Comparison of air kerma measurements for tungsten anode based mammography x-ray beam qualities (EURAMET.RI(I)-S4.1)

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Abstract
A comparison of the air kerma standards for x-radiation qualities used in mammography was performed between the PTB and the IAEA. Two reference-class ionization chamber types Radcal RC6M and Magna A650 of the IAEA and tungsten anode based beam qualities with Mo and Al external filtrations *(W+Mo, W+Al)* established at both laboratories were selected for the comparison. The calibration coefficients, N_{K_air}, were determined for the transfer chambers at the PTB in May 2015 and before and after this at the IAEA Dosimetry Laboratory. The results show good agreement, to be well within the 0.55 % standard uncertainty of the comparison. Correction factors to determine N_{K_air} for these beam qualities based on calibration in RQR-M mammography beam qualities, established according to the IEC 61267 standard, were also calculated for the Radcal RC6M, 10X5-6M, and Magna A650 types of chambers.

1. Introduction

The IAEA Dosimetry Laboratory at Seibersdorf, Austria, performs calibration of reference dosimeters of the IAEA/WHO SSDL Network members (more than 83 laboratories worldwide) free of charge. As member of the CIPM MRA, the IAEA laboratory maintains a quality management system (QMS) complying with the international standard ISO 17025. The laboratory updated its dosimetry Calibration and Measurement Capabilities (CMCs) claims in 2013, in the Appendix C of the CIPM MRA including the mammography x-ray beam qualities generated by x-ray tubes having Mo anodes [1]. For the extension of this RAD-1018 CMC claim with tungsten anode based x-ray beam qualities used by digital mammography machines, a dedicated comparison result as 'supporting evidence' is selected in addition to the traceability of the measured quantity. The comparison partner chosen was the Physikalisch-Technische Bundesanstalt (PTB), Germany, that maintains air kerma primary standards for mammography beams with participation in the on-going key comparison BIPM.RI(I)-K7. The comparison results in the tungsten anode x-ray beams with Mo filtration can be found in [2]. The outcome of the comparison, i.e. the ratios of the calibration coefficients of transfer chamber determined by each laboratory, should be consistent with the combined relative standard uncertainty for the comparison taking into account the correlations between both laboratories, as the IAEA secondary-standard chamber is traceable to the PTB primary standards. If this is the case, it can validate the calibration practice of the participants, and supporting the extended CMC claim of the IAEA.

The current bilateral comparison is identified as EURAMET project #1362 and registered in the BIPM key comparison data base (KCDB) as EURAMET.RI(I)-S4.1 supplementary comparison.

2. Comparison procedure

2.1 *Transfer chambers*

For the comparison two IAEA reference-class transfer chambers have been selected. The technical details of the chambers are listed in Table 1. The reference planes of the parallel-plate Radcal and Magna chambers are the grooves on their side wall at 4 mm behind the plane of their entrance windows.

Table 1. Technical data of the transfer chambers

Type	Reference point	Nominal volume /cm^3	*Polarizing voltage /V	Wall thickness	Diameter /mm
Radcal 10X56M parallel plate chamber #9059	marked on the chamber	6	+300	0.7 mg/cm^2	43(outer) 30 (effective)
Magna A650 parallel plate chamber #D121351	marked on the chamber	3	+300	3.9 mg/cm^2	53(outer) 42 (effective)

* Applied to the central electrode

2.2 Radiation qualities

The radiation qualities used for the comparison were the tungsten-anode based mammography beam qualities as listed in Table 2. As an example, the spectral differences of the different anode materials and filtrations used at 35 kV generating voltage can be seen in Figure 1.

Table 2. Characteristics of the radiation qualities used for the comparison

*Quality	Tube voltage	Filtration	PTB HVL	*Mean energy	IAEA HVL	HVL ratio	BIPM HVL
	kV	µm	mm Al	keV	mm Al	PTB/IAEA	mm Al
WMV 25	25	60 Mo	0.366	16.8	0.340	1.08	0.342
WMV 28	28	60 Mo	0.380	17.2	0.357	1.06	0.356
WMV 30	30	60 Mo	0.392	17.7	0.367	1.07	0.364
WMV 35	35	60 Mo	0.424	19.6	0.393	1.08	0.388
WAV 25	25	500 Al	0.352	16.1	0.312	1.13	--
WAV 28	28	500 Al	0.395	17.0	0.354	1.12	--
WAV 30	30	500 Al	0.426	17.5	0.380	1.12	--
WAV 35	35	500 Al	0.499	18.7	0.435	1.15	--

