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Comparison of air kerma measurements between the PTB and the IAEA for x-radiation qualities used in general diagnostic radiology and mammography

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Abstract

A comparison of the air kerma standards for x-radiation qualities used in general diagnostic radiology and mammography, identified as EURAMET.RI(I)-S10 (EURAMET project #1221), was performed between the PTB and the IAEA. Two spherical and two parallel-plate reference-class ionization chambers of the IAEA and 12 beam qualities standardized in the IEC standard 61267:2005 plus additional 7 standard beam qualities established at both laboratories were selected for the comparison. The calibration coefficients were determined for the transfer chambers at the PTB in September 2012 and before and after this at the IAEA Dosimetry Laboratory. The results show the calibration coefficients of both laboratories to be in good agreement within the standard uncertainty of the comparison of about 0.47 %.

1. Introduction

The IAEA Dosimetry Laboratory, DOL, in Seibersdorf Austria, performs calibration of reference diagnostic dosemeters of IAEA/WHO SSDL[1] Network members (more than 80 laboratories worldwide). As a signatory of the CIPM MRA, the DOL maintains a quality management system (QMS) complying with ISO 17025. The DOL published its dosimetry CMC claims in 2007, in the Appendix C database of the CIPM MRA. To maintain these CMC claims, periodically updated “supporting evidence” for the measuring capabilities is required in addition to the traceability of the measured quantities. The first similar comparison was the EUROMET.RI(I)-S4 comparison with 13 participants started in 2000. Its result was published in 2004 [1]. In the meantime the DOL changed the beam qualities and measurement standards. This comparison of air kerma standards between the IAEA and the PTB is intended to support the measurement and calibration service offered by the IAEA for radiation qualities used in general diagnostic radiology and mammography.

The relevant IAEA secondary standard ionization chambers are traceable to the PTB in terms of air kerma, being calibrated every three years. The comparison partner PTB maintains primary standards of air kerma for radiation qualities used in diagnostic radiology and mammography with degrees of equivalence (DoE) in the key comparison database (KCDB) of the CIPM MRA based on the PTB results in the key comparisons BIPM.RI(I)-K2 (low-energy x-rays), K3 (medium-energy x-rays) and K7 (mammography x-rays) [2-4].

The current bilateral comparison is identified as EURAMET project #1221 and registered in the KCDB as EURAMET.RI(I)-S10 supplementary comparison. The Technical Protocol [5] was approved by the CCRI(I).

2. Comparison procedure

2.1 Transfer chambers

For the comparisons four IAEA reference-class transfer chambers were selected. The technical details of the chambers are listed in Table 1. The reference plane of the spherical chambers is the centre of the sphere. For the parallel-plate Radcal and Magna chambers the reference planes are the grooves on their side wall at 4 mm behind the plane of their entrance windows.

Table 1 Technical data for the transfer chambers

Type	Reference point	Nominal volume (cm^3)	*Polarizing voltage (V)	Wall thickness	Outer diameter (mm)
Exradin A3, spherical chamber #XR071832	chamber centre	3.6	+300	0.25 mm	19.5
Exradin A4, spherical chamber #P=XP072344	chamber centre	30	+500	0.50 mm	39.2
Radcal RC6M parallel plate chamber #10183	marked on the chamber	6	+300	0.7mg/cm^2	43 30 (effective)
Magna A 650 parallel plate chamber #D121351	marked on the chamber	3	+300	3.9 mg/cm^2	53 42 (effective)

* Applied to the central electrode

2.2 Radiation qualities

The radiation qualities used for the comparison were a subset of the RQR, RQA, RQT, RQR-M, RQA-M standard beam qualities of the international standard IEC 61267:2005 [6] and some additional mammographic radiation qualities not included in the standard, as listed in Table 2.

Table 2. Technical data of the radiation qualities

	Quality code (IEC 61267)	Tube voltage	PTB HVL	IAEA HVL	HVL (IEC 61267)
		(kV)	(mm Al)	(mm Al)	(mm Al)
1	RQR-2	40	1.42	1.46	1.42
2	RQR-5	70	2.60	2.61	2.58
3	RQR-10	150	6.55	6.76	6.57
4	RQA-2	40	2.18	2.27	2.2
5	RQA-5	70	6.76	6.97	6.8
6	RQA-10	150	13.23	13.52	13.3
7	RQT-9	120	8.48	8.56	8.4
8	RQR-M1	25	0.283	0.300	0.28
9	RQR-M2	28	0.314	0.332	0.31
10	RQR-M3	30	0.331	0.352	0.33
11	RQR-M4	35	0.366	0.391	0.36
12	*MMV-40	40	0.392	0.421	---
13	*MMV-50	50	0.428	0.461	---
14	RQA-M2	28	0.61	0.629	0.60
15	*MMH-40	40	0.871	0.822	---
16	*MMH-50	50	0.908	0.957	---
17	*MRV-28	28	0.375	0.400	---
18	*MRV-30	30	0.393	0.419	---
19	*MRV-35	35	0.425	0.455	---

*PTB code

2.3 Reference conditions

The calibration coefficients of the transfer chambers were given in terms of air kerma per charge in units of Gy/C and referred to standard conditions of air temperature, pressure and relative humidity of T = 293.15 K, P = 101.325 kPa and h = 50 %. The ambient conditions (temperature, pressure and humidity) during the calibrations were monitored continuously. The observed variations were in the ranges (295-297) K, (98.0-101.0) kPa and (45-60) %, respectively, in both laboratories. The calibration distance (distance from x-ray tube focus to reference plane) was 1000 mm at both laboratories.

