

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

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Abstract A new key comparison has been made between the air-kerma standards of the PTB, Germany, and the BIPM in mammography x-ray beams. The results show the standards to agree at the level of the expanded uncertainty of the comparison of 7.2 parts in 10³. 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 Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Bureau International des Poids et Mesures (BIPM) in the mammography x-ray range from 25 kV to 35 kV to update the previous comparison result of 2010 (Kessler *et al.* 2011) published in the BIPM key comparison database (KCDB 2024) under the reference BIPM.RI(I)-K7. Measurements were done in two sets of mammography qualities, using the Mo- and the W-anode x-ray tubes with Mo filtration. Two parallel-plate ionization chambers were used as transfer instruments. The measurements at the BIPM took place in February 2024 using the reference conditions recommended by the CCRI as described in Kessler and Burns (2024). Final data from the PTB were received in May 2024.

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

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

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 $\prod k_i$ 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 measured for the standard 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 table¹. The value used for W_{air}/e is that recommended in ICRU Report 90 (ICRU 2016) for dry air, also given in Table 1.

3. Details of the standards

The free-air chamber standards are of the conventional parallel-plate design. The BIPM air-kerma standards are described in Boutillon *et al.* (1969) and in Kessler *et al.* (2010) for the W/Mo and Mo/Mo beams, respectively. Implementation of the recommendations of ICRU Report 90 (ICRU

¹ For an air temperature $T \sim 293$ K, pressure P and relative humidity ~ 50 % in the measuring volume, the correction for air density for the standard involves a temperature correction T/T_0 , a pressure correction P_0/P and a humidity correction $k_h = 0.9980$.

2016) is reported in Burns and Kessler (2018). The PTB standard is described in Büermann (2021), including changes made following ICRU Report 90 (ICRU 2016). The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	u_i^a
ρ_{air}^b	1.2045 kg m ⁻³	0.0001
ρ_{air}^c	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 $T_0 = 293.15$ K and $P_0 = 101.325$ kPa adopted at the BIPM.

^c Density of dry air at $T_0 = 293.15$ K and $P_0 = 101.325$ kPa adopted at the PTB.

Table 2. Main characteristics of the standards

Standard	BIPM L-01	BIPM L-02	PTB PK100
Aperture diameter / mm	9.941	9.998	10.008
Air path length / mm	100.0	100.0	97.2
Collecting length / mm	15.466	15.537	20.021
Electrode separation / mm	70	70	234
Collector width / mm	71	70	240
Measuring volume / mm ³	1200.4	1219.8	1574.8
Polarizing voltage / V	1500	1500	6000

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

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

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 is applied to the current measured using transfer instruments, on the basis that the BIPM laboratory is maintained with a relative humidity in the range from 40 % to 55 % and the PTB laboratory remained in the range from 30 % to 60 %.

To derive a comparison result from the calibration coefficients $N_{K,\text{BIPM}}$ and $N_{K,\text{NMI}}$ measured, respectively, at the BIPM and at a national metrology institute (NMI), differences in the radiation qualities must be taken into account. Normally, each quality used for the comparison has the same nominal generating potential 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 $N_{K,NMI}$ determined at the NMI into one that applies at the ‘equivalent’ BIPM quality and is derived from a fit to the $N_{K,NMI}$ values in terms of $\log(\text{HVL})$. The comparison result at each quality is then taken as

$$R_K = \frac{k_Q N_{K,NMI}}{N_{K,BIPM}}. \quad (3)$$

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 thin-window parallel-plate ionization chambers belonging to the PTB, type Radcal RC6M, serial numbers 10288 and 10290, were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. For positioning at the reference distance, the red line around the chamber casing was positioned in the reference plane.

Table 3. Main characteristics of the transfer chambers

Chamber type	Radcal RC6M
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

^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 indicate 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 high-stability generator, a molybdenum-anode x-ray tube with an inherent filtration of 0.8 mm beryllium and 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 using a transmission monitor, which might introduce its own variability, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. 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 25 kV to 35 kV are those recommended by the CCRI and are given in Table 4 in ascending HVL from left to right. The radiation qualities established using the Mo-anode and W-anode x-ray tubes with Mo filtration are identified as Mo/Mo and W/Mo, respectively, followed by the tube voltage applied.

