Metrologia **52** (2015) *Tech. Suppl.* 06003

Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the BEV, Austria 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 BEV 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 3.4 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 Bundesamt für Eich- und Vermessungswesen (BEV), Austria, 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. Two parallel-plate ionization chambers were used as transfer instruments. Additional measurements were made in the W/Mo mammography beams using the same transfer instruments. The measurements at the BIPM took place in June 2014 using the reference conditions recommended by the CCRI and described by Allisy *et al* (2011). Final results were received from the BEV in July 2014.

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]

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

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

Constant	Value	u_i[a]
ρ_{air} (BIPM)[b]	1.2930 kg m^{-3}	0.0001
ρ_{air} (BEV)[c]	1.2045 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 as used for the BIPM standard.
[c] Density of dry air at T_0 = 293.15 K and P_0 = 101.325 kPa as used for the BEV standard.

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 Kessler *et al* (2010). Details of the BEV standard PKM can be found in Annex 1. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

Table 2. Main characteristics of the standards

Standard	BIPM L-02	BEV PKM
Aperture diameter / mm	9.998	20.021
Air path length / mm	100.0	109.9
Collecting length / mm	15.537	56.455
Electrode separation / mm	70	115
Collector width / mm	70	131
Measuring volume / mm^3	1219.8	17773
Polarizing voltage / V	1500	2500

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

$$N_K = \frac{\dot{K}}{I_{\mathrm{tr}}} \qquad (2)$$

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_Q 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

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

For the present comparison, this is discussed in section 7.3.

4.2 Details of the transfer instruments

Two thin-window parallel-plate ionization chambers belonging to the BEV were used as transfer instruments for the comparison. Their main characteristics are given in Table 3. The reference plane for each chamber is given in the table.

Table 3. Main characteristics of the transfer chambers

Chamber type	Exradin A11TW	Radcal 10X5-6M
Serial number	139	8568
Window material	Kapton	metallized polyester
Window thickness / mg cm^{-2}	3.86	0.7
Collector diameter / mm	20	30
Cavity height / mm	3.0	8.5
Nominal volume / cm^3	0.93	6.0
Reference plane	outer surface of window	red line around body
Polarizing potential [a] / V	–300	+300

[a] Potential applied to the chamber window, the collector remaining at virtual ground potential.

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 air-kerma rate determination over the duration of a comparison is normally not more than 3 parts in 10^4. 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 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.

Table 4. Characteristics of the BIPM mammography 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	30 μm 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			
$\dot{K}_{\text{BIPM}}$ / mGy s^{-1}	2.00			

5.2 The BIPM standard and correction factors

The reference plane for the BIPM standard 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.

During the calibration of the transfer chambers, measurements using the BIPM standard were made using positive polarity only as the polarity effect in the standard is less than 1 part in 10^4. The leakage current for the BIPM standard, relative to the ionization current, was measured to be less than 1 part in 10^4.

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 reference distance of 600 mm 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 (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.

5.3 Transfer chamber positioning and calibration at the BIPM

The reference point of the chamber was positioned in the reference plane at 600 mm with a reproducibility of 0.03 mm. The transfer chambers were 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, relative to the ionization current, was less than 1 part in 10^4.

For each transfer chamber and at each radiation quality, two sets of seven measurements were made, each measurement with integration time 40 s for the Exradin and 30 s for the Radcal. The relative standard uncertainty of the mean ionization current for each set was normally below 1 part in 10^4. For both chambers, calibrations at two qualities were repeated after repositioning the chamber. The results confirmed the uncertainty of 5 parts in 10^4 included in Table 12 for the short-term reproducibility of BIPM calibrations in the mammography x-ray beams. The calibration coefficients are given in Table 9.

