Metrologia, **2011, 48,** ***Tech. Suppl.,*** **06011**

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 first key comparison has been made between the air-kerma standards of the PTB 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 3.7 parts in 10^3. A comparison of the standards has also been made in simulated mammography x-ray beams. The standards agree at the level of the combined standard uncertainty of 3.5 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence 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. The comparison was made using two sets of radiation qualities: the mammography qualities, established using a molybdenum anode x-ray tube with a molybdenum filter (Mo/Mo beams), and the simulated mammography beams, established using a tungsten anode x-ray tube with a molybdenum filter (W/Mo beams). Two thin-window parallel-plate ionization chambers were used as transfer instruments. The measurements at the BIPM took place in September 2010 using the reference conditions described in [1].

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

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

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 $\Pi\, k_{\text{i}}$ 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]

3. Details of the standards

The 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 standards are described in [2] and [3]. Details of the PTB standard are given in [4]. 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]	1.2930 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.

Table 2. Main characteristics of the standards

Standard used for the dosimetry of	BIPM L-01 W/Mo beams	BIPM L-02 Mo/Mo beams	PTB PK 100 W/Mo and Mo/Mo beams
Aperture diameter / mm	9.941	9.998	20.008
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	70	70	240
Measuring volume / mm^3	1200.4	1219.8	6294.7
Polarizing voltage / V	1500	1500	6000

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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 a humidity correction $k_{\mathrm{h}} = 0.9980$. At the BIPM, 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.

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

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

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 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_{Q} can be 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

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

4.2 Details of the transfer instruments

Two thin-window parallel-plate ionization chambers of type Radcal RC6M, belonging to the PTB, were used as transfer instruments for the comparison. The main characteristics are given in Table 3. The reference plane for the Radcal chamber was taken to be defined by the red line around the chamber casing and the reference point in this plane was taken to be on the axis defined by the entrance window.

Table 3. Main characteristics of the transfer chamber

Chamber type	Radcal RC6M
Serial numbers	9233 and 9275
Window / mg cm^{-2}	0.7
Collector diameter / mm	30
Cavity height / mm	9
Nominal volume / cm^3	6
Polarizing potential[a] / V (both polarities)	300

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 two low-energy x-ray tubes: one with a tungsten-anode and one with a molybdenum-anode having an inherent filtration of 1.0 mm and 0.8 mm beryllium, respectively. 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 variations in the BIPM air-kerma determination over the duration of a comparison are normally not more than 3×10^{-4} in relative terms.

Mammography beams: a set of four mammography radiation qualities were established using the molybdenum-anode x-ray tube in the range from 25 kV to 35 kV [2]; a molybdenum filter of thickness 0.030 mm is added for all radiation qualities.

Simulated mammography beams: a set of seven radiation qualities were established using the tungsten-anode x-ray tube with a molybdenum filter to simulate clinical mammography beams [5]; the tube is operated in the range from 23 kV to 50 kV and a molybdenum filter of thickness 0.060 mm is added for all radiation qualities.

The radiation qualities used for the present comparison are given in Table 4 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters for the two sets of beams.

Table 4. Characteristics of the BIPM Mo/Mo and W/Mo radiation qualities

Radiation quality	Mo25	Mo28	Mo30	Mo35	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	0.356	0.364	0.388
$(\mu/\rho)_{\text{air}}$ / cm^2 g^{-1}	2.20	1.99	1.91	1.74	1.62	1.58	1.55	1.49
$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	2.00				0.23			

* 0.423 mm of Be was added to all the W/Mo qualities corresponding to the windows used for the air-attenuation measurement

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 thermistors, calibrated to a few mK, 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.

5.2 The BIPM standards and correction factors

Mammography beams: The reference plane for the BIPM standard L-02 was positioned at 600 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. The beam diameter in the reference plane is 100 mm for all radiation qualities.

Simulated mammography beams: The reference plane for the BIPM standard L-01 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. The beam diameter in the reference plane is 100 mm for all radiation qualities. This change from the usual reference distance of 500 mm was made to match the reference distance at the PTB.

The correction factors applied to the ionization current measured at each radiation quality using the BIPM standards, together with their associated uncertainties, are given in Table 5 and Table 6 for the Mo/Mo and W/Mo beams, respectively.