The irradiation area is temperature controlled at around $20 \text{ }^\circ\text{C}$ and is stable over the duration of a calibration to better than $0.1 \text{ }^\circ\text{C}$. Calibrated thermistors measure the temperature of the ambient

air and the air inside the BIPM standards. Air pressure is measured by means of a calibrated barometer.

At the BIPM, the reference distances are 0.6 m and at 0.5 m from the exit windows of the Mo-anode and W-anode x-ray tubes, respectively, whereas at the PTB, the reference distance is 1 m. At the BIPM, the measurement distance can only be modified in the W-anode x-ray tube facility and additional qualities have been established at 1 m. For this comparison, the chambers were calibrated at 0.6 m and at 1 m from the exit windows of the Mo-anode and W-anode x-ray tubes, respectively. The distance effect on the calibration coefficients was determined and is discussed in Section 7.1.

Table 4. Characteristics of the BIPM reference radiation qualities used for the PTB comparison

x-ray tube	Mo-anode x-ray tube				W-anode x-ray tube			
	Mo/Mo 25	Mo/Mo 28	Mo/Mo 30	Mo/Mo 35	W/Mo 25	W/Mo 28	W/Mo 30	W/Mo 35
Generating potential / kV	25	28	30	35	25	28	30	35
Additional filtration	30 μm Mo				60 μm Mo			
Al HVL / mm	0.277	0.310	0.329	0.365	0.342	0.355	0.364	0.388
$(\mu/\rho)_{\text{air}}^{\text{a}} / \text{cm}^2 \text{g}^{-1}$	2.20	1.99	1.91	1.74	1.60	1.58	1.55	1.49
$\dot{K}_{\text{BIPM}} / \text{mGy s}^{-1}$	2				0.2			
Distance / m	0.6				1			

^a Measured for an equivalent air-path length of 100 mm using a variable-pressure tube.

5.2 BIPM standards and correction factors

The reference plane for the BIPM standards was positioned at 0.6 m and 1 m from the exit window of the Mo- and W-anode x-ray tubes, respectively, with a reproducibility of 0.03 mm. The standards were aligned laterally on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane of the Mo-anode x-ray tube facility is 100 mm; using an additional tungsten collimator in the W-anode x-ray facility, the beam diameter at 1 m was 88 mm, similar to the field size at the usual distance of 0.5 m.

For the calibration of transfer chambers, measurements using the BIPM standards were made using positive polarity only. The correction factors of 1.0005 and 1.0000 are applied to correct for the known polarity effect in the standards (see Table 5). The leakage current for the BIPM standards, relative to the ionization current, 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 standards, together with their associated standard uncertainties, are given in Table 5.

The largest correction is that due to the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. The corresponding correction factor k_a is evaluated using the measured mass attenuation coefficients for air $(\mu/\rho)_{\text{air}}$ 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.

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 laterally on the beam axis to an estimated uncertainty of 0.1 mm. The leakage current was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current for each chamber was less than 1 part in 10^4 .

The calibration procedure involves measurements with the 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. For each of the transfer chambers at each radiation quality, the relative standard uncertainty of the mean ionization current was below 2 parts in 10^4 . Based on the results of repeat calibrations including chamber repositioning and on long-term experience of calibrations in these beams, an uncertainty component of 5 parts in 10^4 is included in Table 11 for the short-term reproducibility of the calibration coefficients determined at the BIPM.

Table 5. Correction factors and uncertainties for the BIPM standards

Radiation quality	Mo/Mo 25	Mo/Mo 28	Mo/Mo 30	Mo/Mo 35	u_{iA}	u_{iB}
	W/Mo 25	W/Mo 28	W/Mo 30	W/Mo 35		
Air attenuation k_a^a	1.0274	1.0244	1.0233	1.0212	0.0002	0.0001
	1.0194	1.0193	1.0189	1.0181		
Photon scatter k_{sc}	0.9977	0.9977	0.9978	0.9978	-	0.0003
	0.9974	0.9974	0.9974	0.9974		
Fluorescence k_{fl}	0.9975	0.9976	0.9976	0.9977	-	0.0005
	0.9972	0.9972	0.9972	0.9973		
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.0001
Initial ionization - energy dependence of $W_{air} k_{ii} k_W^b$	0.9968	0.9968	0.9969	0.9969	-	0.0012
	0.9971	0.9971	0.9971	0.9972		
Ion recombination k_s	1.0015	1.0015	1.0015	1.0015	0.0001	0.0001
	1.0004	1.0004	1.0004	1.0004		
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0001	-
	1.0005	1.0005	1.0005	1.0005		
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	-	0.0007
Diaphragm effects k_{dia}	0.9996	0.9995	0.9995	0.9995	-	0.0003
	0.9995	0.9995	0.9995	0.9995		
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0001	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	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 The stated values are for the product $k_{ii}k_W$, as presented in Burns and Kessler (2018).

