Comparison of the national standards of air kerma between the PTB and the CPHR for selected x-ray qualities used in radiation protection, diagnostic radiology and radiation therapy

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Abstract
The air kerma calibration coefficients of a set of four transfer ionization chambers and the air kerma-length product calibration coefficients for a set of two transfer pencil-type ionization chambers were compared at the PTB, Germany, and the CPHR, Cuba, for 15 selected radiation qualities as used in mammography, general diagnostic radiology, computed tomography, radiation therapy and radiation protection. The CPHR performed its measurements in the period January to September 2017 and the PTB before (November 2016) and after (December 2017) that period. The comparison results for the selected beam qualities expressed as the ratio of calibration coefficients were in the range (0.98-1.01) and mostly (12 out of 18) consistent within the relative standard uncertainty of the comparison which ranged between 0.6 % and 1 %. Five results were within the extended (k=2) standard uncertainty. One result deviated relatively by 1.9%. A possible reason for the larger deviation is discussed. The results are published in the Key Comparison Data Base (KCDB) of the BIPM as supplementary comparison COOMET.RI(I)-S4.

1. Introduction

The object of this project was to carry out a bilateral comparison of the national standards of air kerma between the Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Centro de Protección e Higiene de las Radiaciones (CPHR), Cuba, for selected x-ray qualities used in radiation protection, diagnostic radiology and radiation therapy. The objective of the comparison was to provide evidence that may be used to support the corresponding existing and planned CMC entries of the CPHR, according to the CIPM-MRA [1]. The CPHR does not maintain primary air kerma standards for x-rays but uses calibrated national standards traceable to the International Atomic Energy Agency (IAEA) or the PTB. The CPHR is a member of the IAEA-SSDL network. The PTB maintains primary air kerma standards for low- and medium-energy x-rays and participated in the corresponding relevant key comparisons BIPM-RI(I)-K2 [2], -K3 [3] and –K7 [4]. Furthermore, the PTB has valid CMC-entries for the air kerma derived application specific quantity air kerma-length product. Therefore, a comparison of the CPHR standards against the corresponding PTB standards can provide evidence to support measurements based on the CPHR standards and the associated CMC entries.

2. Comparison procedure

2.1 Radiation qualities

A total of 15 radiation qualities according to the document CCEMRI 1972 [5] and international standards IEC 61267 [6] and ISO 4037 [7] were selected and are listed in Table 1. The beam codes WMV denote a W-anode x-ray tube filtered with 0.06 Mo and WMH means WMV with an added filter of 2 mm Al.

Table 1. List of radiation qualities used for the comparison

No.	Quality code	Tube Voltage (kV)	Nominal first half-value layer in mm	Quantity to be compared	Document / Standard	Application
1	CCRI 25 kV	25	0.24 Al	air kerma	CCEMRI 1972 [5]	Radiotherapy (Low energy)
2	CCRI 50 kVb	50	1.02 Al			
3	WMV 28*	28	0.37 Al			Mammography
4	WMH 28*	28	0.61 Al			
5	RQR 3	50	1.78 Al		IEC:61267 [6])	General Radiology
6	RQR 5	70	2.58 Al			
7	RQR 9	120	5.00 Al			
8	RQT 8	100	6.9 Al	air kerma & air kerma-length product		Computed Tomography
9	RQT 9	120	8.4 Al			
10	RQT 10	150	10.1 Al			
11	CCRI 100kV	100	4.03 Al	air kerma	CCEMRI 1972 [5]	Radiotherapy (Med. energy)
12	CCRI 135 kV	135	0.49 Cu			
13	N60	60	0.24 Cu		ISO 4037-1 [7]	Radiation protection
14	N100	100	1.11 Cu			
15	N150	150	2.36 Cu			

*PTB Code

2.2 Transfer chambers

Three different types of transfer chambers were used for the groups of radiation qualities shown in Table 2. Two transfer chambers of the same type were used for each group. At the RQT qualities (nos. 8-10 in Table 1) calibration coefficients were determined in terms of air kerma <u>and</u> air kerma-length product.