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

Radiation quality	Mo25	Mo28	Mo30	Mo35	u_{iA}	u_{iB}
Air attenuation k_a[a]	1.0269	1.0244	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
Saturation 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.

Table 6. Correction factors for the BIPM L-01 standard

Radiation quality	W/Mo25	W/Mo28	W/Mo30	W/Mo35	u_{iA}	u_{iB}
Air attenuation k_a[a]	1.0197	1.0193	1.0189	1.0181	0.0002	0.0005[b]
Scattered radiation k_{sc}	0.9974	0.9974	0.9974	0.9974	-	0.0003
Fluorescence k_{fl}	0.9972	0.9972	0.9972	0.9973	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.0001
Saturation k_s	1.0004	1.0004	1.0004	1.0004	0.0001	0.0001
Polarity k_{pol}	1.0005	1.0005	1.0005	1.0005	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}	0.9995	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

[b] This uncertainty is larger than that for the usual reference distance of 500 mm for reasons outlined in the text.

During the calibration of the transfer chambers, measurements using the BIPM standards were made using positive polarity; the polarity effect in the standard L-02 is less than 1 part in 10^4 and a correction of 1.0005 is applied to the current measured with the L-01. The leakage current for the BIPM standards, relative to the ionization current, was measured to be less than 1×10^{-4}.

In Table 5, the correction factor k_a is evaluated for the reference distance of 600 mm using the measured mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 4 for the mammography beams; for the simulated mammography beams, the correction factor k_a of Table 6 is evaluated for the distance of 1000 mm using the mass attenuation coefficients $(\mu/\rho)_{air}$ given in Table 4. Note that the $(\mu/\rho)_{air}$ values for the simulated beams at 1000 mm are obtained by interpolation from measured values for the CCRI qualities at 1000 mm; the uncertainty for $(\mu/\rho)_{air}$ in Table 6 is increased accordingly. 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 standards 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.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point for the Radcal transfer chambers was positioned in the reference plane with a reproducibility of 0.03 mm. The chambers were aligned on the beam axis to an estimated uncertainty of 0.1 mm.

The leakage currents were measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage currents for the transfer chambers were always less than 1×10^{-4}.

The chambers were repositioned and a second calibration was made for some qualities. Based on these data, a relative standard uncertainty component of 7×10^{-4} is included to account for the short-term reproducibility of the calibrations at the BIPM.

6. Calibration at the PTB

6.1 The PTB irradiation facility and reference radiation qualities

The PTB laboratory R128 houses two constant-potential generators and two x-ray tubes: a tungsten-anode and a molybdenum-anode tube with an inherent filtration of 7 mm and 1 mm beryllium, respectively. A voltage divider manufactured and calibrated at the PTB is used to measure the generating potential. A transmission monitor chamber manufactured at the PTB is used to normalize the x-ray output.

Mammography beams: a set of seven mammography radiation qualities were established at the PTB using the molybdenum-anode x-ray tube in the range from 20 kV to 50 kV with a molybdenum filter of thickness 0.030 mm added for all radiation qualities.

Simulated mammography beams: a set of seven simulated mammography radiation qualities were established at the PTB using the tungsten-anode x-ray tube in the range from 20 kV to 50 kV with a molybdenum filter of thickness 0.060 mm added for all radiation qualities.

The characteristics of the mammography qualities used for the present comparison are given in Table 7.

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. A thermistor measures the temperature of the air inside the shielding box surrounding the free-air chamber. Air pressure is measured by means of a calibrated barometer positioned in the irradiation room. The PTB laboratory humidity is not controlled and as it varies between 30 % and 60 %, this is taken into account by an additional uncertainty in the humidity correction factor. No humidity correction was applied to the current measured using the transfer instrument.