*PTB code and values

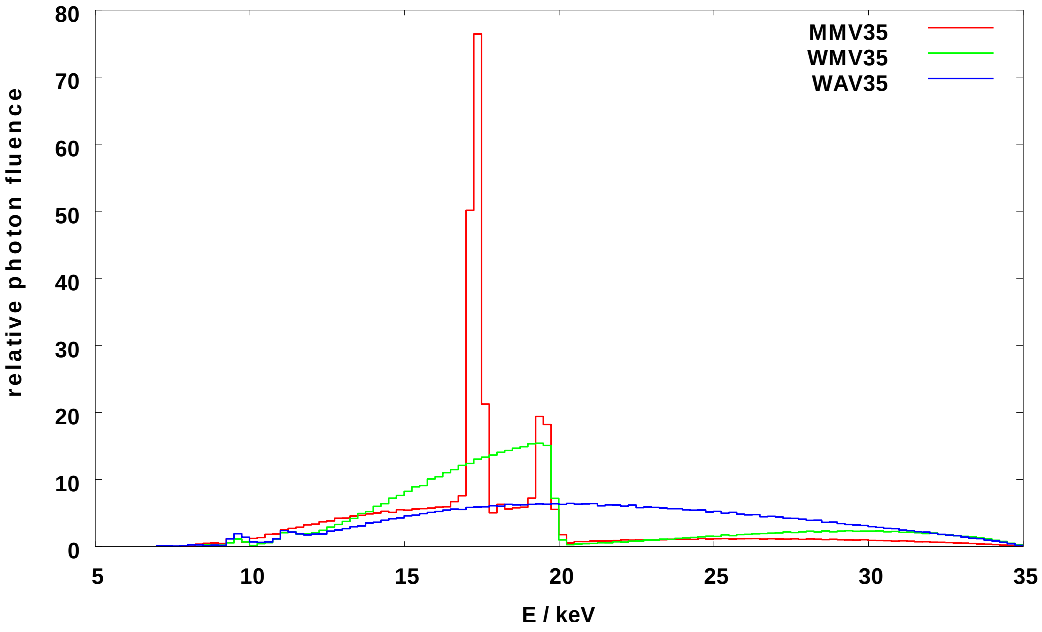

Figure 1. Photon fluence spectra of the RQR M3 (PTB code: MMV 35), WMV 35 and WAV 35 beam qualities determined at the PTB by use of a high purity Germanium (HpGe) spectrometer.

A HPGe detector was used for pulse height spectral measurements; its energy response function was determined using the Monte Carlo code DOSRZnrc. The Bayesian deconvolution method was applied to obtain the photon fluence spectra [3].

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 WMV (W+Mo) and WAV (W+Al) mammography beam qualities used in this comparison are produced with a bipolar x-ray tube of type MB450-1H450 (THALES ELECTRON DEVICES) with a W-anode angle of 21° combined with types MGG46 and MGG47 constant potential generators produced by the Yxlon International X-Ray GmbH. The inherent filtration is 7 mm beryllium. The diameter of the circular beam at 1 m distance from the focus was 10 cm. The air kerma rates were in the range of (4.3-26) mGy/min.

The high voltage was measured invasively with a voltage divider manufactured and calibrated at the 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 the PTB was used 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 integrated in 60 s using the primary 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.

3.2 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

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

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.

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-radiation beams 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 [4]. 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. The various sources of uncertainty are grouped according to the GUM [5] as Type A u_{iA} (statistical) and Type B u_{iB} non-statistical, based on scientific judgement.

Table 5. Correction factors for the PTB standard for the WMV beam qualities

Radiation quality PTB code	WMV 25	WMV 28	WMV 30	WMV 35	$u_{i\mathrm{A}}$ %	$u_{i\mathrm{B}}$ %
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	1.0010	1.0012	1.0015	0.05	0.05
Guard strip attenuation k_{ap}	1.0041	1.0039	1.0039	1.0038	0.05	0.05
Aperture edge trans. 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 fluorescent photons.

Table 6. Correction factors for the PTB standard for the WAV beams

Radiation quality PTB code	WAV 25	WAV 28	WAV 30	WAV 35	$u_{i\mathrm{A}}$ %	$u_{i\mathrm{B}}$ %
Air attenuation k_a[a]	1.0213	1.0205	1.0194	1.0176	0.05	0.05
Scattered radiation k_{sc}[b]	0.9909	0.9911	0.9913	0.9915	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_s	1.0016	1.0020	1.0025	1.0033	0.05	0.05
Guard strip attenuation k_{ap}	1.0044	1.0043	1.0041	1.0037	0.05	0.05
Aperture edge trans. k_l	0.9996	0.9996	0.9995	0.9994	-	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 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 relative combined standard uncertainty of 0.30 %.

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

Source of uncertainty	$u_{i\mathrm{A}}$ / %	$u_{i\mathrm{B}}$ / %
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	$u_{i\mathrm{A}}$ / %	$u_{i\mathrm{B}}$ / %
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	$u_{i\mathrm{A}}$ / %	$u_{i\mathrm{B}}$ / %
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	

4. Calibration at the IAEA

4.1 Transfer chambers and x-ray facilities

An x-ray tube type Isovolt MXR160/0.4-3.0, with 20° anode angle and 1 mm Be window was used to generate the mammography W-Mo and W-AL x-ray beam qualities. The output of the high-voltage generator, type ISOVOLT 160 Titan E, is monitored using a high-voltage divider, type FUG HVT 160 000, calibrated at the PTB. Ionization currents are measured using Keithley K6517A electrometers and normalized to the monitor chamber, type Geo-1. The internal capacitance and all ranges of the electrometers are calibrated using a Keithley calibrator, type 263, traceable to voltage and capacitor standards of the Bundesamt für Eich- und Vermessungswesen (BEV), Austria.