Table 2. Main characteristics of the transfer chambers

Quality no.(see table 1)	Type	Shape	Nominal volume	Nominal response	Chamber voltage	Max. dose rate for ≥ 99% sat.
1-4	2x PTW 34069	Plane parallel	6 cm^3	230 nC/Gy	200 V	0.53 Gy/s
5-15	2x PTW 23361	Cylindrical	30 cm^3	1 µC/Gy	400 V	60 mGy/s
8-10	2x PTW 30009	Pencil type	3.14 cm^3	14 nC/(Gy*cm)	-100 V	12.4 Gy/s (≥ 95% sat.)

2.3 Measurement procedure and reference conditions

Measurements were not started before the chamber had equalized to the ambient temperature. Measurements were started not earlier than about 1 hour after connection of the high voltage to the ionisation chambers. The currents of the transfer chambers at the place of measurement were always measured with and without the radiation beam. The signal to background ratio of the currents were not less than 1000. The background current was subtracted from the signal current. A complete measurement consisted of at least 5 repeated single measurements and the mean value was taken as the result. The relative percentage Type A standard uncertainty of the repeated measurements did not exceed 0.1%.

The calibration coefficients of the transfer chambers were measured and given in terms of air kerma or air kerma-length product per unit charge in units of Gy/C or Gy m/C referring to standard conditions of air temperature, pressure and relative humidity of $T = 293.15$ K, $P = 101.325$ kPa and $h = 50$ %. The relative air humidity was always between 20 % and 80 % during the calibrations otherwise a correction to $h = 50$ % was applied. There was no need to apply any correction for the incomplete charge collection which can be expected to be negligible at both participants sites within the dose rate ranges used in the comparison (see section 5.). The latter were always far below those values where significant saturation effects could be expected (see Table 2). The focus to reference point distance was 50 cm for CCRI 25 kV and CCRI 50 kVb, otherwise it was 100 cm.

3. Calibration at the PTB

3.1 X-ray facilities

The X-ray source used for the investigations of the radiation qualities no. 3 - 15 of table 2 was of type MG452, manufactured by the YXLON International X-Ray GmbH. The converter-type generators of types MGG46 and MGG47 operate at a frequency of 40 kHz and yield a constant potential which can be varied between 20 kV and 450 kV in steps of 20 V. The bipolar X-ray tube MB 450/1H450 has a Tungsten anode with an angle of 21° and a 7 mm beryllium exit window. The qualities no. 1 and 2 of Table 2 were realized using a unipolar x-ray tube of type Comet MXR 160 with a W anode angle of 20° combined with a constant potential generator (40 kHz) of type MPG41 manufactured by the YXLON International X-Ray GmbH. The tube potential can be varied between 7.5 kV and 160 kV. The exit window is made of 1 mm beryllium.

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 had previously been measured with a high-purity germanium detector. Characteristic radiation quality data such as mean energies and half-value layers are evaluated from these spectra.

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.

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:

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

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 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 [8]. 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 Table 5.

The relative standard uncertainties associated with the air-kerma rate determination using the PK100 are summarized in Table 6 and result in a combined standard uncertainty of 0.30 %.

They were evaluated according to the GUM [9]. The uncertainty components for the calibration of a secondary-standard ionization chamber in terms of air kerma with the PK100 are listed in Table 7.

Table 5. Correction factors for the PTB standard PK100 for the used radiation qualities. Relative uncertainties are given in %.

Radiation quality	WMV 28	WMH 28	CCRI 25kV	CCRI 50 kVb	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a[a]	1.0185	1.0112	1.0299	1.0089	0.05	0.05
Scattered radiation k_{sc}[b]	0.9911	0.9920	0.9901	0.9928	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombinationk_s	1.0011	1.0005	1.0122	1.0108	0.05	0.05
Guard strip attenuation k_{ap}	1.0038	1.0023	1.0086	1.0025	0.05	0.05
Aperture edge trans. k_l	0.9996	0.9995	0.9997	0.9991	-	0.05
Field distortion	0.9920	0.9920	0.9920	0.9920	-	0.15
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	0.05	-
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	-	0.05
Humidity k_h	0.9980	0.9980	0.9980	0.9980	-	0.05

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

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

Table 6. 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	

Table 7. 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	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	

3.4 Free-air chamber type "Faßkammer"

The PTB cylindrical free-air chamber type Faßkammer (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 8. 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 Tables 9 and 10. More details of the FK standard are given in [8].