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

Radiation quality	Mo/Mo-25	Mo/Mo-28	Mo/Mo-30	Mo/Mo-35	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a[a]	1.0269	1.0243	1.0233	1.0212	0.0002	0.0001
Scattered radiation k_sc	0.9977	0.9977	0.9978	0.9978	–	0.0003
Fluorescence k_fl	0.9975	0.9976	0.9976	0.9977	–	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	–	0.0001
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
$1 - g_\mathrm{air}$	1.0000	1.0000	1.0000	1.0000	–	0.0001

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

6. Calibration at the BEV

6.1 The BEV irradiation facility and reference radiation qualities

The mammography x-ray facility at the BEV is a Seifert Isovolt HS 160 unit with Panalytic PW-2185/00 molybdenum-anode x-ray tube having an inherent filtration of 1.0 mm beryllium (and a target angle of 20°). The x-ray output is monitored by means of the transmission ionization chamber M50E-8205. The characteristics of the BEV realization of the mammography comparison qualities are given in Table 6.

Two calibrated platinum resistance thermometers were used to measure air temperature, one positioned inside the primary standard respectively near the transfer chamber during calibration, a second inside the transmission monitor. Air pressure was measured using a calibrated barometer positioned at the height of the beam axis. The relative humidity was in the range from 30 % to 60 %. No humidity correction has been applied to the transfer chamber current measurements.

Table 6. Characteristics of the BEV 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	30 µm Mo			
Al HVL / mm	0.286	0.322	0.340	0.379
$(\mu/\rho)_{\text{air}}$ [a]/ $\text{cm}^2\ \text{g}^{-1}$	1.663	1.508	1.434	1.295
Reference distance / mm	900			
$\dot{K}_{\text{BEV}}$ [b] / mGy s^{-1}	0.83	0.83	0.81	0.81

[a] Air attenuation coefficient at 293.15 K and 101.325 kPa, calculated using NIST data (http://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/air.html) and measured spectra.

[b] The air-kerma rate was increased by a factor of 2 for the Exradin calibration.

6.2 The BEV standard and correction factors

The reference plane for the BEV standard was positioned at 900 mm from the focus of the x-ray tube, 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 150 mm for all radiation qualities.

During the calibration of the transfer chambers, measurements using the BEV standard were made at one polarity. The polarity corrections (and their uncertainty) are derived from previous measurements with the standard. The leakage current was measured to be less than 5 parts in 10^5.

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

The correction factor k_{a} is evaluated using the measured mass attenuation coefficients $(\mu/\rho)_{\text{air}}$ given in Table 6. 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 BEV

The reference plane for each transfer chamber (as given in Table 3) was positioned at the reference distance (900 mm from the focus of the x-ray tube) with a reproducibility of 0.2 mm. Alignment on the beam axis was to an estimated uncertainty of 0.5 mm.

Several calibrations were made for each transfer chamber before and after the measurements at the BIPM. Each calibration at a given radiation quality consisted of a set of 10 measurements, each measurement with integration time 60 s. For each set the standard uncertainty of the mean ratio of the transfer and monitor chamber currents was typically 3 parts in 10^4.

The leakage current, relative to the ionization current, was less than 4 parts in 10^4 for the Exradin chamber and about 2 parts in 10^4 for the Radcal chamber.

Table 7. Correction factors for the BEV PKM standard

Radiation quality	Mo/Mo-25	Mo/Mo-28	Mo/Mo-30	Mo/Mo-35	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a [a]	1.0223	1.0202	1.0192	1.0173	0.0002	0.0010
Scattered radiation k_{sc}	0.9946	0.9948	0.9949	0.9951	–	0.0010
Fluorescence k_{fl}	0.9968	0.9969	0.9969	0.9970	–	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	–	0.0005
Ion recombination k_s	1.0018	1.0018	1.0018	1.0018	0.0003	0.0006
Field distortion k_d	1.0000	1.0000	1.0000	1.0000	–	0.0010
Diaphragm correction k_{dia}	0.9989	0.9989	0.9988	0.9987	–	0.0021
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.0002	0.0002
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	0.0002	0.0005
Humidity k_h	0.9980	0.9980	0.9980	0.9980	–	0.0005
$1 - g_{air}$	0.9998	0.9998	0.9998	0.9998	–	0.0002