The calibrations of the transfer chambers were performed against the IAEA reference secondary-standard chamber, type Radcal RC6M, calibrated at the PTB in 2014. Its energy response is within ± 0.4 % normalised to the RQR-M2 beam quality [8] for the beam qualities listed in Table 2. The air kerma rate was 50 mGy/min for all beam qualities.

The uncertainties associated with the calibrations for mammography at the IAEA Dosimetry Laboratory, DOL, are listed in Table 10. The various sources of uncertainty are grouped according to [5] 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.

Table 10. Uncertainty budget of transfer chambers calibrations at the IAEA

Air Kerma rate	Type A	Type B
	Uncertainty (%)	
Step 1: Reference standard		
Calibration from PTB		*0.42
Long term stability of the reference standard		0.20
Spectral difference of the beam at IAEA and PTB		0.10
Chamber positioning		0.03
Current measurements including range and time base corrections	0.02	0.05
Uncertainty due to temperature measurements		0.03
Uncertainty due to pressure measurements		0.01
Monitor chamber contribution	0.02	
Relative combined standard uncertainty of K_{air}	**0.03**	**0.48**
Step 2: Transfer chamber		
Current measurements including user electrometer	0.02	0.05
Uncertainty due to temperature measurements	0.01	0.03
Uncertainty due to pressure measurements	0.01	0.01
Monitor chamber contribution	0.02	
Chamber positioning		0.03
Difference in radial non-uniformity of the beam		*0.10*
Relative combined standard uncertainty in Step 2	**0.03**	**0.12**
Relative combined standard uncertainty (Steps 1 + 2)	**0.04**	**0.50**
Overall relative uncertainty	**0.50**	

**The original 0.5% uncertainty is reduced with the uncertainties of the physical constants, the correction factors, and volume of the PTB primary standard involved in the air kerma determination at the PTB.*

The beam profiles of calibration setups at both laboratories are similar based on the two beam profiles measured. The measured IAEA vertical and horizontal beam profiles at the 1 m calibration distance are shown in Figure 2. Instead of the application of calculated radial non-uniformity correction factors, an additional type B uncertainty component of 0.1% was estimated in both laboratories, probably overestimated the effect of the beam profile difference in the two laboratories.

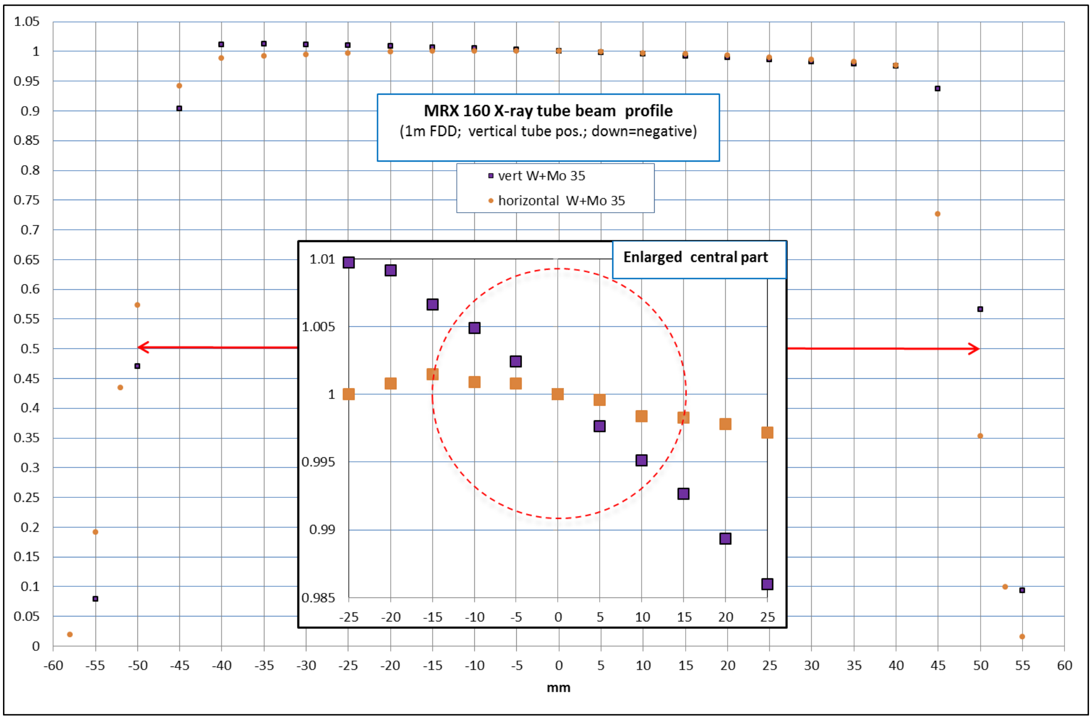

Figure 2. Measured beam profile of the W+Mo 35 kV beam quality established using the Isovolt MXR160/0.4-3.0 x-ray tube at the IAEA. The Radcal transfer chamber is marked with a dotted circle in the enlarged central area. Its rectangular marker size scaled to the 0.1 % estimated standard uncertainty of measured points.