Table 8. The main characteristics of the PTB medium-energy cylindrical free-air chamber as configured for the comparison

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 9. Correction factors for the PTB Faßkammer standard [a]. **Relative uncertainties are given in %.**

Radiation quality	RQR3	RQR5	RQR9	RQT 8	RQT 9	RQT 10	u_{iA}	u_{iB}
Air attenuation k_a[b]	1.0699	1.02148	1.01514	1.0125	1.0114	1.01054	-	0.10
Ionization gain k_{sc}[c]	0.9898	0.9906	0.9923	0.9929	0.9935	0.9941	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	0.05
Ion recombination k_s	1.0012	1.0012	1.0021	1.0012	1.0012	1.0012	0.05	-
Field distortion k_d	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	0.05	-
Shadow effect, k_{sh}	1.0000	1.0003	1.0013	1.0018	1.0021	1.0022	-	0.05
Aperture edge trans. k_l	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	0.05	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.10
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	-	-

[a] Components of the uncertainty below 0.0002 have been neglected.

[b] Nominal values for 293.15 K and 101.325 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.

Table 10. Correction factors for the PTB Faßkammer standard [a]. Relative uncertainties are given in %.

Radiation quality	CCRI 100 kV	CCRI 135 kV	ISO N60	ISO N100	ISO N150	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air attenuation k_a[b]	1.0168	1.0115	1.0131	1.0096	1.0085	-	0.10
Ionization gain k_{sc}[c]	0.9917	0.9936	0.9922	0.9950	0.9956	-	0.05
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0005	-	0.05
Ion recombination k_s	1.0012	1.0012	1.0009	1.0009	1.0009	0.05	-
Field distortion k_d	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	0.05	-
Shadow effect k_{sh}	1.0010	1.0020	1.0009	1.0032	1.0019	-	0.05
Aperture edge trans. k_l	1.0000	1.0000	1.0000	1.0000	0.9998	-	0.05
Wall transmission k_p	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	-	0.10
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	-	-

[a] Components of the uncertainty below 0.0002 have been neglected.
[b] Nominal values for 293.15 K and 101.325 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 standard are summarized in Table 11 and result in a combined standard uncertainty of 0.30 %. They were evaluated according to the GUM [9].

Table 11. Relative standard uncertainties (in %) associated with the standard “Faßkammer”

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	0.20
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 12.

Table 12. 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	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	

3.5 Calibration of the air kerma-length product chamber at a nominal length of 5cm

The calibration of an air kerma-length product chamber is done in two steps:

1. The air kerma rate is measured at a distance of 1m from the source with the primary standard free air chamber type FK according to chapter 3.4.

2. A rectangular lead aperture, 6 mm in thickness, with an opening of width 50.11 mm and height 30.08 mm was centred on the central axis of the beam with the beam size limiting edge of the conical shaped aperture facing the source at a distance of 98 cm from the focal spot. The chamber was positioned horizontally perpendicular to the beam axis with the centre of the marked ring on the middle of the chamber located on the beam axis at 100 cm from the focal spot.

The conventional true value of the air kerma-length product P_{KL} is obtained from equation (2).

$$P_{KL} = K_{\mathrm{FK}} * L * k_{\mathrm{nu}} * k_{\mathrm{residual}} \qquad (2)$$

where K_{FK} is the air kerma measured with the free-air chamber, L is the effective irradiated length of the CT chamber, k_{nu} corrects for influences of the non-uniformity of the beam in horizontal direction along the axis of the CT chamber and k_{residual} corrects for the influences of photons transmitted through and scattered at the rectangular aperture edges. The correction factor k_{nu} was obtained from measurements of the horizontal beam dose profile with a standard farmer type ionisation chamber of type PTW TM30013-451. The dose rate varies by less than 0.3% along the irradiated length of the CT chamber. As the dose rate varies approximately linearly the correction factor k_{nu} was estimated to be close to 1 with a relative standard uncertainty of 0.1%. The correction k_{residual} was obtained from similar methods as described in [10] and found to be close to 1 with an estimated relative standard uncertainty of 0.1%. The effective irradiated length of the CT chamber was estimated at 51.08 mm with a standard uncertainty of 0.3 mm which is about 0.59 % and is the largest contribution to the uncertainty. Using these values and the relative uncertainty of K_{FK} shown in Table 11 the relative standard uncertainty of P_{KL} was estimated at 0.67 % as shown in Table 13. The relative standard uncertainty associated with the calibration of the CT chamber was estimated at 0.69 % as shown in Table 14.