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

7. Additional considerations for transfer chamber calibrations

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

As can be seen from Tables 4 and 6, the air-kerma rates used to calibrate the Radcal chamber at the BEV are lower than those at the BIPM. A correction for ion recombination would decrease the N_K at the BIPM by 4 parts in 10^4, as documented in Burns and Csete (2002). However, no correction for ion recombination $k_{s,tr}$ is applied at either laboratory and an uncertainty of 2 parts in 10^4 is included in Table 13 to account for recombination differences. For the calibration of the Exradin chamber, the air-kerma rates are similar at the two laboratories.

The transfer chambers were used with the same polarity at each laboratory and so no corrections are applied for polarity effects in the transfer chambers.

No correction is applied for field size and an additional relative standard uncertainty of 5 parts in 10^4 is introduced in Table 13 to account for the difference in the field diameter at the BEV (150 mm) and at the BIPM (100 mm).

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 5 parts in 10^4 is introduced in Table 13 for this effect.

7.2 Calibration distance

The chambers were calibrated at the BEV at the reference distance of 900 mm; at the BIPM, the chambers were calibrated at the reference distance of 600 mm (it is not possible to measure at 900 mm in these beams). The effect of distance on the calibration coefficients was evaluated from the measurements made at 500 mm and at 1000 mm in the W/Mo mammography radiation qualities (see Section 10). The ratios of the calibration coefficients determined at both distances for both chambers are presented in Table 8. Assuming that the same effect is present in the Mo/Mo beams, a scaled correction factor $k_{\mathrm{dist,tr}}$ was calculated for each chamber and applied to the N_K values measured at the BIPM at the distance of 600 mm in the Mo/Mo beams; a relative standard uncertainty of 5 parts in 10^4 is introduced in Table 13 for this effect.

Table 8. Distance correction factors

Chamber	Radiation quality	W/Mo-25	W/Mo-35	mean
Exradin A11TW	$N_{K,\,1000\ \mathrm{mm}}$ / $N_{K,\,500\ \mathrm{mm}}$	0.9935	0.9939	0.9937
	Scaled correction factor $k_{\mathrm{dist,tr}}$			0.9962
Radcal 10X5-6M	$N_{K,\,1000\ \mathrm{mm}}$ / $N_{K,\,500\ \mathrm{mm}}$	0.9978	0.9975	0.9976
	Scaled correction factor $k_{\mathrm{dist,tr}}$			0.9986

7.3 Radiation quality correction factors k_Q

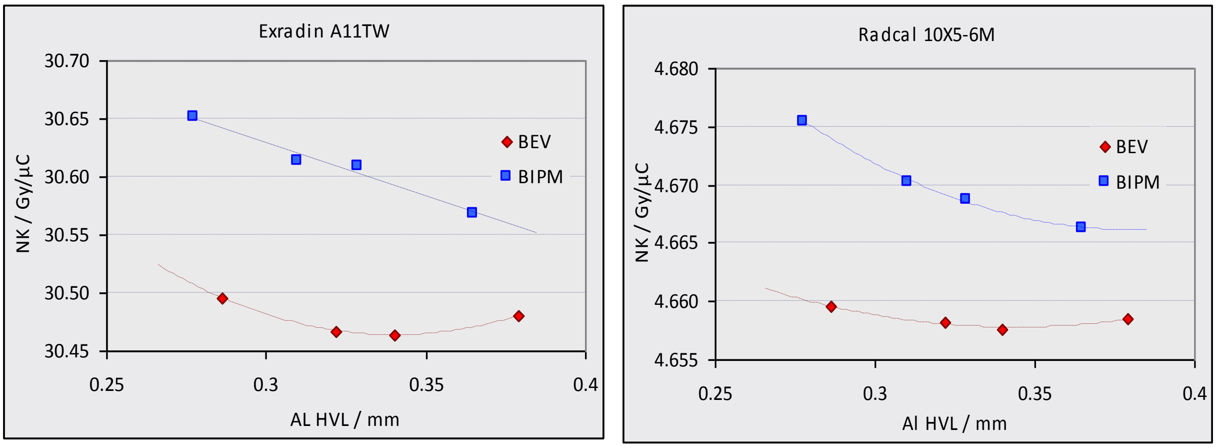
As noted in Section 4.1, differences in radiation qualities must be taken into account to evaluate a comparison result. From Tables 4 and 6 it is evident that the radiation qualities at the BIPM and the BEV are not well matched in terms of HVL, despite the use of the same calibrated generating potentials and molybdenum filters with the same nominal thickness. To derive a comparison result for the BIPM HVL values, a quadratic fit was made to the BEV data set for each chamber, as shown in Figure 1.