Table 7. Characteristics of the PTB Mo/Mo and W/Mo radiation qualities

Radiation quality	MMV 25	MMV 28	MMV 30	MMV 35	WMV 25	WMV 28	WMV 30	WMV 35
Generating potential / kV	25	28	30	35	25	28	30	35
Additional filtration	30 µm Mo				60 µm Mo			
Al HVL / mm	0.29	0.32	0.33	0.37	0.36	0.37	0.38	0.41
$(\mu/\rho)_{\text{air}}$ / cm^2 g^{-1}	2.15	1.97	1.89	1.73	1.67	1.61	1.60	1.54
$\dot{K}_{\text{PTB}}$ / mGy s^{-1}	0.79	0.80	0.78	0.81	0.08	0.10	0.14	0.17

6.2 The PTB standard and correction factors

The reference plane for the PTB standard was positioned at 1000 mm from the radiation source, with a reproducibility of 0.05 mm. The standard was aligned on the beam axis to an estimated uncertainty of 0.1 mm. The beam diameter in the reference plane is 100 mm for all radiation qualities.

The PTB standard was used at positive polarity only, with a correction for the polarity effect as given in Table 8.

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 8 and Table 9 for the mammography and the simulated mammography beams, respectively.

The correction factor k_a is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{\text{air}}$ given in Table 7. 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.

Table 8. Correction factors for the PTB standard for Mo/Mo beams

Radiation quality	MMV 25	MMV 28	MMV 30	MMV 35	$u_{i\text{A}}$	$u_{i\text{B}}$
Air attenuation k_a[a]	1.0255	1.0234	1.0223	1.0205	0.05	0.05
Scattered radiation k_{sc}[b]	0.9905	0.9907	0.9908	0.9910	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_s	1.0054	1.0055	1.0054	1.0056	0.05	0.05
Guard strip attenuation k_{ap}	1.0052	1.0048	1.0046	1.0042	0.05	0.05
Aperture edge transmission k_l	0.9997	0.9996	0.9996	0.9996	-	0.05
Field distortion	0.9920	0.9920	0.9920	0.9920	-	0.15
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.05	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	-	0.05
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.05

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

[b] This correction includes the re-absorption of scattered and of fluorescent photons.

Table 9. Correction factors for the PTB standard for W/Mo beams

Radiation quality	WMV 25	WMV 28	WMV 30	WMV 35	u_{iA}	u_{iB}
Air attenuation k_a[a]	1.0197	1.0190	1.0189	1.0182	0.05	0.05
Scattered radiation k_{sc}[b]	0.9910	0.9911	0.9911	0.9912	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_s	1.0010	1.0012	1.0014	1.0017	0.05	0.05
Guard strip attenuation k_{ap}	1.0041	1.0039	1.0039	1.0038	0.05	0.05
Aperture edge transmission k_l	0.9996	0.9996	0.9996	0.9996	-	0.05
Field distortion	0.9920	0.9920	0.9920	0.9920	-	0.15
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.05	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	-	0.05
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.05

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

[b] This correction includes the re-absorption of scattered and of fluorescent photons.

6.3 Transfer chamber positioning and calibration at the PTB

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 0.1 mm.

The leakage currents were measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage currents for the Radcal chambers were less than 4×10^{-4} for all measurements.

The chambers were calibrated two times before the measurements at the BIPM and two times following the BIPM measurements. A relative standard uncertainty component of 1×10^{-3} is included to account for the short-term reproducibility of calibrations at the PTB. The uncertainty arising from the long-term stability of the transfer chambers is implicitly included in the comparison results obtained for the different chambers (σ_{mean} of Table 12).

7. Additional considerations for transfer chamber calibrations

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

The air-kerma rates at the PTB are lower than those at the BIPM. No corrections $k_{s,tr}$ are applied for ion recombination and a relative standard uncertainty of 5×10^{-4} is introduced to account for the difference in the kerma rates at the two laboratories.

The transfer chambers were used with both polarities at each institute and the mean of the calibration coefficients measured with each polarity was used to evaluate the comparison results.

No correction $k_{rn,tr}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For the Radcal chamber, with collector diameter 30 mm, the correction factor for the BIPM reference field is around 1×10^{-3} and this effect is likely to cancel to some extent at the two laboratories. A relative standard uncertainty of 5×10^{-4} is introduced for this effect.