Table 13. Relative standard uncertainties (in %) associated with the determination of the air-kerma length product P_{KL}

Source of uncertainty	PTB	
	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Air kerma K_{FK}	0.13	0.26
Irradiated length L	0.59	
Correction factor k_{nu}	0.10	
Correction factor k_{residual}	0.10	
P_{KL}	0.62	0.26
	0.67	

Table 14. Relative standard uncertainties (in %) associated with the calibration of the transfer ionization chamber in terms of air kerma-length product

Source of uncertainty	u_{iA}	u_{iB}
Air-kerma length product P_{KL}	0.62	0.26
Ionization current	0.10	0.06
Positioning	0.05	
Monitor normalization		0.05
Air density correction	0.05	
$N_{KL,\mathrm{PTB}}$	0.63	0.27
	0.69	

4. Calibration at the CPHR

4.1 X-ray facilities and standard test conditions

The X-ray facility used at CPHR is the constant potential machine PANTAK HF160C operated in the range between 5 and 160 kV. The tube has a tungsten anode with an exit window of 1 mm of beryllium. The high voltage was measured non-invasively. The radiation qualities were established according to international recommendations and standards [5,6,7]. The transmission monitor chamber PTW 34014 was used to normalize the x-ray output. The temperature was measured close to the monitor chamber and at the point of measurement. The air pressure and the humidity were measured at one location in the room. No humidity correction was applied to the measurements since their values vary between 40 % and 60 % and the influence is included in the uncertainty budget. Two sets of 5 charge readings were used for measurements with the reference and transfer chambers. The ionization current was measured with the electrometer type Unidos Webline s/n 0023 with traceability to the NIST through the metrology institute of Mexico (ININ). The leakage current was subtracted from the mean of the measured charge.

4.2 Calibration at diagnostic qualities RQR and RQT

The CPHR standard is the cylindrical ionization chamber of type Radcal 10X5-6 s/n 16376 calibrated at PTB against a primary standard free air chamber. It is a reference class chamber with a nominal volume of 6 cm^3. The reference plane was located at the chamber axis 13 mm below the top edge of the chamber. A voltage of + 300 V was applied to the outer wall of the chamber. The calibration coefficients of the two transfer chambers were determined by the substitution method. The calibration was done at 100 cm distance from the focal spot and a field size of 8.4 cm (50 % isodose). The estimated uncertainty budget of the calibration coefficient is shown in Table 15.

4.3 Calibration at mammographic qualities

The CPHR standard is the plane-parallel ionization chamber of type Radcal 10X5-6M s/n 8852 calibrated at the PTB. The reference plane of the Radcal chamber was defined by intersection of the line on the chamber axis with the plane marked by the red line around the outer part of the chamber. A polarizing voltage of + 300 V was applied to the chamber wall.
The calibration coefficients of the transfer chambers were determined by the substitution method. The calibration was done at 100 cm distance from the focal spot and a field size of 8.4 cm (50 % isodose). The estimated uncertainty budget of the calibration coefficient is shown in Table 16.

Table 15. Uncertainty budget for calibration at diagnostic qualities at the CPHR

Uncertainty budget for Diagnostic Radiology	u_{iA} (%)	u_{iB} (%)
1. Reference standard		
1.1 Calibration coefficient		0.39
1.2 Long term stability		0.29
1.3 Calibration of electrometer		0.14
1.4 Readings	0.012	0.01
1.5 Recombination		0.00
1.6 Air density correction		0.10
1.7 Spectrum energy differences		0.06
2. Ionization chamber to be calibrated		
2.1 Readings	0.015	0.01
2.2 Recombination		0.00
2.3 Air density correction		0.10
3. Elements affecting both systems		
3.1 X-ray output		0.29
3.2 Chamber positioning		0.12
Relative uncertainty (%)		**0.62**

Table 16. Uncertainty budget for calibration at mammography qualities at the CPHR