From the fit, a set of k_Q values was derived to correct each BEV calibration coefficient into one that applies at the 'equivalent' BIPM quality. The k_Q values so obtained are presented in Table 9. The comparison result is then evaluated as

$$R_{K,\mathrm{BEV}} = \frac{N_{K,\mathrm{BEV}}\, k_Q}{N_{K,\mathrm{BIPM}}\ k_{\mathrm{dist,tr}}} \tag{4}$$

where the factor $k_{\mathrm{dist,tr}}$ is as described in the preceding section. An additional uncertainty of 2 parts in 10^4 is included in Table 13 for this fitting procedure.

Figure 1. Calibration coefficients determined at the BEV and the BIPM



8. Comparison results

The calibration coefficients $N_{K,\mathrm{BEV}}$ and $N_{K,\mathrm{BIPM}}$ for the transfer chambers are presented in Table 9. The values $N_{K,\mathrm{BEV}}$ measured before and after the measurements at the BIPM give rise to the relative standard uncertainties $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ for the two chambers, which represent the uncertainty in N_K arising from transfer chamber stability.

Table 9. Calibration coefficients for the transfer chambers

Radiation quality	Mo/Mo-25	Mo/Mo-28	Mo/Mo-30	Mo/Mo-35
Exradin A11TW-139				
$N_{K,\mathrm{BEV}}$ (pre-BIPM) / Gy μC^{-1}	30.492	30.456	30.456	30.478
$N_{K,\mathrm{BEV}}$ (post-BIPM) / Gy μC^{-1}	30.500	30.478	30.472	30.482
$s_{\mathrm{tr},1}$ (relative) [a]	0.0002	0.0005	0.0003	0.0001
k_Q for $N_{K,\mathrm{BEV}}$ (Exradin)	1.0004	1.0002	1.0001	0.9997
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	30.768	30.730	30.725	30.685
$k_{\mathrm{dist,tr}}$	0.9962			
Radcal 10X5-8568				
$N_{K,\mathrm{BEV}}$ (pre-BIPM) / Gy μC^{-1}	4.6556	4.6546	4.6542	4.6552
$N_{K,\mathrm{BEV}}$ (post-BIPM) / Gy μC^{-1}	4.6635	4.6617	4.6611	4.6617
$s_{\mathrm{tr},2}$ (relative) [a]	0.0011	0.0010	0.0009	0.0009
k_Q for $N_{K,\mathrm{BEV}}$ (Radcal)	1.0001	1.0001	1.0000	0.9999
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	4.6821	4.6770	4.6754	4.6730
$k_{\mathrm{dist,tr}}$	0.9986			

[a] For each pre-post pair of $N_{K,\mathrm{BEV}}$ 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 $n = 2$, $s_{\mathrm{tr},i} = d / 0.8$.