3. Calibration at the PTB

3.1 X-ray facilities

The PTB mammographic beam qualities used in this comparison are produced with a unipolar x-ray tube of type Panalytical PW2185/Mo with a Mo anode angle of 26° combined with a constant potential generator. The inherent filtration is 1 mm beryllium, with the additional filtration being either 0.03 mm molybdenum or 0.025 mm rhodium, depending on the type of beam quality. Mammographic radiation qualities are established for tube voltages in the range from 20 kV to 50 kV. The diameter of the circular beam at 1 m distance from the focus was 10 cm. The air kerma rates were about 45 mGy/min and 5 mGy/min in the non-attenuated and attenuated beams, respectively.

The IEC 61267 RQR, RQA and RQT radiation qualities used in this comparison are produced with a unipolar x-ray tube of type Comet MXR 165 with a W anode angle of 30° combined with a constant potential generator. The inherent filtration is 4 mm beryllium. The diameter of the circular beam at 1 m distance from the focus was 8 cm. The air kerma rates were about 3 mGy/min, 20 mGy/min and 70 mGy/min in the RQA, RQR and RQT beams, respectively.

For both x-ray facilities the high voltage was measured invasively with a voltage divider manufactured and calibrated at PTB. Photon fluence spectra of all radiation qualities were measured with a high-purity germanium detector. Characteristic radiation quality data such as mean energies and half-value layers are evaluated from these spectra. The first Al-half-value layers of the qualities used in this comparison are listed in Table 2.

A transmission-type monitor chamber manufactured at PTB was used at both facilities to normalize the x-ray output. 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 because it varies between 30 % and 60 % and 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. Each calibration is based on 5 repeated measurements of the ionization charge measured in 60 s with the standard and the chamber to be calibrated. The leakage is measured before and after the 5 repeated measurements and the mean value is subtracted from the mean of the measured charge.

Beam profiles of the mammography radiation qualities in 1 m distance from the focus and nominal field size of 10 cm in diameter were measured with a flat panel image sensor type Hamamatsu C7942. This sensor has 2400 x 2400 pixels of size 50 mm and thus covers an area of 12 cm x 12 cm. As an example, the profile of the IEC 61267 RQR-M2 radiation quality is shown in Figure 1.

