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Comparison of the air kerma standards of the IAEA and the BIPM in mammography x-rays

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1. Introduction

The Dosimetry Laboratory of the International Atomic Energy Agency (IAEA), Seibersdorf, Austria, calibrates reference standards in mammography x-ray beams for IAEA/WHO SSDL Network members (more than 80 laboratories world wide) free of charge. As a signatory of the Mutual Recognition Arrangement (CIPM MRA), the IAEA laboratory maintains a Quality Management System (QMS) complying with ISO 17025 and in 2007 the laboratory published its dosimetry calibration and measurement capabilities (CMC) in Appendix C of the CIPM MRA key comparison database. To maintain the validity of CMCs, updated "supporting evidence" for the measuring capabilities is required periodically in addition to the traceability of the measured quantities. For this purpose, an indirect comparison has been made between the air-kerma standards of the IAEA and the Bureau International des Poids et Mesures (BIPM) in the mammography x-ray range from 25 kV to 35 kV. Two thin-window parallel-plate ionization chambers belonging to the IAEA were used as transfer instruments. The measurements at the BIPM took place in June 2012 using the reference conditions described in [1].

2. Determination of the air-kerma rate

2.1 Determination of the air-kerma rate at the BIPM

At the BIPM, the air-kerma rate is determined from measurements made with a free-air ionization chamber standard with measuring volume V using 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, taken from [1]. The BIPM free-air chamber standard for air kerma is described in [2].

2.2 Determination of the air-kerma rate at the IAEA

At the IAEA, a secondary standard ionization chamber Radcal 10X5-6M calibrated at the Physikalisch-Technische Bundesanstalt (PTB), Germany is used to determined the air-kerma rate using the relation

$$\dot{K} = I\ N_{K,\mathrm{PTB}} \prod_i k_i \qquad (2)$$

where I is the current measured with the IAEA standard, $N_{K,\mathrm{PTB}}$ is the calibration coefficient of the standard determined at the PTB and k_i is the product of the correction factors to be applied to the measured current (pressure and temperature correction). The most recent PTB calibration of the standard was made in October 2009.

3. The transfer instruments

3.1 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

$$N_K = \frac{\dot{K}}{I_\mathrm{tr}} \qquad (3)$$

where $\dot{K}$ is the air-kerma rate determined by the standard using (1) at the BIPM and (2) at the IAEA, 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 $N_{K,\mathrm{IAEA}}$ measured, respectively, at the BIPM and at the IAEA, differences in the radiation qualities must be taken into account. For the present comparison, this is discussed in Section 6.2.

3.2 Details of the transfer instrument

Two thin-window parallel-plate ionization chambers of type Radcal 10X5-6M and Magna M600, belonging to the IAEA, were used as the transfer instrument for the comparison. Their main characteristics are given in Table 1.

Table 1. Main characteristics of the transfer chamber

Chamber type	Magna N600	Radcal 10X5-6M
Serial number	M973161	8362
Window material	Kapton	Polyester
Window thickness / mg cm^{-2}	3.8	0.7
Collector diameter / mm	12.7	30.0
Cavity height / mm	8	8.5
Nominal volume / cm^3	1	6
Polarizing potential[a] / V	-300 V	-300 V

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

The reference plane for the Radcal chamber was taken to be defined by the red line around the chamber casing and for the Magna, by the entrance window; the reference point in these planes was taken to be on the axis defined by the entrance window.

4. Calibration at the BIPM

4.1 The BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory houses a constant-potential generator and a molybdenum-anode x-ray tube with an inherent filtration of 0.8 mm beryllium. A molybdenum filter of thickness 0.030 mm is added for all radiation qualities. A voltage divider is used to measure the generating potential, which is stabilized using an additional feedback system of the BIPM. Rather than use a transmission monitor, the anode current is measured and the ionization chamber current is normalized for any deviation from the reference anode current. The resulting variation in the BIPM FAC-L-02 free-air chamber current over the duration of a comparison is normally not more than 3×10^{-4} in relative terms. The radiation qualities used in the range from 25 kV to 35 kV are given in Table 2 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters.