For each chamber at each radiation quality, the mean of the BEV results before and after the BIPM measurements is used to evaluate the comparison results $N_{K,\mathrm{BEV}} / N_{K,\mathrm{BIPM}}$ given in Table 10. These ratios $N_{K,\mathrm{BEV}} / N_{K,\mathrm{BIPM}}$ are corrected by the appropriate factors $k_{\mathrm{dist,tr}}$ and k_Q given in Table 8 and Table 9, respectively. The final results $R_{K,\mathrm{BEV}}$ in Table 10 are evaluated as the mean for the two transfer chambers. For each quality, the corresponding uncertainty s_{tr} is the usual standard uncertainty of the mean, or taken as

$$s_{\mathrm{tr}} = \sqrt{\left(s_{\mathrm{tr},1}^2 + s_{\mathrm{tr},2}^2\right)/2} \qquad (5)$$

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 $s_{\mathrm{tr},1}$ and $s_{\mathrm{tr},2}$ from Table 9). The mean value of s_{tr} for the four qualities, $s_{tr,comp}$, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 13.

Table 10. Comparison results

Radiation quality	Mo/Mo-25	Mo/Mo-28	Mo/Mo-30	Mo/Mo-35
$N_{K,\mathrm{BEV}}$ /$N_{K,\mathrm{BIPM}}$ using Exradin[a]	0.9953	0.9954	0.9953	0.9968
$N_{K,\mathrm{BEV}}$ /$N_{K,\mathrm{BIPM}}$ using Radcal[a]	0.9967	0.9975	0.9977	0.9982
s_{tr}	0.0007	0.0011	0.0012	0.0007
$s_{tr,comp}$	0.0009			
$\boldsymbol{R_{K,\mathrm{BEV}}}$	**0.9960**	**0.9965**	**0.9965**	**0.9975**

[a] These values are corrected by the factors k_Q and $k_{\mathrm{dist,tr}}$

9. Uncertainties

The uncertainties associated with the primary standards are listed in Table 11 and those for the transfer chamber calibrations in Table 12. The combined standard uncertainty u_c for the comparison results $R_{K,\mathrm{BEV}}$ is presented in Table 13.

Table 11. Uncertainties associated with the standards at each laboratory

Standard	BIPM L-02		BEV PKM	
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	0.0004	0.0013
Positioning	0.0001	0.0001	-	0.0004
Volume	0.0003	0.0005	-	0.0010
Correction factors (excl. k_h)	0.0003	0.0010	0.0005	0.0029
Humidity k_h	-	0.0003	-	0.0005
Physical constants	-	0.0015	-	0.0015
$\dot{K}$	0.0005	0.0019	0.0007	0.0037

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. In the analysis of the results of BIPM comparisons in low-energy x-rays in terms of degrees of equivalence described by Burns (2003), correlation in the values for the correction factors k_e, k_{sc} and k_{fl} is taken into account if the NMI has used values derived from Monte Carlo calculations, as is the case for the BEV standard.

Table 12. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		BEV	
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	0.0007	0.0037[a]
I_{tr}	0.0002	0.0002	0.0004	0.0008
Positioning of transfer chamber	0.0001	-	-	0.0004
Short-term reproducibility	0.0005	-	- [b]	-
N_K	0.0007	0.0019	0.0008	0.0038

[a] The uncertainty for the W/Mo beams is 0.0032, used for the additional measurements in these beams, as explained in Section 10.

[b] The reproducibility of the BEV transfer chamber calibrations over the duration of the comparison is implicitly included in s_{tr} in Table 10.

Table 13. Uncertainties associated with the comparison results

Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
$N_{K,\mathrm{BEV}}$ / $N_{K,\mathrm{BIPM}}$	0.0011	0.0030[a]
Ion recombination $k_{\mathrm{s,tr}}$	-	0.0002
Radial non-uniformity $k_{\mathrm{rn,tr}}$	-	0.0005
Distance $k_{\mathrm{dist,tr}}$	-	0.0005
Field size		0.0005
Fitting procedure k_Q	-	0.0002
Transfer chambers $s_{\mathrm{tr,comp}}$	0.0009	-
$R_{K,\mathrm{BEV}}$	0.0014	0.0031
Combined standard uncertainty u_{c}	0.0034	

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

10. Additional measurements in the W/Mo mammography beams

At the same time as running the BIPM.RI(I)-K7 comparison in the Mo/Mo beams, additional measurements using the BEV transfer chambers were also made in the W/Mo mammography beams, in the x-ray range from 25 kV to 35 kV. The BIPM FAC L-01 primary standard is described in Boutillon *et al* (1969) and the BIPM W/Mo radiation qualities and the correction factors for the standard in Kessler (2006). The BEV standard for the W/Mo beams is the PKK free-air chamber, described in the BIPM.RI(I)-K2 comparison report (Burns *et al* 2014).