5. Measurement results

The calibration coefficients were determined at both laboratories using the substitution method, from a minimum of 3 repeated measurements at the IAEA before and after the calibration performed at the PTB. The reproducibility of the calibration at the IAEA was estimated using the standard deviation of the repeated measurements, being less than 0.1 %. The leakage currents of the transfer chambers never exceeded 0.02 % of the measured currents at both laboratories, and were subtracted in each case.

The differences in the HVL values of the same radiation qualities in terms of kV and total filtration at the two laboratories, can be addressed through the application of suitable correction factors, k_Q. These k_Q factors have been calculated for the PTB HVL values by linear interpolation of the energy response curves of both transfer chambers measured at the IAEA in the (0.31-0.50) mm HVL range.

The estimated uncertainties of the k_Q values are less than 0.05 % and 0.1 % for the RADCAL and Magna transfer chamber respectively supposing maximum 0.4 % uncertainty in the HVL determinations and 0.2 % uncertainty in the calibration coefficients. No any further correction factor was applied to the calibration coefficients $N_{K,\mathrm{PTB}}$. and $N_{K,\mathrm{IAEA}}$. The calibration coefficients of the transfer chambers determined at the PTB and IAEA are shown in Figures 3a and 3b.

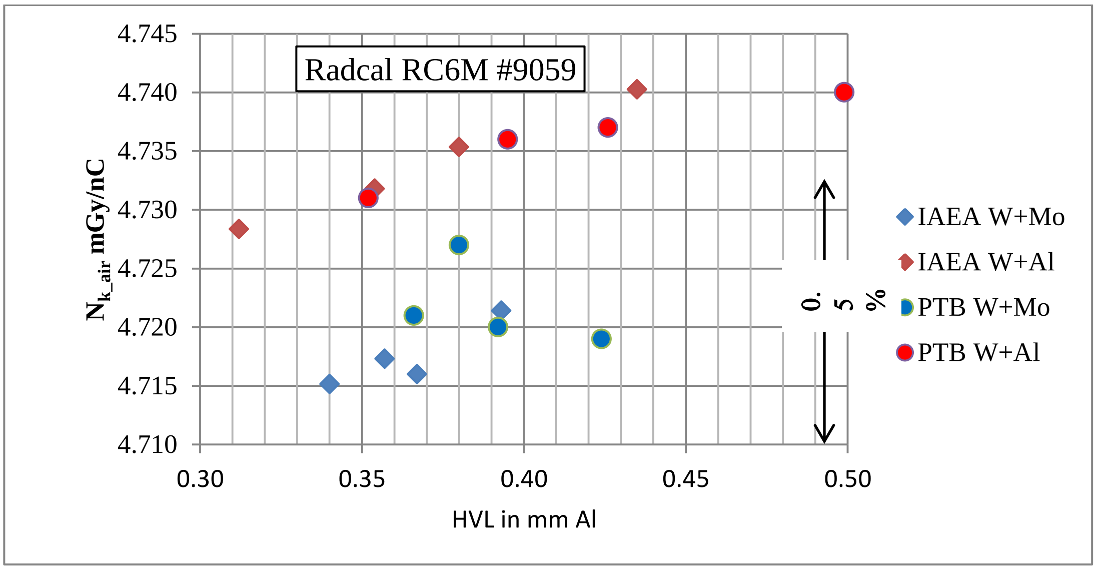

Figure 3a. Calibration coefficients of the RADCAL RC6M transfer chamber for the beam qualities listed in Table 2.