The chambers were calibrated at the PTB at the reference distance of 1000 mm for both sets of radiation qualities; for this comparison, the chambers were calibrated at the BIPM at 1000 mm in the W/Mo beams in order to reproduce the PTB measurement conditions (the BIPM reference distance for these beams is 500 mm). However, the BIPM calibration in the Mo/Mo beams was carried out at the reference distance of 600 mm (it is not possible to measure at 1000 mm in these beams). To estimate the effect on the response of the chambers calibrated at different distances, measurements at 500 mm were also made at the BIPM in the W/Mo beams. The calibration coefficients at both distances measured for 3 qualities in the HVL range of the Mo/Mo beams differ by 2.1 parts in 10^3 (mean $N_{K,\,1000\ \mathrm{mm}}$ / $N_{K,\,500\ \mathrm{mm}}$= 0.9979(5)). A similar effect was measured previously at the BIPM for other Radcal chambers, not only in the W/Mo beams but also in the CCRI reference qualities. Assuming that the same effect is present in the Mo/Mo beams, a scaled distance correction factor k_{dist} of 0.9983 has been applied to the N_K values measured at the BIPM at the distance of 600 mm in the Mo/Mo beams to account for the distance difference between the PTB and the BIPM (400 mm). Given the approximate nature of this correction, a relative standard uncertainty of 1.0×10^{-3} is introduced for this effect.

No uncertainty is included for field size as the field is similar in the two laboratories.

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 7 it is evident that the radiation qualities at the BIPM and 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 transfer chambers were calibrated at the PTB before and after the BIPM measurements. The calibration coefficients determined at the BIPM and at the PTB are given in Table 10 and Table 11 for the Mo/Mo and W/Mo radiation beams, respectively.

Table 10. Calibration coefficients for the transfer chambers in the Mo/Mo beams

Chamber		Date	Radiation quality			
			Mo25	Mo28	Mo30	Mo35
Radcal 9233	$N_{K,\mathrm{PTB}}$ / Gy μC^{-1}	2010-08	4.6909	4.6883	4.6864	4.6872
	$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	2010-09	4.6895	4.6861	4.6849	4.6839
	$N_{K,\mathrm{PTB}}$ / Gy μC^{-1}	2010-11	4.6936	4.6894	4.6885	4.6871
Ratio $N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$			1.0006	1.0006	1.0005	1.0007
Radcal 9275	$N_{K,\mathrm{PTB}}$ / Gy μC^{-1}	2010-08	4.7458	4.7462	4.7427	4.7474
	$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	2010-09	4.7652	4.7613	4.7620	4.7614
	$N_{K,\mathrm{PTB}}$ / Gy μC^{-1}	2010-11	4.7609	4.7588	4.7593	4.7593
Ratio $N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$			0.9975	0.9982	0.9977	0.9983

Table 11. Calibration coefficients for the transfer chambers in the W/Mo beams

Chamber		Date	Radiation quality			
			W/Mo25	W/Mo 28	W/Mo 30	W/Mo 35
Radcal 9233	$N_{K,\mathrm{PTB}}$ / Gy µC^{-1}	2010-08	4.6896	4.6910	4.6909	4.6944
	$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	2010-09	4.6718	4.6738	4.6753	4.6815
	$N_{K,\mathrm{PTB}}$ / Gy µC^{-1}	2010-11	4.6856	4.6880	4.6871	4.6913
Ratio $N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$			1.0034	1.0034	1.0029	1.0024
Radcal 9275	$N_{K,\mathrm{PTB}}$ / Gy µC^{-1}	2010-08	4.7434	4.7463	4.7470	4.7542
	$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	2010-09	4.7476	4.7490	4.7474	4.7573
	$N_{K,\mathrm{PTB}}$ / Gy µC^{-1}	2010-11	4.7546	4.7560	4.7568	4.7635
Ratio $N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$			1.0003	1.0005	1.0009	1.0003

The best estimate of the comparison result $R_{K,\mathrm{PTB}}$ for each radiation quality is taken to be the mean value for the two transfer chambers. The results are given in Table 12 along with the standard uncertainty of each mean value, σ_{mean}.