6. Calibration at the PTB

6.1 PTB irradiation facility and reference radiation qualities

The low-energy x-ray facility at the PTB uses a constant potential generator and a unipolar x-ray tube of type Y.TU 160-D02 (Comet Yxlon, Germany) with tungsten-anode and an inherent filtration of 0.8 mm beryllium as well as a unipolar x-ray tube of type PW 2185 (PANalytical, Netherlands) with molybdenum-anode and an inherent filtration of 1 mm Be. The x-ray output is monitored by means of a transmission monitor ionization chamber. For a given radiation quality, the short-term reproducibility of the air-kerma rate relative to the transmission monitor is typically 2 parts in 10^4 . The generating potential is measured invasively with a voltage divider manufactured and calibrated at the PTB. The characteristics of the PTB realization of the CCRI comparison qualities are given in Table 6.

The irradiation area is temperature controlled around 20 °C and is stable over the duration of a calibration to better than 0.5 °C. Two calibrated thermometers are used to measure air temperature, one positioned near the primary standard and near the transfer chamber during calibration, and the second near the transmission monitor. The air pressure is measured by means of a calibrated barometer.

Table 6. Characteristics of the PTB reference radiation qualities

x-ray tube	Mo-anode x-ray tube				W-anode x-ray tube			
	Mo/Mo 25	Mo/Mo 28	Mo/Mo 30	Mo/Mo 35	W/Mo 25	W/Mo 28	W/Mo 30	W/Mo 35
Generating potential / kV	25	28	30	35	25	28	30	35
Additional filtration	30 µm Mo				60 µm Mo			
Al HVL / mm	0.275	0.305	0.322	0.357	0.344	0.356	0.364	0.391
$(\mu/\rho)_{\text{air}}^a / \text{cm}^2 \text{g}^{-1}$	2.20	2.02	1.93	1.77	1.72	1.68	1.65	1.58
$\dot{K}_{\text{PTB}} / \text{mGy s}^{-1}$	0.4 to 0.5				0.1			
Distance / m	1 m							

^a Measured for an air path length of 98 mm, corrected to reference conditions 293.15 K and 101.325 kPa.

6.2 PTB standard and correction factors

The reference plane for the PTB standard was positioned at 1 m from the source, with an uncertainty of around 0.1 mm and a reproducibility of 0.05 mm. The standard was aligned laterally on the beam axis with a reproducibility of 0.05 mm. The beam diameter in the reference plane is 100 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the PTB standard were made using positive polarity only. No correction is applied and a relative standard uncertainty for the polarity effect is included in Table 7. The leakage current for the PTB standard was below 3.5 fA, corresponding to less than 1 part in 10^4 .

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

6.3 Transfer chamber positioning and calibration at the PTB

The reference point for each chamber was positioned in the reference plane with an uncertainty of around 0.1 mm and a reproducibility of 0.05 mm. Each transfer chamber was aligned laterally on the beam axis to an estimated uncertainty of 0.1 mm. The leakage current was measured for each measurement series and a correction applied. The leakage current was typically below 1 fA, corresponding to less than 1 part in 10^4 relative to the ionization current.

For each transfer chamber at each radiation quality, a calibration was made before the measurements at the BIPM and following the return of the chambers to the PTB. The uncertainty arising from these repeat measurements is discussed in Section 8.