Uncertainty budget for mammography	u_{iA} (%)	u_{iB} (%)
1. Reference standard		
1.1 Calibration coefficient		0.50
1.2 Long term stability		0.29
1.3 Calibration of electrometer		0.14
1.4 Readings	0.01	0.01
1.5 Recombination		0.00
1.6 Air density correction		0.10
1.7 Spectrum energy differences		0.00
2. Ionization chamber to be calibrated		
2.1 Readings	0.02	0.01
2.2 Recombination		0.00
2.3 Air density correction		0.1
3. Elements affecting both systems		
3.1 X-ray output		0.29
3.2 Chamber positioning		0.12
Relative uncertainty (%)		**0.69**

4.4 Calibration at diagnostic qualities RQT in terms of air kerma-length product

The air kerma-length product was measured in two steps: First, the air kerma rate was measured in the reference plane by use of the standard Radcal 10X5-6 s/n 16376. Second, a lead rectangular aperture of size 20 mm x 75 mm was placed in front of the reference plane. The aperture devices were specially manufactured in order to limit the production of scattered radiation. A suitable separation between aperture and reference plane of measurement was 50 mm. Thus, a field size length of 21.1 mm was obtained in the plane of measurement at 100 cm distance from the focal spot. This field size was previously checked by film.

The pencil-type transfer chambers were positioned with its axis in the reference plane and the calibration coefficients in terms of air kerma–length product were determined. The estimated uncertainty budget of the calibration coefficient is shown in Table 17. The most significant contribution was the positioning of the aperture device together with the pencil chamber since it defines the effective irradiated length at the reference plane.

Table 17. Uncertainty budget for calibration at RQT qualities in terms of air kerma-length product at the CPHR.

Uncertainty budget for Diagnostic Radiology	u_{iA} (%)	u_{iB} (%)
1. Reference standard		
1.1 Calibration coefficient		0.39
1.2 Long term stability		0.29
1.3 Calibration of electrometer		0.14
1.4 Readings	0.012	0.01
1.5 Recombination		0.00
1.6 air density correction		0.10
1.7 Spectrum energy differences		0.08
2. Ionization chamber to be calibrated		
2.1 Readings	0.015	0.01
2.2 Recombination		0.00
2.3 Air density correction		0.1
3. Elements affecting both systems		
3.1 X-ray output		0.29
3.2 Chamber and aperture positioning		0.55
Relative uncertainty (%)		**0.82**

4.5 Calibration at CCRI low-energy x-ray qualities

The secondary standard is the ionization chamber type PTW 23344 s/n 748 traceable to the BIPM through the IAEA. The reference point of the plane parallel chamber was defined by the intersection of the axis of the chamber with the plane on the entrance window. The applied voltage to the chamber wall was - 300 V. The calibration coefficients of the transfer chambers were determined by the substitution method. The calibration was done at 60 cm distance from the focal spot, as it was calibrated at the IAEA. The field size at this distance was 8.0 cm (50 % isodose). The evaluated uncertainty budget is shown in Table 16. The dominant component was the long-term stability which was assessed carefully during the time of comparison.

Table 18. Uncertainty budget for calibration at CCRI low-energy x-ray qualities at the CPHR.

Uncertainty budget	u_{iA} (%)	u_{iB} (%)
1. Reference standard		
1.1 Calibration coefficient		0.41
1.2 Long-term stability		0.58
1.3 Calibration of electrometer		0.14
1.4 Readings	0.01	0.01
1.5 Recombination		0.00
1.6 Air density correction		0.10
1.7 Spectrum energy differences		0.08
2. Ionization chamber to be calibrated		
2.1 Readings	0.02	0.01
2.2 Recombination		0.00
2.3 Air density correction		0.10
3. Elements affecting both systems		
3.1 X-ray output		0.29
3.2 Chamber positioning		0.12
Relative uncertainty (%)		**0.81**

4.6 Calibration at CCRI medium-energy x-ray qualities

The CPHR standard is the ionization chamber type NPL 2561 s/n 323 traceable to the BIPM through the IAEA. The reference point of the chamber was located at the chamber axis 5 mm below the top edge of the chamber without the build-up cap. The applied voltage to the chamber walls was -200 V. The calibration coefficients of the transfer chambers were determined by the substitution method. The calibration was done at 100 cm distance from the focal spot. The field size at this distance was 8.4 cm (50 % isodose). The evaluated uncertainty budget of the calibration coefficient is shown in Table 19.