Table 2. Characteristics of the BIPM mammography radiation qualities

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	30 µm Mo			
Al HVL / mm	0.277	0.310	0.329	0.365
Reference distance / mm	600			
$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	2.00			

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.

4.2 Transfer chamber positioning and calibration at the BIPM

The reference point for each transfer chambers was positioned in the reference plane at 600 mm from the centre of the x-ray tube 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 current was measured before and after each series of ionization current measurements and a correction made using the mean value. The relative leakage current for the transfer chambers was always less than 1×10^{-4}.

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

5. Calibration at the IAEA

5.1 The IAEA irradiation facility and reference radiation qualities

The IAEA diagnostics x-ray laboratory houses a constant-potential generator and a molybdenum-anode x-ray tube with an inherent filtration of 1.0 mm beryllium. A molybdenum filter of thickness 0.033 mm is added for all radiation qualities. A voltage divider is used to measure the generating potential. A transmission monitor is used to normalize the response of the ionization chamber to variations of the x-ray tube output. The resulting variation in the normalized ionization current over the duration of a calibration is normally less than 5×10^{-4} in relative terms. The radiation qualities used in the range from 25 kV to 35 kV are given in Table 3 in ascending order, from left to right, of the half-value-layer (HVL) measured using aluminium filters.

Table 3. Characteristics of the IAEA mammography radiation qualities

Radiation quality	Mo-25	Mo-28	Mo-30	Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	33 µm Mo			
Al HVL / mm	0.30	0.33	0.35	0.39
Reference distance / mm	1000			
$\dot{K}_{\mathrm{IAEA}}$ / mGy s^{-1}	0.80			

5.2 Transfer chamber positioning and calibration at the IAEA

The reference point for each transfer chambers was positioned in the reference plane at 1000 mm with a reproducibility of 0.05 mm. The 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 relative leakage current for the transfer chambers was always less than 1×10^{-4}.

6. Additional considerations for transfer chamber calibrations

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

No corrections $k_{\mathrm{s,tr}}$ 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 the same polarity at each institute and so no corrections are applied for polarity effects in the transfer chambers.

No correction $k_{\mathrm{rn,tr}}$ is applied at either laboratory for the radial non-uniformity of the radiation field. For a chamber with collector diameter around 30 mm, the non-uniformity correction for the BIPM reference field is around 1×10^{-3} in relative terms 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 IAEA at the reference distance of 1000 mm; at the BIPM, the chambers were calibrated at the reference distance of 600 mm (it is not possible to measure at 1000 mm in these beams). Measurements made at the BIPM during the comparison with the PTB in the W/Mo beams [3], at the reference distance of 500 mm and at 1000 mm, showed that the calibration coefficients for the Radcal chamber 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 at the BIPM for other Radcal chambers, not only in the W/Mo beams but also in the CCRI reference qualities. To estimate this effect for the Magna chamber, additional measurements were made during the present comparison at 500 mm and at 1000 mm in the BIPM W/Mo beams; the calibration coefficients measured at the 23 kV W/Mo quality (0.3315 mm Al HVL) differed by 1.1 parts in 10^2 (mean $N_{K,\ 1000\ \mathrm{mm}}$ / $N_{K,\ 500\ \mathrm{mm}}$= 0.9891(5)). Assuming that the same effect is present in the Mo/Mo beams, a scaled correction factor of 0.9983 was applied to the N_K measured at the BIPM at the distance of 600 mm in the Mo/Mo beams for the Radcal chamber; for the Magna chamber, the corresponding scaled factor of 0.9913 was applied. 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.