Table 7. Correction factors and uncertainties for the PTB standard

Radiation quality	Mo/Mo 25	Mo/Mo 28	Mo/Mo 30	Mo/Mo 35	u_{iA}	u_{iB}
	W/Mo 25	W/Mo 28	W/Mo 30	W/Mo 35		
Air attenuation k_a ^a	1.0261	1.0240	1.0229	1.0209	0.0005	0.0005
	1.0204	1.0199	1.0195	1.0187		
Photon scatter k_{sc} ^b	0.9904	0.9906	0.9907	0.9909	-	0.0005
	0.9909	0.9910	0.9910	0.9912		
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.0005
Initial ionization - energy dependence of $W_{air} k_{ii} k_W$ ^c	0.9969	0.9969	0.9970	0.9970	-	0.0011
	0.9970	0.9970	0.9971	0.9971		
Guard strip attenuation k_{ap}	1.0056	1.0051	1.0049	1.0045	0.0005	0.0005
	1.0043	1.0042	1.0041	1.0040		
Ion recombination k_s	1.0028	1.0033	1.0034	1.0036	-	0.0011
	1.0012	1.0011	1.0011	1.0011		
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0005	0.0005
Field distortion k_d	0.9910	0.9910	0.9910	0.9910	-	0.0010
Aperture transmission k_l	0.9997	0.9996	0.9996	0.9996	0.0005	0.0005
	0.9996	0.9996	0.9996	0.9996		
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0005	-
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.

^b This includes the effect of fluorescence, treated separately for the BIPM standard as k_{fl} .

^c The stated values are for the product $k_{ii}k_W$.

7. Additional considerations for transfer chamber calibrations

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

Ion recombination: As can be seen from Tables 4 and 6, the PTB and BIPM air-kerma rates are different, mainly for the Mo/Mo qualities. Ion recombination was determined at the BIPM for a Radcal RC6M chamber type. The results show that the correction to be applied for each beam will not differ by more than 2 parts in 10^4 . No correction for the ion recombination effect was applied and a relative standard uncertainty of 2 parts in 10^4 is included in Table 12.

Polarity: Each transfer chamber was used with the same polarity at each laboratory and so no correction is applied for the polarity effect.

Radial non-uniformity: No correction is applied at either laboratory for the radial non-uniformity of the radiation field. It is reasonable to assume some cancellation at the two laboratories. A corresponding uncertainty of 5 parts in 10^4 is included in Table 12.

Distance: The mammography qualities at the PTB have been established at the reference distance of 1 m. As mentioned in Section 5.1, the reference distances at the BIPM are at 0.6 m and at 0.5 m from the exit windows of Mo-anode and W-anode x-ray tubes, respectively, but additional qualities are also available at 1 m from the exit window of the W-anode x-ray tube. For this comparison, the chambers were calibrated in the W/Mo beams at 0.5 m and at 1 m to evaluate the effect of distance on the calibration coefficients. The mean ratio of the calibration coefficients determined at both distances $N_{K\ 1\ m} / N_{K\ 0.5\ m}$ for each chamber is 0.9979(3). Assuming that the same effect is present in the Mo/Mo beams, a scaled correction factor $k_{\text{dist, tr}}$ of 0.9983 was calculated for each chamber and applied to the N_K values measured at the BIPM at the distance of 0.6 m in the Mo/Mo beams; a relative standard uncertainty of 5 parts in 10^4 is introduced in Table 12 for this effect.

Field size: As the field diameters don't differ significantly, no correction is applied

7.2 Radiation quality correction factors k_Q

As noted in Section 4.1, slight differences in radiation qualities might require a correction factor k_Q . However, from Tables 4 and 6 it is evident that the radiation qualities at the BIPM and at the PTB are very closely matched in terms of HVL and so the correction factor k_Q is taken to be unity for all qualities, with a negligible uncertainty.

8. Comparison results

The calibration coefficients $N_{K, \text{PTB}}$ and $N_{K, \text{BIPM}}$ for the transfer chambers are presented in Table 8. For each chamber at each radiation quality, the values $N_{K, \text{PTB}}$ provided before and after the measurements at the BIPM give rise to the mean value used for the final comparison result and a relative standard uncertainty s_{stab} representing the chamber stability².

The comparison results R_K are presented in Table 9, evaluated according to Equation (3). For each radiation quality the final comparison result is evaluated as the mean for the two transfer chambers.

² Because of the very small sample size, the modified standard uncertainty including the appropriate t -factor is used, which for $n = 2$ gives $s_{\text{stab}} = 1.8 s_{\text{dev, s}} / \sqrt{2}$. Likewise for s_{tr} . See Burns (2024).