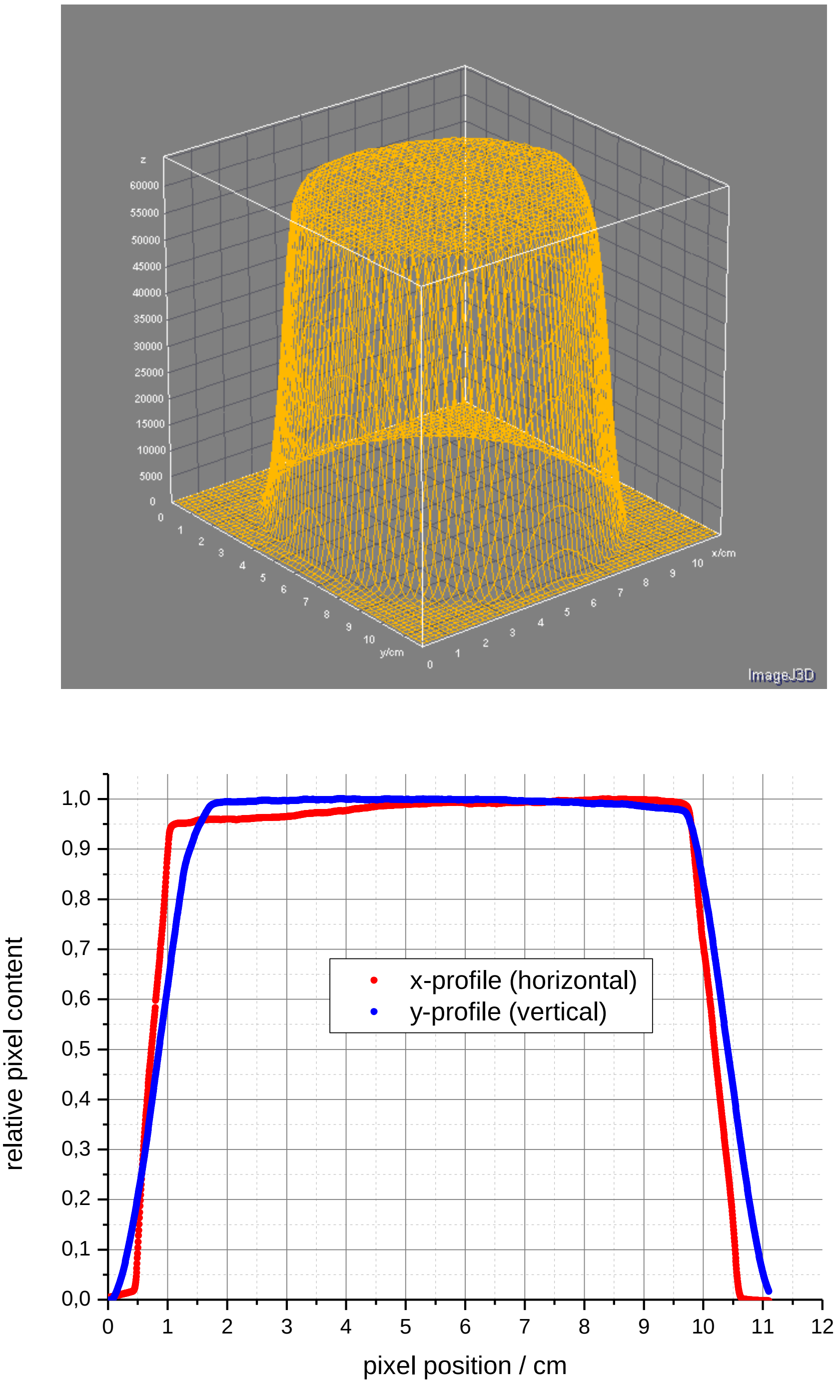


Figure 1. PTB beam profile of the IEC 61267 RQR-M2 radiation quality. 3D profile plot produced with the software package „ImageJ” (upper) and x- and y- profile plots extracted from the pixel image (lower). The anode - cathode axis is oriented horizontally so that the hHeel effect is visible in the horizontal profile.

The horizontal intensity profile reflects the expected distribution due to the Heel-effect which causes a reduction in the x-ray beam intensity toward the anode side of the x-ray field. As the aperture of the PK100 free air chamber was 2 cm in diameter (see 3.2) and the mammographic transfer chambers sensitive volume cross sections were not significantly larger, no beam non-uniformity correction was applied. However, a type B uncertainty of 0.1 % was included in the uncertainty budget (see Table 8).

3.2 Determination of the air-kerma rate

The PTB maintains two primary standard free-air chambers. One is of the parallel-plate type and named “PK100” which can be used for radiation qualities produced with tube voltages between 10 kV and 100 kV. The other is of cylindrical type and named “Fasskammer (FK)” which can be used for radiation qualities produced with tube voltages between 30 kV and 300 kV.

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 k_{i} are 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 3. 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.

Table 3. 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.

3.3 Free-air chamber type “PK100”

The free-air chamber type “PK100” is in use as a primary air kerma standard for x-radiations produced with tube voltages between 10 kV and 100 kV. The measuring volume V is defined by the diameter of the chamber aperture and the length of the collecting region. Details of the PTB standard “PK100” are given in [7]. The main dimensions, the measuring volume and the polarizing voltage for this standard are shown in Table 4.

Table 4. Main characteristics of the free-air standard PK100

Aperture diameter / mm	20.008
Air path length / mm	97.2
Collecting length / mm	20.021
Electrode separation / mm	234
Collector width / mm	240
Measuring volume / mm^3	6294.7
Polarizing voltage / V	6000

Correction factors for the PK100 were calculated by means of Monte Carlo methods and mean values for radiation qualities were determined based on the measured photon fluence spectra. Values and uncertainties of the correction factors of the PK100 for the radiation qualities used in this comparison are given in Tables 5 and 6.

Table 5. Correction factors for the PTB standard for non-attenuated Mo/Mo beams

Radiation quality PTB code	MMV 25	MMV 28	MMV 30	MMV 35	MMV 40	MMV 50	u_{iA}	u_{iB}
IEC 61267 code	RQR-M1	RQR-M2	RQR-M3	RQR-M4	-	-		
Air attenuation k_a[a]	1.0255	1.0234	1.0223	1.0205	1.0192	1.0176	0.05	0.05
Scattered radiation k_{sc}[b]	0.9905	0.9907	0.9908	0.9910	0.9911	0.9913	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_s	1.0052	1.0053	1.0052	1.0054	1.0056	1.0059	0.05	0.05
Guard strip attenuation k_{ap}	1.0052	1.0048	1.0046	1.0042	1.0040	1.0037	0.05	0.05
Aperture edge trans. k_l	0.9997	0.9996	0.9996	0.9996	0.9996	0.9996	-	0.05
Field distortion	0.9920	0.9920	0.9920	0.9920	0.9920	0.9920	-	0.15
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.05	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Humidity k_h	0.9980	0.9980	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 6. Correction factors for the PTB standard for attenuated Mo/Mo beams and Mo/Rh beams

Radiation quality PTB code	MMH 28	MMH40	MMH 50	MRV 28	MRV 30	MRV 35	u_{iA}	u_{iB}
IEC 61267 code	RQR-M2	-	-	-	-	-		
Air attenuation k_a[a]	1.0114	1.0096	1.0088	1.0197	1.0189	1.0176	0.05	0.05
Scattered radiation k_{sc}[b]	0.9919	0.9924	0.9927	0.9910	0.9911	0.9913	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_s	1.0010	1.0011	1.0010	1.0056	1.0045	1.0049	0.05	0.05
Guard strip attenuation k_{ap}	1.0024	1.0021	1.0020	1.0041	1.0039	1.0036	0.05	0.05
Aperture edge trans. k_l	0.9995	0.9993	0.9992	0.9996	0.9996	0.9996	-	0.05
Field distortion	0.9920	0.9920	0.9920	0.9920	0.9920	0.9920	-	0.15
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.05	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Humidity k_h	0.9980	0.9980	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.