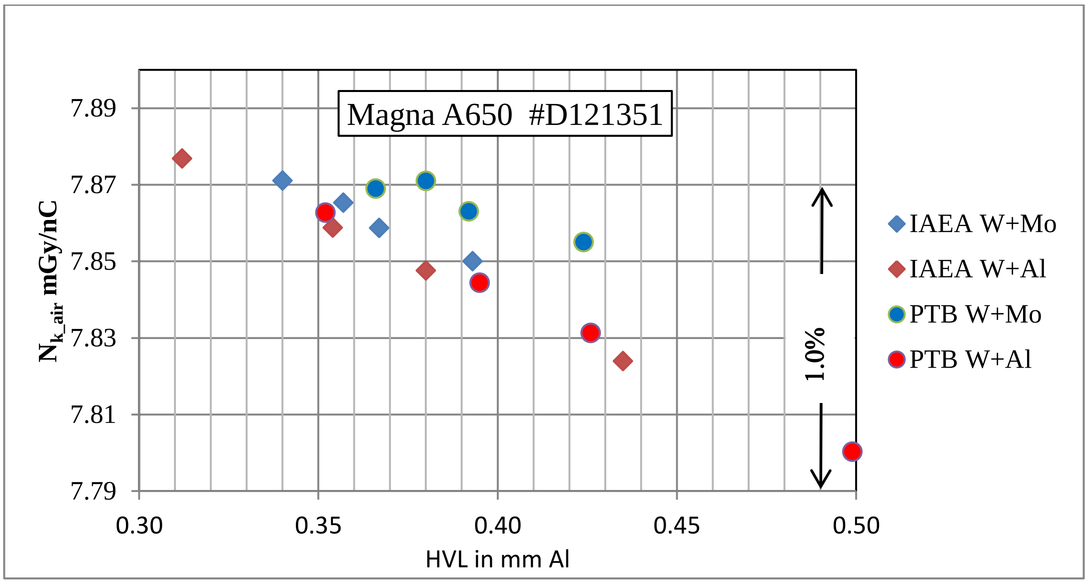

Figure 3.b Calibration coefficients of the Magna A650 transfer chamber for the beam qualities listed in Table 2.

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, volume and the correction factors of the PTB 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 %, as expressed in Table 9, and those of the IAEA reduce to 0.50 % based on the uncertainty budget as given in Table 10. The relative uncertainty of the k_Q values was estimated as 0.1 % and is included in the uncertainty budget. Quadratic summation of these three components, being not correlated, leads to the combined standard uncertainty for the comparison result of 0.55 % for both W+Mo and W+Al mammography beam quality series. These values are summarized in Table 11.

Table 11. Relative standard uncertainties (in %) associated with the ratio of the calibration coefficients obtained at PTB and IAEA

Source of uncertainty	
u(N_K) PTB	0.21
u(N_K) IAEA	0.50
u(k_Q) IAEA	0.10
u($N_{K,\text{ PTB}}$/ $N_{K,\text{ IAEA,corr}}$)	0.55

6.2 Final results of the comparison

The comparison result, R, for each transfer chamber and beam quality was calculated as the ratio of the calibration coefficient, R = $N_{K,\text{ PTB}}$ / $N_{K,\text{ IAEA,corr}}$, ,where the $N_{K,\text{ IAEA,corr}}$ is the corrected IAEA value with the k_Q factors to account for the HVL difference.

The final results of the comparison for the W+Mo and W+Al beam quality series were calculated as the average ratios of the PTB and IAEA calibration coefficients obtained with the two transfer chambers. The comparison results and the calculated k_Q values are given in Tables 12a and 12b.

Table 12a. Calibration coefficients, N_K,of the transfer chambers in (mGy/nC) unit, and the final comparison result for the W+Mo beam qualities. The k_Q values correct the $N_{K,\text{ IAEA}}$ values according to the PTB HVL values.

Magna A650 #D121351	**W-Mo-25**	**W-Mo-28**	**W-Mo-30**	**W-Mo-35**
PTB	7.8690	7.8710	7.8630	7.8550
IAEA	7.8711	7.8653	7.8587	7.8500
k_Q for PTB HVL	0.9987	0.9987	0.9989	0.9983
corr. IAEA	7.8606	7.8549	7.8500	7.8370
PTB/IAEA	**1.0011**	**1.0021**	**1.0017**	**1.0023**
Radcal #9059	**W-Mo-25**	**W-Mo-28**	**W-Mo-30**	**W-Mo-35**
PTB	4.7210	4.7270	4.7200	4.7190
IAEA	4.7151	4.7173	4.7160	4.7214
k_Q for PTB HVL	1.0005	1.0004	1.0010	1.0006
corr. IAEA	4.7176	4.7192	4.7206	4.7242
PTB/IAEA	**1.0007**	**1.0016**	**0.9999**	**0.9989**
average (Radcal+Magna)	**1.0009**	**1.0018**	**1.0008**	**1.0006**
Magna/Radcal	1.0004	1.0005	1.0018	1.0034

Table 12b. Calibration coefficients, N_K,of the transfer chambers in (mGy/nC) unit, and the final comparison result for the W+Al beam qualities. The k_Q values correct the $N_{K,\text{IAEA}}$ values to the PTB HVL values.