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	Mo/Mo 25	Mo/Mo 28	Mo/Mo 30	Mo/Mo 35	W/Mo 25	W/Mo 28	W/Mo 30	W/Mo 35
<i>Radcal RC6M-10288</i>								
$N_{K,PTB}$ (pre-BIPM) / Gy μC^{-1}	4.764	4.761	4.758	4.757	4.758	4.757	4.756	4.760
$N_{K,PTB}$ (post-BIPM) / Gy μC^{-1}	4.765	4.759	4.757	4.754	4.758	4.759	4.760	4.764
$s_{\text{stab},1}$	0.0002	0.0004	0.0002	0.0006	-	0.0004	0.0008	0.0008
$N_{K,BIPM}$ / Gy μC^{-1}	4.743	4.740	4.739	4.736	4.738	4.738	4.737	4.740
<i>Radcal RC6M-10290</i>								
$N_{K,PTB}$ (pre-BIPM) / Gy μC^{-1}	4.761	4.756	4.755	4.753	4.750	4.749	4.747	4.750
$N_{K,PTB}$ (post-BIPM) / Gy μC^{-1}	4.771	4.765	4.763	4.759	4.756	4.756	4.758	4.759
$s_{\text{stab},2}$	0.0019	0.0017	0.0015	0.0012	0.0012	0.0014	0.0021	0.0017
$N_{K,BIPM}$ / Gy μC^{-1}	4.748	4.743	4.742	4.738	4.741	4.740	4.742	4.744

The uncertainty s_{tr} is the standard uncertainty of this mean, or taken as

$$s_{\text{tr}} = \frac{\sqrt{s_{\text{stab},1}^2 + s_{\text{stab},2}^2}}{2} \quad (4)$$

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 $s_{\text{stab},1}$ and $s_{\text{stab},2}$ from Table 8). The rms value of s_{tr} for the eight qualities, $s_{\text{tr,comp}} = 0.0014$, is taken to represent the 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 PTB in the previous comparison in 2010, revised for the changes made to the standards at each laboratory.

Table 9. Combined comparison results

Radiation quality	Mo/Mo 25	Mo/Mo 28	Mo/Mo 30	Mo/Mo 35	W/Mo 25	W/Mo 28	W/Mo 30	W/Mo 35
R_K using Radcal RC6M-10288	1.0045	1.0042	1.0039	1.0041	1.0042	1.0042	1.0044	1.0046
R_K using Radcal RC6M-10290	1.0038	1.0037	1.0036	1.0038	1.0025	1.0026	1.0022	1.0022
s_{tr}	0.0006	0.0005	0.0003	0.0003	0.0016	0.0015	0.0020	0.0022
Final R_K	1.0042	1.0040	1.0038	1.0040	1.0034	1.0034	1.0033	1.0034
<i>Updated results of 2010</i>	0.9992	0.9995	0.9992	0.9996	1.0018	1.0018	1.0019	1.0013

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 is presented in Table 12. This uncertainty takes into account correlation in the type B uncertainties associated with the physical constants, the humidity correction and the factor k_{ikw} . Correlation in the values for k_e , k_l , 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 low-energy x-rays in terms of degrees of equivalence described in Burns (2003).

Table 10. Uncertainties associated with the standards

Standard	BIPM L-01, L-02		PTB PK100	
	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Relative standard uncertainty				
Ionization current	0.0002	0.0002	0.0014	-
Positioning	0.0001	0.0001	-	0.0001
Volume	0.0003	0.0005	-	0.0006
Correction factors (excl. k_h)	0.0003	0.0015	0.0011	0.0022
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0035	-	0.0035
\dot{K}	0.0005	0.0039	0.0018	0.0042

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

Institute	BIPM		PTB	
	u_{iA}	u_{iB}	u_{iA}	u_{iB}
\dot{K}	0.0005	0.0039	0.0018	0.0042
I_{tr}	0.0002	0.0002	0.0006	-
Monitor ionization current I_{mon}	-	-	0.0013	-
Air density correction k_{rho}	-	-	-	0.0007
Positioning of transfer chamber	0.0001	-	-	0.0001
Reproducibility	0.0005	-	- ^a	-
N_K	0.0007	0.0039	0.0023	0.0043

^a The reproducibility of the PTB transfer chambers calibrations over the duration of 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}
$N_{K,PTB} / N_{K,BIPM}$	0.0024	0.0022 ^a
Ion recombination	-	0.0002
Radial non-uniformity	-	0.0005
Distance	-	0.0005
Transfer chambers $S_{tr,comp}$	0.0014	-
R_K	0.0028	0.0023 ^a
	$u_c = 0.0036^a$	

^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 4 parts in 10^3 , which is within the expanded uncertainty for the comparison of 7.2 parts in 10^3 .

No trend is observed in the results for the different radiation qualities. While the use of transfer chambers might introduce more uncertainty in the comparison results than for a direct comparison of the primary standards, useful information is gained on the reproducibility of calibration coefficients.

