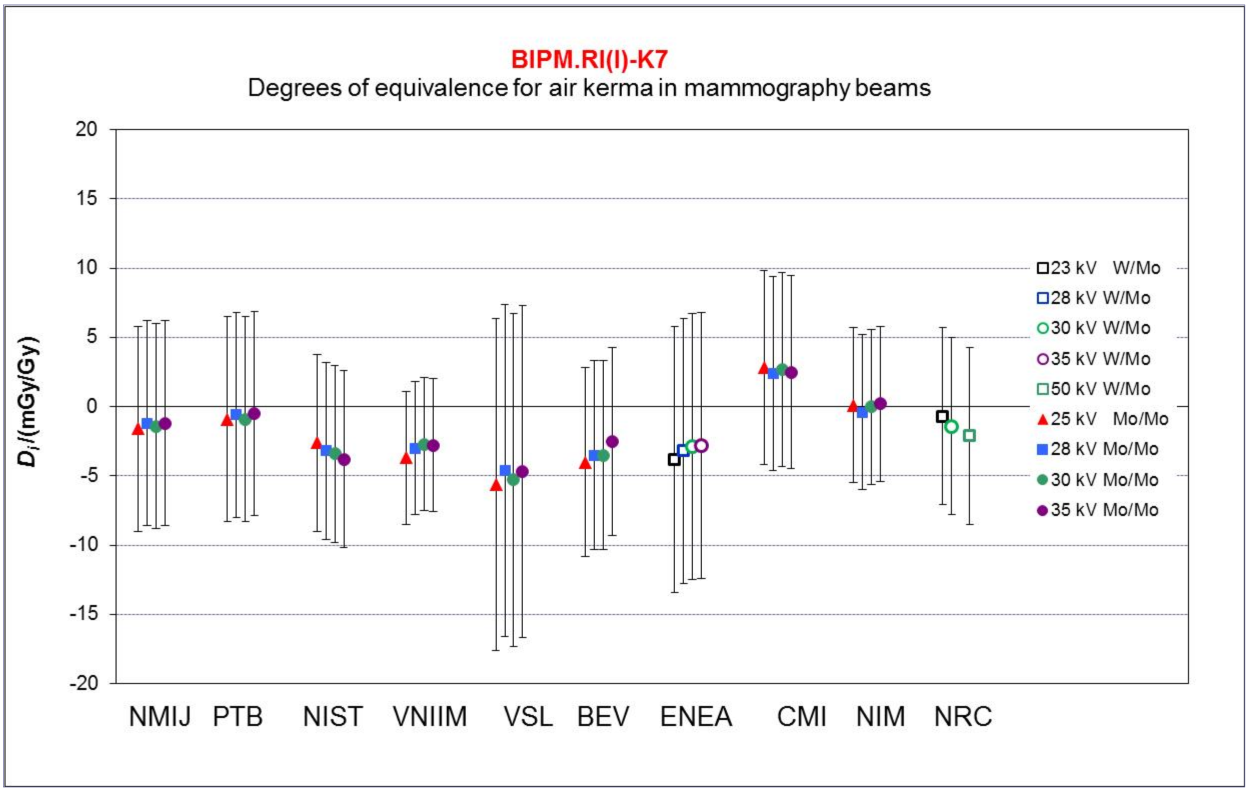

Figure 1. Degrees of equivalence for each NMI *i* with respect to the key comparison reference value

12. Conclusions

The key comparison BIPM.RI(I)-K7 for the determination of air kerma in mammography beams shows the standards of the NRC and the BIPM to be in general agreement at the level of the standard uncertainty for the comparison of 3.2 parts in 10^3. Degrees of equivalence, including those for the NRC, 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.

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KCDB 2020 The BIPM key comparison database is available online at https://www.bipm.org/kcdb/