Magna A650 #D121351	**W-Al-25**	**W-Al-28**	**W-Al-30**	**W-Al-35**
PTB	7.8850	7.8610	7.8470	7.8150
IAEA	7.8818	7.8586	7.8510	7.8285
k_Q for PTB HVL	0.9976	0.9982	0.9975	0.9964
corr. IAEA	7.8627	7.8445	7.8313	7.8003
PTB/IAEA	**1.0028**	**1.0021**	**1.0020**	**1.0019**
Radcal #9059	W-Al-25	W-Al-28	W-Al-30	W-Al-35
PTB	4.7310	4.7360	4.7370	4.7400
IAEA	4.7288	4.7325	4.7361	4.7412
k_Q for PTB HVL	1.0008	1.0010	1.0009	1.0014
corr. IAEA	4.7328	4.7372	4.7404	4.7478
PTB/IAEA	**0.9996**	**0.9997**	**0.9993**	**0.9983**
average (Radcal+Magna)	**1.0012**	**1.0009**	**1.0006**	**1.0001**
Magna/Radcal	1.0032	1.0024	1.0027	1.0036

As it can be seen from Tables 12a and 12b all the comparison results are in the range (0.9983-1.0028). The final comparison results for both beam quality series are in the range (1.0001-1.0018). There was no explanation for the systematic deviations between the two transfer chambers.

7. Correction factors for W+Mo and W+Al beam qualities based on calibration in standard RQR-M qualities

Some secondary standard dosimetry laboratories, SSDLs, have only traditional x-ray tube with tungsten anode and no dedicated mammography x-ray tube with molybdenum or rhodium anode for ionization chamber calibration. There is an increasing demand for calibration of mammography chambers even in tungsten anode based beam qualities using a variety of external filter materials (Mo, Rh, Al, Pd). Increasingly digital mammography machines are using tungsten anode with Mo Rh or Al filtration.

The calibrations of Radcal and Magna A650 chambers performed at the PTB and the IAEA, being frequently used as secondary standards at SSDLs, ensure representative statistics, and enable us to evaluate their typical energy responses. These normalised calibration curves using minimum 10 results for the same type of chamber to the RQR-M2 beam quality can be seen in Figure 4. The more apparent energy response of the Magna A650 chamber can be explained with the thicker entrance window, see Table 1.

More detailed calibration data for these chamber types including additional W+Mo and W+Al and Mo+Rh beam quality series are shown in Figures 5a, 5b and 5c. These figures include the standard deviation of the available calibration points, and the equation of linear fittings as well. These linear functions could be used to estimate the small correction for the HVL differences for each of the beam quality series.

The calculated correction factors to determine the calibration coefficient N_{K_Q} for the W+Mo and W+Al beam qualities from the $N_{K\_RQR\text{-}M2}$ standard reference mammography beam quality (28 kV, nominal first HVL=0.31 mm Al [8]) are in Table 13. The uncertainty of these small corrections is typically 0.1 %.

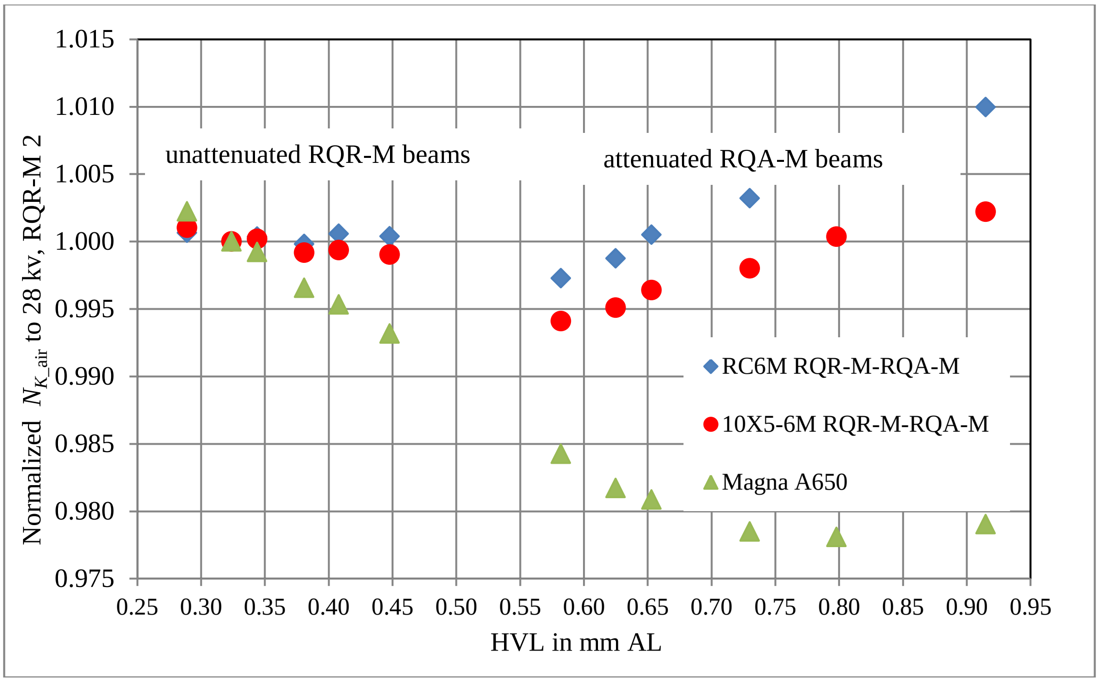

Figure 4. Relative calibration coefficients of Radcal RC6M, 10X5-6M and MAGNA A650 types of chambers for the mamography beam qualities RQR-M and RQA-M according to [8].