The relative standard uncertainties associated with the air-kerma rate determination using the PK100 are summarized in Table 7 and result in a combined standard uncertainty of 0.30 %. They were evaluated according to the GUM [8].

Table 7. Relative standard uncertainties (in %) associated with the standard PK100

Source of uncertainty	Type A	Type B
Ionization current	0.10	0.06
Volume		0.06
Positioning		0.01
Correction factors	0.09	0.21
Physical constants		0.15
$\dot{K}_{\mathrm{PK100}}$	0.13	0.27
	0.30	

The uncertainty components for the calibration of a secondary-standard ionization chamber in terms of air kerma with the PK100 are listed in Table 8. If the uncertainties in the physical constants and correction factors are omitted, the uncertainty budget shown in Table 9 is obtained.

Table 8. Relative standard uncertainties (in %) associated with the calibration of the transfer ionization chambers

Source of uncertainty	Type A	Type B
Air-kerma rate $\dot{K}_{\mathrm{LAB}}$	0.13	0.27
Ionization current	0.10	0.06
Positioning	0.05	
Monitor normalization		0.05
Air density correction	0.05	
Beam non-uniformity		0.10
$N_{K,\mathrm{PTB}}$	0.18	0.30
	0.35	

Table 9. Relative standard uncertainties (in %) associated with the calibration of the transfer ionization chambers at PTB omitting the uncertainties due to the physical constants and correction factors of the standard PK100

Source of uncertainty	Type A	Type B
Air-kerma rate $\dot{K}_{\mathrm{PK100}}$	0.10	0.06
Ionization current	0.10	0.06
Positioning	0.05	
Monitor normalization		0.05
Air density correction	0.05	
Beam non-uniformity		0.10
$N_{K,\mathrm{PTB}}$	0.16	0.14
	0.21	

3.4 Free-air chamber type “Faßkammer”

The PTB cylindrical free-air chamber FK is in use as a primary air-kerma standard for x-radiations produced with tube voltages between 30 kV and 300 kV. A set of five central collecting electrodes, each 7 mm in diameter and with lengths between 5 cm and 25 cm, can be used in combination with a set of five diaphragms with diameters between 0.8 cm and 3.0 cm, yielding a measuring volume between 2.5 cm^3 and 180 cm^3. The main dimensions and technical data for the chamber in the configuration used for the comparison are given in Table 10. A particularity of the cylindrical geometry is that the x-ray beam enters the chamber 45 mm off-axis, parallel to the central electrode. This necessitates the use of a correction factor, k_{sh}, not relevant for parallel-plate chambers, that corrects for the shadowing of the collector due to absorption of some secondary electrons resulting in ionization loss. This and the other correction factors applied to the FK standard for the radiation qualities used in this comparison are given in Table 11. More details of the FK standard are given in [7].

Table 10. Main characteristics of the PTB medium-energy cylindrical free-air chamber

Aperture diaphragm diameter / cm	2.0009
Aperture diaphragm thickness / cm	1
Collecting (central) electrode length / cm	20.001
Outer electrode diameter / cm	20
Measuring volume / cm^3	62.892
Polarising voltage / V	+3000
Air attenuation path length / cm	48.1
Leakage current / fA	<100

Table 11. Correction factors for the PTB Faßkammer standard [a]

Generating potential / kV	RQR2	RQR5	RQR10	RQA2	RQA5	RQA10	RQT9	$u_{i\text{A}}$	$u_{i\text{B}}$
Air attenuation k_{a} [b]	1.0314	1.0218	1.0136	1.0221	1.0124	1.0094	1.0115	-	0.10
Ionization gain k_{sc} [c]	0.9893	0.9906	0.9929	0.9901	0.9926	0.9949	0.9935	-	0.05
Electron loss k_{e}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_{s}	1.0028	1.0033	1.0026	1.0012	1.0012	1.0012	1.0084	0.05	-
Field distortion k_{d}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.10
Polarity effect k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.05	-
Shadow effect, k_{sh}	1.0000	1.0003	1.0015	1.0000	1.0014	1.0025	1.0021	-	0.05
Aperture edge trans. k_{l}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Wall transmission k_{p}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.05	-
Humidity k_{h}	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.10
$1 - g_{\text{air}}$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	-

[a] Component uncertainties below 0.0002 have been neglected.

[b] Nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air density measured at the time.

[c] This corrects for the re-absorption of scattered radiation and of fluorescence photons.