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 $D_i = (\dot{K}_i - \dot{K}_{BIPM,i}) / \dot{K}_{BIPM,i} = x_i - 1$ 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 for both the Mo/Mo and W/Mo radiation qualities, noting that an NMI (such as the PTB) with results for both will have degrees of equivalence only for Mo/Mo.

12. Conclusions

The key comparison BIPM.RI(I)-K7 for the determination of air kerma in mammography beams shows the standards of the PTB and the BIPM to agree at the level of the expanded uncertainty of the comparison of 7.2 parts in 10^3 .

Tables and a graph of degrees of equivalence, including those for the PTB, 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. In accordance with the validity rules for comparison data agreed by the CCRI(I), results older than 15 years are considered no longer valid and have been removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database (KCDB 2024).

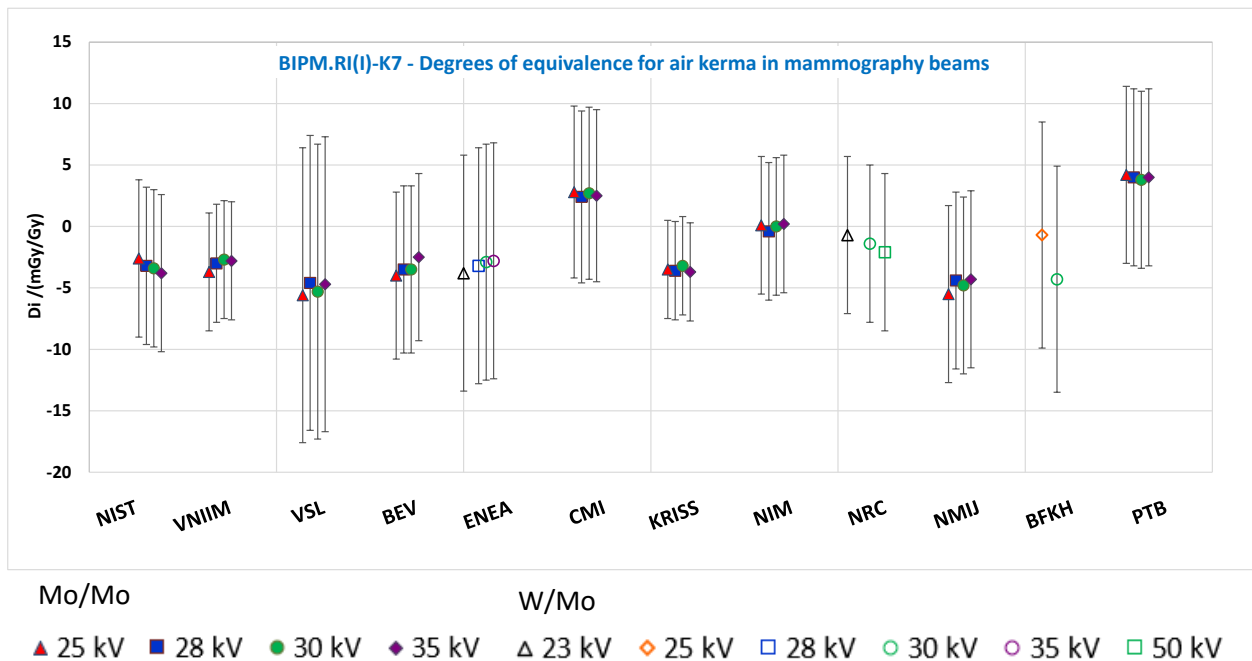
Table 13. Degrees of equivalence (Mo/Mo)

	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)	
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	4.0	-3.6	4.0	-3.2	4.0	-3.7	4.0
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
PTB	4.2	7.2	4.0	7.2	3.8	7.2	4.0	7.2

Degrees of equivalence (W/Mo)

	W/Mo-23		W/Mo-25		W/Mo-28		W/Mo-30		W/Mo-35		W/Mo-50	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
NRC	-0.7	6.4	-	-	-	-	-1.4	6.4	-	-	-2.1	6.4
ENEA-INMRI	-3.8	9.6	-	-	-3.2	9.6	-2.9	9.6	-2.8	9.6	-	-
BFKH	-	-	-0.7	9.2	-	-	-4.3	9.2	-	-	-	-

Figure 1. Graph of degrees of equivalence with the KCRV



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