6.2 Radiation quality correction factors k_Q

As noted in Section 3.1, slight differences in radiation qualities might require a correction factor k_{Q}. From Tables 2 and 3 it is evident that the radiation qualities at the BIPM and at the IAEA are not well matched in terms of HVL, despite the use of the same calibrated generating potentials and the same nominal thickness for the molybdenum filter. In this event, the usual practice would be to derive comparison results for the BIPM HVLs by fitting the results obtained at the IAEA. However, from the form of the $N_{K,\mathrm{IAEA}}$ values, rising significantly at the lowest HVL (see Table 4), it is evident that extrapolation of a quadratic fit to the lowest BIPM HVL would result in significant uncertainty. For this reason, the converse procedure was adopted. To calculate the comparison result for the IAEA HVL values, a fit to the BIPM data was made and a set of k_{Q} values was derived, leading to a set of comparison results

$$R_{K,IAEA} = \frac{N_{K,IAEA}}{k_{\mathrm{Q}} N_{K,\mathrm{BIPM}}} \tag{4}$$

The uncertainty arising from the fitting procedure is evaluated as 7 parts in 10^4 and is included in Table 8.

7. Comparison results

The calibration coefficients $N_{K,\mathrm{IAEA}}$ and $N_{K,\mathrm{BIPM}}$ for the two transfer chambers are presented in Table 4, the latter corrected for distance as noted in Section 6.1. The values $N_{K,\mathrm{IAEA}}$ measured before and after the measurements at the BIPM give rise to the relative standard deviation σ_{dist} for each radiation quality, whose r.m.s. value for the four qualities, $\sigma_{stab,tr}$, is taken as a global representation of the stability of each transfer chamber. Also included in the table are the results for the radiation quality correction factors k_Q evaluated as described in Section 6.2.

Table 4. Calibration coefficients for the transfer chambers

Radiation quality	Mo25	Mo28	Mo30	Mo35
Radcal 10X5-6M				
$N_{K,\mathrm{IAEA}}$ (pre-BIPM)	4.655	4.642	4.640	4.640
$N_{K,\mathrm{IAEA}}$ (post-BIPM)	4.658	4.646	4.639	4.644
σ_{dist} (relative)	0.0005	0.0006	0.0002	0.0006
$\sigma_{stab,tr}$	0.0005			
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	4.648	4.641	4.641	4.641
k_Q	0.9991	1.0000	0.9998	1.0000
Magna				
$N_{K,\mathrm{IAEA}}$ (pre-BIPM)	22.138	22.042	22.007	21.987
$N_{K,\mathrm{IAEA}}$ (post-BIPM)	22.157	22.059	22.000	21.993
σ_{dist} (relative)	0.0006	0.0005	0.0002	0.0002
$\sigma_{stab,tr}$	0.0004			
$N_{K,\mathrm{BIPM}}$ / Gy μC^{-1}	22.132	22.064	22.037	22.008
k_Q	0.9978	0.9986	0.9990	0.9999

For each chamber at each quality, the mean of the IAEA results before and after the BIPM measurements is used for the comparison result $N_{K,\mathrm{IAEA}}$ / $N_{K,\mathrm{BIPM}}$ given in Table 5 for each transfer chamber. The final results $R_{K,\mathrm{IAEA}}$ are evaluated as the arithmetic mean for the two transfer chambers. The results and combined uncertainties are discussed in Section 8.

Table 5. Comparison results

Radiation quality	Mo25	Mo28	Mo30	Mo35
$R_{K,\mathrm{IAEA}}$ for Radcal chamber	1.0027	1.0006	0.9999	1.0002
$R_{K,\mathrm{IAEA}}$ for Magna chamber	1.0029	1.0008	0.9995	0.9993
Combined $R_{K,\mathrm{IAEA}}$	**1.0028**	**1.0007**	**0.9997**	**0.9998**

8. Uncertainties

The uncertainties associated with the air-kerma determination are listed in Table 6 and those for the transfer chamber calibrations in Table 7.