The relative standard uncertainties associated with the air kerma rate determination with the FK are summarized in Table 12 and result in a combined standard uncertainty of 0.30 %. They were evaluated according to the GUM [8].

Table 12. Relative standard uncertainties (in %) associated with the standard "Faßkammer"

Source of uncertainty	PTB	
	Type A	Type B
Ionization current	0.10	0.06
Volume		0.06
Positioning		0.01
Correction factors	0.09	0.20
Physical constants		0.15
$\dot{K}_{\mathrm{FK}}$	0.13	0.26
	0.30	

The uncertainty components for the calibration of a secondary-standard ionization chamber in terms of air kerma with the FK are listed in Table 13. If the uncertainties in the physical constants and correction factors are omitted, the uncertainty budget shown in Table 14 is obtained.

Table 13. Relative standard uncertainties (in %) associated with the calibration of the transfer ionization chambers

Source of uncertainty	Type A	Type B
Air-kerma rate $\dot{K}_{\mathrm{FK}}$	0.13	0.26
Ionization current	0.10	0.06
Positioning	0.05	
Monitor normalization		0.05
Air density correction	0.05	
Beam non-uniformity		0.10
$N_{K,\mathrm{PTB}}$	0.18	0.29
	0.34	

Table 14. Relative standard uncertainties (in %) associated with the calibration of the transfer ionization chambers at PTB omitting the uncertainties due to the physical constants and correction factors of the standard FK

Source of uncertainty	Type A	Type B
Air-kerma rate $\dot{K}_{\mathrm{FK}}$	0.10	0.06
Ionization current	0.10	0.06
Positioning	0.05	
Monitor normalization		0.05
Air density correction	0.05	
Beam non-uniformity		0.10
$N_{K,\mathrm{PTB}}$	0.16	0.14
	0.21	

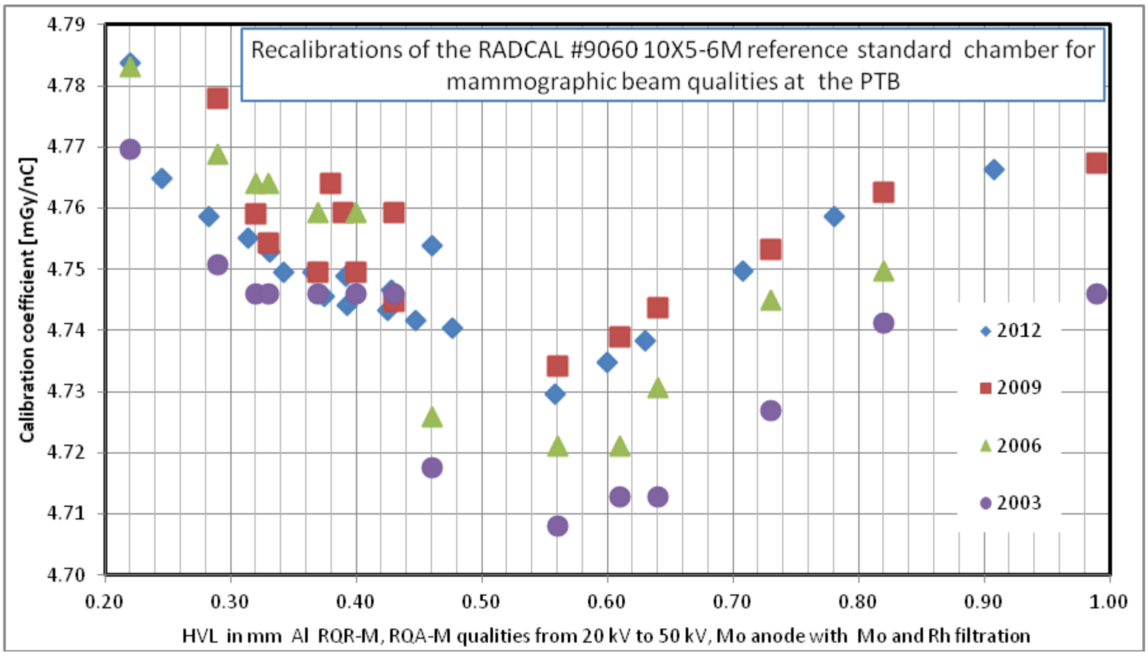
4. Calibration at the IAEA

4.1 X-ray facilities

X-ray tubes type RTW MCD 100H-5Mo and Isovolt MXR160/0.4-3.0 are used to generate the mammographic and general diagnostic x-ray beam qualities, respectively. The output of the high-voltage generator, type ISOVOLT 160 Titan E, is monitored by a high-voltage divider, type FUG HVT 160 000, calibrated at the PTB. Ionization currents are measured by Keithley K6517A electrometers and normalized to the monitor chamber, type PTW FN 34014. The internal capacitance and all ranges of the electrometers are calibrated by a Keithley calibrator, type 263, traceable to voltage and capacitor standards of the BEV. The calibrations of the four transfer chambers were performed against the IAEA reference secondary-standard chambers, type Exradin A3, A4 and Radcal MDL 4001 10X5-6M, calibrated at the PTB in 2011, 2012 and 2012, respectively.