The calibration coefficients determined at the BEV and at the BIPM are shown in Table 14.

Table 14. Comparison results in the W/Mo radiation beams

Transfer chamber	Radiation quality	W/Mo-25	W/Mo-35
Exradin A11TW-139	$N_{K,\mathrm{BEV}}$ / Gy μC^{-1}	30.619	30.527
	$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	30.663	30.559
	$N_{K,\mathrm{BEV}}$ / $N_{K,\mathrm{BIPM}}$	0.9986	0.9989
Radcal 10X5-8568	$N_{K,\mathrm{BEV}}$ / Gy μC^{-1}	4.6597	4.6602
	$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	4.6633	4.6652
	$N_{K,\mathrm{BEV}}$ / $N_{K,\mathrm{BIPM}}$	0.9992	0.9989
Mean **$N_{K,\mathrm{BEV}}$ / $N_{K,\mathrm{BIPM}}$**		**0.9989**	**0.9989**
Combined standard uncertainty u_c		0.0030	

The uncertainties related to the ratio $N_{K,\mathrm{BEV}}$ / $N_{K,\mathrm{BIPM}}$ are described in Section 9 of the present report.

11. Discussion

The comparison results presented in Table 10 show agreement between the BEV and BIPM standards at the level of 3 to 4 parts in 10^3 with a combined standard uncertainty of 3.4 parts in 10^3.

This comparison was conducted using two transfer chambers rather than by direct comparison of the primary standards. While the use of transfer chambers introduces more uncertainty in the comparison results, the results obtained are more directly related to the disseminated quantity.

The comparison results in the W/Mo beams presented in Table 14 are consistent with the results for the BIPM.RI(I)-K2 comparison (Burns *et al* 2014); this agreement is expected as both laboratories use the same primary standard for the calibration of transfer chambers in the W/Al and W/Mo radiation beams.

12. 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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ 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 15 for both the Mo/Mo and W/Mo radiation qualities, noting that an NMI (such as the BEV) with results for both will have degrees of equivalence only for Mo/Mo.

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).

Table 15. 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**	11.6	**-4.6**	11.6	**-5.3**	11.6	**-4.7**	11.6
BEV	**-4.0**	6.8	**-3.5**	6.8	**-3.5**	6.8	**-2.5**	6.8

	W/Mo-23		**W/Mo-30**		**W/Mo-50**	
	D_i	U_i	D_i	U_i	D_i	U_i
	/(mGy/Gy)		**/(mGy/Gy)**		**/(mGy/Gy)**	
NRC	**0.9**	6.0	**1.5**	6.0	**1.0**	6.0

13. Conclusion

The key comparison BIPM.RI(I)-K7 for the determination of air kerma in mammography x-ray beams shows the standards of the BEV and the BIPM to be in agreement at the level of the standard uncertainty of 3.4 parts in 10^3.

Degrees of equivalence, including those for the BEV, are presented for entry in the BIPM key comparison database. The formal results under the CIPM MRA are those available in the key comparison database.

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Annex 1: Description of the BEV Standard PKM

The BEV primary standard free-air ionization chamber PKM (Parallelplatten Kammer Mittel = medium parallel-plate chamber) was designed for diagnostic radiation qualities (kV-range from 25 kV up to 150 kV). The characteristics (main dimensions, measuring volume and polarizing voltage) are given in Table 2 and Figure 2.

Figure 2. Free-air ionization chamber PKM, schematic drawing