Table 6. Uncertainties associated with the determination of the air-kerma rate

Institute	BIPM		IAEA	
Relative standard uncertainty	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Ionization current [a]	0.0002	0.0002	0.0002	0.0006
Positioning	0.0001	0.0001	-	0.0003
IAEA monitor normalization	-	-	0.0002	-
Volume BIPM FAC-L-02	0.0003	0.0005	-	-
Correction factors for FAC-L-02	0.0003	0.0010	-	-
Humidity k_h	-	0.0003	-	-
Physical constants	-	0.0015	-	-
Calibration coefficient $N_{K,\mathrm{PTB}}$	-	-	-	0.0048
Long-term stability of $N_{K,\mathrm{PTB}}$	-	-	-	0.0020
Spectral difference IAEA / PTB	-	-	-	0.0010
$\dot{K}$	0.0005	0.0019	0.0003	0.0053

[a] Includes the uncertainty of temperature and pressure corrections.

Table 7. Uncertainties associated with the calibration of the transfer chambers

Institute	BIPM		IAEA	
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	0.0003	0.0053
I_tr [a]	0.0002	0.0002	0.0002	0.0006
Positioning of transfer chamber	0.0001	-	-	0.0003
IAEA monitor normalization	-	-	0.0002	-
Short-term reproducibility	0.0004	-	0.0005	-
N_K	0.0007	0.0019	0.0006	0.0054

[a] Includes the uncertainty of temperature and pressure corrections.

The combined standard uncertainty u_c for the comparison results $R_{K,\mathrm{IAEA}}$ is presented in Table 8. This combined standard uncertainty takes into account correlation in the type B uncertainties between the PTB and the BIPM associated with the physical constants, humidity correction and the correction factors derived from Monte Carlo calculations [4] that enter in the determination of air kerma using the primary standards. A component of 7 parts in 10^4 arising from the fitting procedure to derive k_Q values and a component of 4 parts in 10^4 to account for the stability of the transfer chambers are included in the analysis of the uncertainties associated with the comparison result.

Table 8. Uncertainties associated with the comparison results

Relative standard uncertainty	u_{iA}	u_{iB}
$N_{K,\mathrm{IAEA}}$ / $N_{K,\mathrm{BIPM}}$	0.0009	0.0052[a]
Radial non-uniformity $k_{\mathrm{rn,tr}}$	-	0.0005
Ion recombination $k_{\mathrm{s,tr}}$	-	0.0005
Fitting procedure for k_Q	-	0.0007
Distance correction	-	0.0010
Stability of transfer chambers	0.0004	-
$R_{K,\mathrm{IAEA}}$	0.0010	0.0054
	u_c = 0.0055	

[a] Takes account of correlation in type B uncertainties between the PTB and BIPM primary standards.

9. Discussion

The comparison results presented in Table 5 show general agreement at the level of 7 parts in 10^4 for the Mo/Mo beams from 28 kV to 35 kV and up to 2.8 parts in 10^3 for the 25 kV Mo/Mo quality, which is within the combined relative standard uncertainty for the comparison of 5.5 parts in 10^3. This close agreement is consistent with the results of the comparison of the BIPM and PTB standards made in the context of the key comparison BIPM.RI(I)-K7, the results of which are available online in the BIPM key comparison database [5].

10. Conclusion

The IAEA and BIPM standards for mammography x-rays are shown to be in agreement within the standard uncertainty of the comparison of 5.5 parts in 10^3. This agreement can be used to support the calibration and measurements capabilities of the IAEA listed in Appendix C of the key comparison database.

References

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[4] BURNS D.T., 2003, Degrees of equivalence for the key comparison BIPM.RI(I)-K2 between national primary standards for low-energy x-rays, *Metrologia* **40**, *Tech. Suppl.*, 06031

[5] The BIPM key comparison database is available online at: http://kcdb.bipm.org/appendixB