The long-term stability of the Radcal reference chamber can be seen in Figure 2. The other two reference chamber stabilities are also better than 0.3 %. No further corrections (saturation, beam non-uniformity, spectral differences etc.) were applied for the determination of the reference air-kerma rates. The measured air-kerma rate was in the range (50-75) mGy/min for all beam qualities except for attenuated beam qualities, where the air-kerma rate was 3 mGy/min.

Figure 2. Stability of the IAEA reference chamber for mammography beam qualities.



The uncertainties associated with the calibrations at the IAEA are listed in Table 15. The various sources of uncertainty are grouped according to [8] as type A (statistical) and Type B (non-statistical, based on scientific judgement) The uncertainty of the calibration coefficient, N_{Kair}, is obtained essentially by combining the uncertainty of the reference air kerma rate and of the ionization current corrected for all influence quantities.

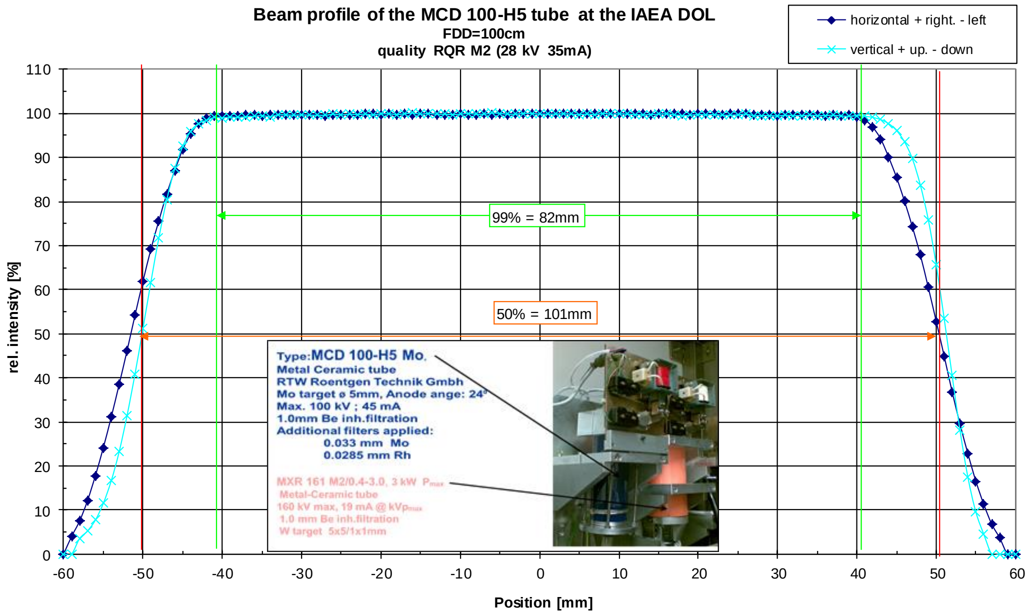
However, for this comparison the uncertainty components of the IAEA air kerma standard due to the physical constants and correction factors of the PTB primary standard should be removed because the IAEA secondary-standard chambers are traceable to the PTB primary standards.

Examples of the beam profile at the calibration distances measured at the IAEA (x-ray tube RTW MCD 100H-5Mo, horizontal and vertical orientations) are shown in Figure 3. The satisfactory beam profiles of setups at both laboratories at the calibration distance ensured relatively uniform irradiation of all the transfer chambers, and instead of the application of a calculated radial non-uniformity correction factor, an additional uncertainty component was introduced in both laboratories.

Table 15. Uncertainty budget for the transfer chamber calibration at the IAEA

Uncertainty budget of the diagnostic calibrations at the DOL	Type A *Uncertainty (%)*	Type B	Type A *Uncertainty (%)*	Type B
Step 1: Reference standard	**Mammographic qualities**		**Diagnostic qualities**	
Calibration from BIPM/PSDL		0.50		0.40
Long term stability of the reference standard		0.30		0.20
Spertral diffence of the beam at DOL and PSDL		0.1		0.06
Chamber positioning		0.03		0.03
Current measurements including range and time base corrections	0.02	0.05	0.02	0.05
Uncertainty due to temperature measurements		0.03		0.03
Uncertainty due to pressure measurements		0.01		0.01
Monitor chamber contribution	0.02		0.02	
Relative combined standard uncertainty of K_{air}	**0.03**	**0.60**	**0.03**	**0.46**
Step 2: Instrument to be calibrated				
Current measurements including user electrometer	0.10	0.05	0.10	0.05
Uncertainty due to temperature measurements	0.01	0.03	0.01	0.03
Uncertainty due to pressure measurements	0.01	0.01	0.01	0.01
Monitor chamber contribution	0.02		0.02	
Chamber positioning		0.03		0.03
Difference in radial non-uniformity of the beam		0.20		0.20
Relative combined standard uncertainty in Step 2	**0.10**	**0.21**	**0.10**	**0.21**
Relative combined standard uncertainty (Steps 1 + 2)	**0.11**	**0.63**	**0.11**	**0.50**
Overall relative uncertainty (u_c)	**0.64**		**0.51**	
u_c reduced (0.21%) uncertainty for the reference standards (see Table 9 and Table 14) and 0.1% for the difference in the non-uniformity of the beam for the reference and transfer chambers	**0.42**		**0.34**	