Table 12. Combined comparison results

Radiation quality	Mo/Mo beams				W/Mo beams			
	Mo25	Mo28	Mo30	Mo35	W/Mo25	W/Mo 28	W/Mo 30	W/Mo 35
$R_{K,\mathrm{PTB}}$	**0.9991**	**0.9994**	**0.9991**	**0.9995**	**1.0018**	**1.0019**	**1.0019**	**1.0014**
σ_{mean}	0.0015	0.0012	0.0014	0.0012	0.0015	0.0015	0.0010	0.0010

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 13 and those for the transfer chamber calibrations in Table 14. The combined uncertainty for the comparison results $R_{K,\mathrm{PTB}}$, presented in Table 15, includes a component of 1.3 parts in 10^3 arising from the spread of the results for the different transfer chambers, and is in effect the mean value for σ_{mean} from Table 12. This implicitly includes the long-term stability of the transfer chambers and no additional component is explicitly included for the change observed in the pre- and post-BIPM calibrations made at the PTB (notably for the Radcal 9275 chamber).

Table 13. Uncertainties associated with the standards

Standard	BIPM		PTB	
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	0.0010	0.0006
Volume	0.0003	0.0005	-	0.0006
Positioning	0.0001	0.0001	-	0.0002
Correction factors (excl. k_h)	0.0003	0.0010	0.0010	0.0020
Humidity k_h	-	0.0003	-	0.0003
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0014	0.0027

Table 14. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		PTB	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$\dot{K}$	0.0005	0.0019	0.0014	0.0027
Positioning of transfer chamber	0.0001	-	-	0.0004
I_tr	0.0003	0.0002	0.0010	0.0006
Monitor normalization	-	-	-	0.0005
Short-term reproducibility	0.0007	-	0.0010	-
N_K	0.0009	0.0019	0.0020	0.0028

The combined standard uncertainty u_c of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction. Correlation in the values for the correction factors k_sc and k_fl at the two laboratories, derived from Monte Carlo calculations in each laboratory, is taken into account in an approximate way by assuming half of the uncertainty value at each laboratory (note that the PTB value for k_sc includes k_fl). 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 [6].

Table 15. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{PTB}}$ / $N_{K,\mathrm{BIPM}}$	0.0022	0.0024[a]
$k_{\mathrm{rn,tr}}$	-	0.0005
$k_{\mathrm{s,tr}}$	-	0.0005
k_{dist}[b]	-	0.0010
Results for different chambers	0.001 3	-
$R_{K,\mathrm{PTB}}$	0.0025	0.0027
	$u_c = 0.0037$[c]	

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

[b] Applied only to the Mo/Mo beams.

[c] Removing uncertainty for k_{dist}, $u_c = 0.0035$ for the W/Mo beams.

10. Discussion

The comparison results presented in Table 12 show general agreement at the level of 7 parts in 10^4 for the Mo/Mo beams, which is within the combined relative standard uncertainty for the comparison of 3.7 parts in 10^3. For the W/Mo beams, the agreement between the standards is at the level of 1.8 parts in 10^3, also within the combined relative standard uncertainty for the comparison of 3.5 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 and on the behaviour of transfer instruments of the type used in the dissemination chain.

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 [6] 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 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 16 for the Mo/Mo beams. No degrees of equivalence are evaluated for the W/Mo beams.

The degree of equivalence of laboratory i with respect to each laboratory j that has taken part in a BIPM comparison is the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$. The combined standard uncertainty u_{ij} is mainly the combined uncertainty of the air-kerma rate determinations for laboratories i and j. In evaluating each u_{ij}, correlation between the standards is removed, notably that arising from k_{sc} and k_{fl}. As described in [6], if correction factors based on Monte Carlo calculations are used by both laboratories, or by neither, then half the uncertainty value is taken for each factor. Note that the uncertainty of the BIPM determination of air-kerma rate does not enter in u_{ij}, although the uncertainty arising from the comparison procedure is included.

Table 16. Degrees of equivalence

	Mo25		Mo28		Mo30		Mo35	
	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**

12. Conclusion

The first participation of the PTB, Germany in the BIPM ongoing comparison for mammography dosimetry has been completed successfully. The comparison was carried out indirectly using two transfer standards of the PTB and the results are in agreement within one standard uncertainty. The degrees of equivalence have been calculated and the formal results under the CIPM MRA are those available in the BIPM key comparison database.

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