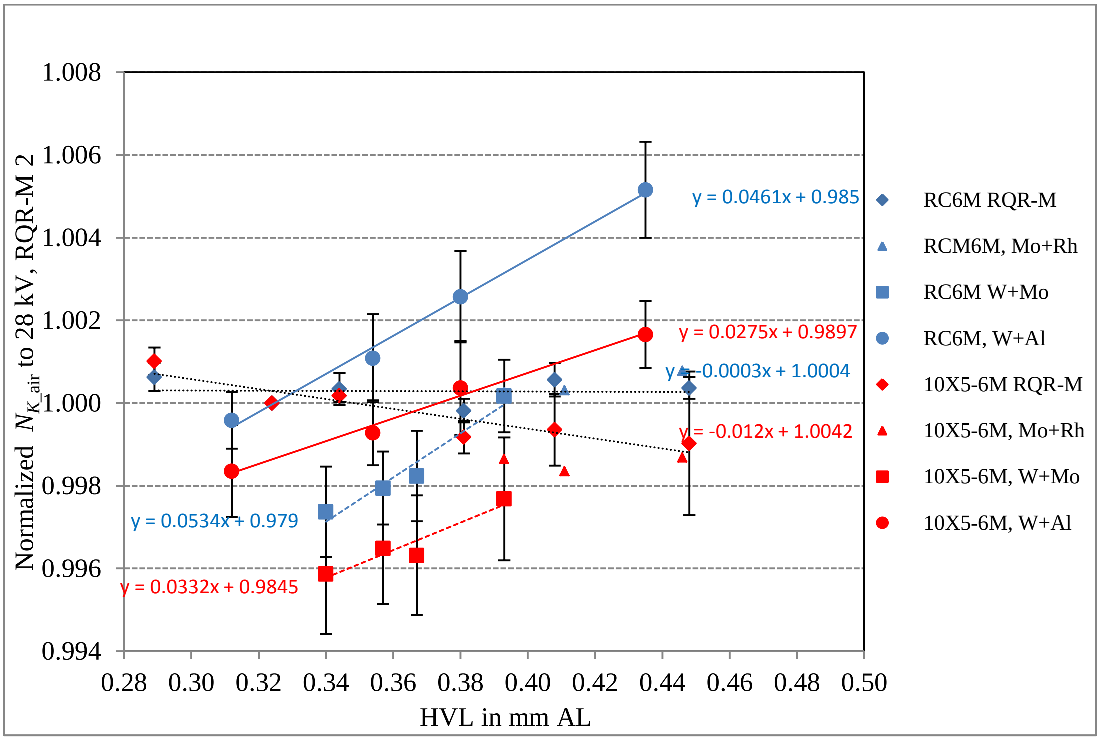

Figure 5a. Relative calibration coefficients of Radcal RC6M, and 10X5-6M types of chambers for unattenuated beam qualities.