Figure 3. Mammographic x-ray beam profile at the IAEA



5. Measurement results

The calibration coefficients were determined using the substitution method at both laboratories, from a minimum of 3 repeated measurements using different setups at the IAEA lab and with some beam qualities also repeated at the PTB. The reproducibility of the calibration at the IAEA before and after the calibration at the PTB was estimated using the standard deviation of the repeated measurements. It was typically less than 0.1 %. The major part of this statistical uncertainty comes from the monitor chamber in the case of the attenuated mammography qualities, where the measured currents were the lowest. The calibration coefficients of the transfer chamber were also calculated without normalizing the measured currents to the monitor chamber and the results were the same within 0.05 % for all beam qualities. The leakage currents of the transfer chambers never exceeded 0.2 % of the measured currents at both laboratories, and were subtracted in each case.

The slight differences in the HVL values of the same radiation qualities at the two laboratories can be addressed through the application of suitable correction factors, k_{Q}.[9] Although these small k_{Q} factor have been calculated for the PTB values by interpolation of the energy response curves of the four transfer chambers (and can be seen in Tables 16-19 when they are larger than 0.02 %), they were applied only that six cases (bold numbers in the tables) when the abs(1- k_{Q}) was higher than the estimated uncertainty of the k_{Q} values. The calibration coefficient of the transfer chambers determined at the PTB and IAEA and their ratios are given in Tables 16-19.

Table 16. Calibration coefficients of the Extradin A3 #XR071832 chambers

Beam quality	k_Q	PTB N_{Kair} (mGy/nC)	IAEA N_{Kair} (mGy/nC)	PTB/IAEA
RQR-2	0.9998	8.1331	8.1011	1.0040
RQR-5	`--	8.0320	8.0276	1.0005
RQR-10	`--	8.0590	8.0489	1.0013
RQT-9	`--	8.0930	8.0897	1.0004

Table 17. Calibration coefficients of the Extradin A4 #XP072344 chamber

Beam quality	k_Q	PTB N_{Kair} (mGy/nC)	IAEA N_{Kair} (mGy/nC)	PTB/IAEA
RQA-2	**0.9984**	0.9887	0.9918	0.9970
RQA-5	`--	0.9797	0.9797	1.0000
RQA-10	`--	0.9834	0.9809	1.0025

Table 18. Calibration coefficients of the Radcal RC6M #10183 chamber

Beam quality	k_Q	PTB N_{Kair} (mGy/nC)	IAEA N_{Kair} (mGy/nC)	PTB/IAEA
RQR-M1	0.9995	4.7790	4.7733	1.0012
RQR-M2	0.9995	4.7730	4.7711	1.0004
RQR-M3	0.9996	4.7720	4.7709	1.0002
RQR-M4	0.9997	4.7710	4.7698	1.0003
MMV-40	0.9996	4.7720	4.7733	0.9997
MMV-50	0.9999	4.7720	4.7742	0.9995
RQA-M2	1.0010	4.7640	4.7623	1.0003
MMH-40	1.0005	4.8070	4.7961	1.0023
MMH-50	1.0006	4.8210	4.8144	1.0014
MRV-28	`--	4.7700	4.7701	1.0000
MRV-30	`--	4.7680	4.7675	1.0001
MRV-35	`--	4.7690	4.7691	1.0000

Table 19. Calibration coefficients of the Magna A650 #D121351 chamber

Beam quality	k_Q	PTB N_{Kair} (mGy/nC)	IAEA N_{Kair} (mGy/nC)	PTB/IAEA
RQR-2	0.9996	7.6660	7.6634	1.0003
RQR-5	`--	7.6787	7.6791	0.9999
RQR-10	0.9992	7.5780	7.5748	1.0004
RQT-9	`--	7.5620	7.5773	0.9980
RQR-M1	**0.9978**	7.9369	7.9348	1.0003
RQR-M2	**0.9985**	7.9114	7.9230	0.9985
RQR-M3	**0.9983**	7.8978	7.9089	0.9986
RQR-M4	**0.9983**	7.8768	7.8892	0.9984
MMV-40	**0.9983**	7.8654	7.8749	0.9988
MMV-50	0.9993	7.8620	7.8656	0.9995
RQA-M2	0.9991	7.7750	7.7507	1.0031
MMH-40	`--	7.7450	7.7142	1.0040
MMH-50	`--	7.7450	7.7148	1.0039
MRV-28	`--	7.8880	7.8847	1.0004
MRV-30	`--	7.8790	7.8787	1.0000
MRV-35	`--	7.8620	7.8644	0.9997

6. Results and discussion

6.1 Uncertainty of the comparison

The reference ionization chambers of the IAEA are traceable to the primary standards of the PTB. Therefore, the uncertainties associated with the physical constants and the correction factors of the free air chambers do not contribute to the uncertainty in the comparison of the calibration coefficients determined at the PTB and the IAEA. If these uncertainties are omitted, the relative uncertainties of the calibration coefficients determined at the PTB reduce to 0.21 % according to the budgets given in Tables 9 and 14, and those of the IAEA reduce to 0.42 % and 0.34 % for mammographic and diagnostic qualities, respectively, according to the budgets given in Table 15. Quadratic summation of the components leads to the combined standard uncertainties of the comparison of 0.47 % and 0.40 % for mammographic and diagnostic qualities, respectively. These values are summarized in Table 20.

Table 20. Relative standard uncertainties (in %) associated with the ratio of the calibration factors obtained at PTB and IAEA

Source of uncertainty	Mammo-graphic	General diagnostic
u(N_K) PTB (without constants)	0.21	0.21
u(N_K) IAEA (without reference)	0.42	0.34
Combined standard uncertainty	0.47	0.40

6.2 Final results of the comparison

The final results of the comparison were calculated as the average ratios of the PTB and IAEA calibration coefficients obtained with the different transfer chambers and are given in Table 21. It can be concluded that level of agreement of the calibration coefficients of both laboratories is well within the relative standard uncertainty of the comparison of about 0.47 %.

Table 21 Final ratio of the PTB and IAEA calibration coefficients calculated as the average of the transfer chambers applied.

	Quality code (IEC 61267)	Tube voltage (kV)	PTB/IAEA
1	RQR-2	40	1.0021
2	RQR-5	70	1.0002
3	RQR-10	150	1.0008
4	RQA-2	40	0.9970
5	RQA-5	70	1.0000
6	RQA-10	150	1.0025
7	RQT-9	120	0.9992
8	RQR-M1	25	1.0008
9	RQR-M2	28	0.9995
10	RQR-M3	30	0.9994
11	RQR-M4	35	0.9994
12	*MMV-40	40	0.9991
13	*MMV-50	50	0.9995
14	RQA-M2	28	1.0017
15	*MMH-40	40	1.0031
16	*MMH-50	50	1.0026
17	*MRV-28	28	1.0002
18	*MRV-30	30	1.0001
19	*MRV-35	35	0.9998

*PTB code

7. Conclusions

The air kerma calibration coefficients of a set of four transfer ionization chambers were determined at the PTB and the IAEA for 19 selected radiation qualities as used in mammography and general diagnostic radiology. Due to the fact that the IAEA reference standards are traceable to the primary standards of the PTB, correlations had to be taken into account in the evaluation of the standard uncertainty of the comparison results, taken as the ratio of calibration coefficients PTB/IAEA. It was estimated to be as low as about 0.4 %. The comparison results for the selected beam qualities were in the range (0.997-1.0031) and were consistent within the uncertainty of the comparison. Taking into account the flat energy response curves of the transfer chambers, the results for the remaining beam qualities, not selected, would be expected to be within this 0.47 % relative standard uncertainty, thus supporting all the relevant CMC claims of the IAEA.

8. References:

[1] J. Witzani1, H. Bjerke, F. Bochud, I. Csete, M. Denoziere, W. de Vries, K. Ennow, J. E. Grindborg, C. Hourdakis, A. Kosunen, H. M. Kramer, F. Pernicka, T. Sander *Calibration of dosemeters used in mammography with different X ray qualities: Euromet Project No. 526* *Radiation Protection Dosimetry* **108**:33-45 (2004)

[2] D. T. Burns, L. Büermann, H.-M. Kramer, B. Lange *Comparison of the air-kerma standards of the PTB and the BIPM in the low-energy x-ray range*, 2001, Rapport BIPM-01/08

[3] D. T. Burns, L. Büermann, H.-M. Kramer, B. Lange *Comparison of the air-kerma standards of the PTB and the BIPM in the medium-energy x-ray range*, 2002, Rapport BIPM-02/07

[4] C. Kessler, D.T. Burns, L. Büermann "*Key Comparison BIPM.RI(I)-K7 of the air kerma standards of the PTB, Germany and the BIPM in mammography X-rays*" Metrologia, 2011, 48, tech. Suppl.,06011 http://www.bipm.org/utils/common/pdf/final_reports/RI/RI(I)-K7/BIPM.RI(I)-K7_PTB_2010.pdf

[5] EURAMET.RI-S10, Technical Protocol

[6] CEI IEC 61267:2005-11 "*Medical diagnostic X-ray equipment - Radiation conditions for use in the determination of characteristics*"

[7] ENGELKE B.-A., OETZMANN W., STRUPPEK, G., Die Meßeinrichtungen der Physikalisch-Technischen Bundesanstalt zur Darstellung der Einheiten der Standard-Ionendosis, Photonen-Äquivalentdosis und Luftkerma, *PTB-Report* Dos-16, 1988 (Physikalisch-Technische Bundesanstalt, Braunschweig)

[8] ISO/IEC *Guide to the Expression of Uncertainty of Measurement*, JCGM 100:2008

[9] IAEA TRS 457 Dosimetry in Diagnostic Radiology: an International Code of Practice 2007