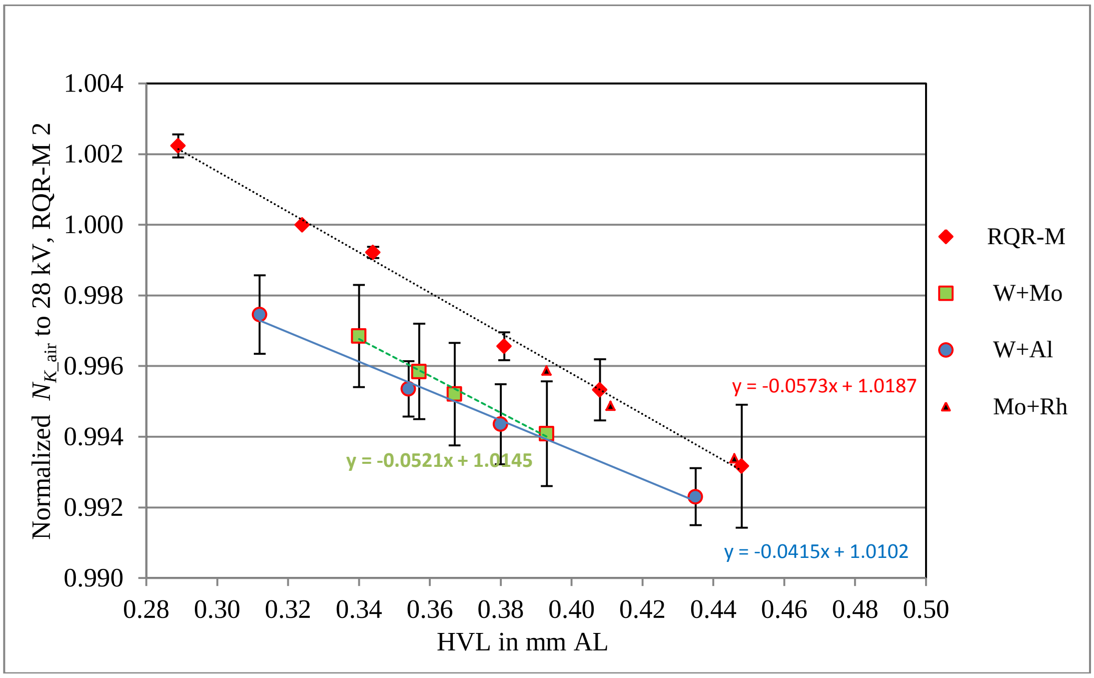

Figure 5b. Relative calibration coefficients of Magna A650 type of chamber for unattenuated beam qualities.

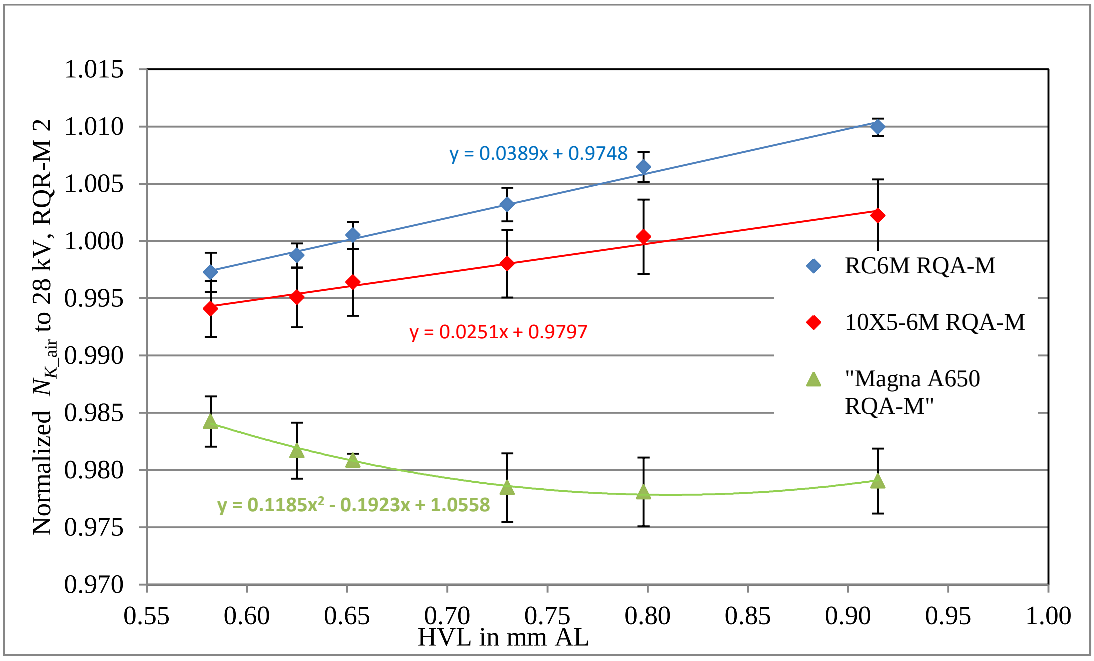

Figure 5c. Relative calibration coefficients of Radcal RC6M, 10X5-6M and Magna A650 types of chambers for attenuated beam qualities.

Table 13. Correctios factors for W+Mo and W+Al beam qualities based on calibration in reference Mo+Mo beam quality RQR-M2 [8]

Beam quality Q	Magna A650	Radcal 10X5-6M	Radcal RC6M
W-Mo-25	0.9946	0.9947	0.9967
W-Mo-28	0.9958	0.9962	0.9979
W-Mo-30	0.9960	0.9959	0.9979
W-Mo-35	0.9975	0.9981	1.0004
W-AL-25	0.9952	0.9971	0.9990
W-AL-28	0.9954	0.9991	1.0011
W-AL-30	0.9951	1.0000	1.0022
W-AL-35	0.9957	1.0023	1.0053

8. Conclusions

It can be concluded that the level of agreement of the calibration coefficients between both laboratories is well within the 0.55 % relative standard uncertainty of the comparison. The results of this bilateral comparison validate the calibration practice of the IAEA and can support the extension of mammography CMC claims of the IAEA with the W-Mo and W-Al beam qualities. Taking into account the flat energy response curves of the IAEA secondary standard chambers type RADCAL RC6M and 10X5-6M in the (25-35) kV range, and the achieved agreement of 0.2 %, similar comparison results for further mammography beam qualities (anode-filtration combinations) would be expected, supporting further mammography CMC claims of the IAEA.

Application of the correction factors established in Table 13 can reduce the uncertainty of calibration coefficient of these reference quality mammography chambers for other beam qualities to comply with the $u_c(N_{K\_Q}) \leq 1\%$ IAEA recommendation [7].

9. References:

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[4] 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)

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

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