4.7 Calibration at ISO 4037 Narrow Spectrum Series qualities

The CPHR standard is the chamber NE 2575 C s/n 515 traceable to the PTB through the IAEA. The reference point of the chamber was defined by the intersection of chamber axis and the plane marked by a line around the outer part of the chamber. The voltage applied to the chamber wall was - 250 V. The calibration coefficients of the transfer chambers were determined by the substitution method. The calibration was done at 200 cm distance from the focal spot and a field size of 26.8 cm (50 % isodose). The evaluated uncertainty budget of the calibration coefficient is shown in Table 20.

Table 19. Uncertainty budget for calibration at CCRI medium-energy x-ray qualities at the CPHR.

Uncertainty budget	u_{iA} (%)	u_{iB} (%)
1. Reference standard		
1.1 Calibration coefficient		0.42
1.2 Long-term stability		0.29
1.3 Calibration of electrometer		0.14
1.4 Readings	0.01	0.01
1.5 Recombination		0.00
1.6 Air density correction		0.10
1.7 Spectrum energy differences		0.06
2. Ionization chamber to be calibrated		
2.1 Readings	0.02	0.01
2.2 Recombination		0.00
2.3 Air density correction		0.10
3. Elements affecting both systems		
3.1 X-ray output		0.29
3.2 Chamber positioning		0.12
Relative uncertainty (%)		**0.63**

Table 20. Uncertainty budget for calibration at ISO 4037 Narrow Spectrum Series qualities at the CPHR

Uncertainty budget	u_{iA} (%)	u_{iB} (%)
1. Reference standard		
1.1 Calibration coefficient		0.60
1.2 Long-term stability		0.40
1.3 Calibration of electrometer		0.14
1.4 Readings	0.012	0.01
1.5 Recombination		0.00
1.6 Air density correction		0.10
1.7 Spectrum energy differences		0.20
2. Ionization chamber to be calibrated		
2.1 Readings	0.015	0.01
2.2 Recombination		0.00
2.3 Air density correction		0.10
3. Elements affecting both systems		
3.1 X-ray output		0.29
3.2 Chamber positioning		0.12
Relative uncertainty (%)		**0.84**

5. Results

In the following three sections results are given separately for each of the pairs of transfer chambers. N_K and $u(N_K)$ are air kerma calibration coefficients and their standard uncertainties. R_K and $u(R_K)$ are ratios of two air kerma calibration coefficients and their standard uncertainties. N_{KL} and $u(N_{KL})$ are air kerma-length calibration coefficients and their standard uncertainties. R_{KL} and u (R_{KL}) are ratios of two air kerma-length calibration coefficients and their standard uncertainties. D and u are the percentage differences and the standard uncertainties of the comparison results. The calibration coefficients measured at the PTB before and after the comparison measurements at the CPHR are denoted as “pre- and post-comp.” It is noted that the uncertainties of the comparison, $u(R_K)$ and $u(R_{KL})$, were estimated taking correlations like the physical constants into account. If the air kerma standards of the CPHR were traceable to the PTB in addition the free air chamber correction factors used at PTB are correlated and this was taken into account.

5.1 Transfer chambers PTW 34069

Table 21. Air kerma rates used for the calibrations at PTB and CPHR

Quality Code	PTB $\dot{K}_a$ / mGy/min	CPHR $\dot{K}_a$ /mGy/min
WMH28	0.32	0.69
WMV28	5.37	12.5
CCRI 25 kV	89.0	86.1
CCRI 50 kVb	86.4	137.4

Table 22. Results obtained with the transfer chamber TM34069 S/N 198. (Calibration coefficients N_K are given in units of 10^6 Gy/C)

Quality Code	PTB N_K pre-comp	PTB N_K post-comp	PTB R_K pre / post	PTB N_K mean	PTB $u(N_K)$ %	CPHR N_K	CPHR $u(N_K)$ %	CPHR / PTB R_K	CPHR / PTB $u(R_K)$ %
WMH28	4.331	4.330	0.9998	4.331	0.35	4.250	0.69	0.9813	0.71
WMV28	4.426	4.425	0.9998	4.426	0.35	4.401	0.69	0.9944	0.71
CCRI 25 kV	4.626	4.648	1.0046	4.637	0.35	4.595	0.81	0.9909	0.88
CCRI 50 kVb	4.293	4.293	1.0001	4.293	0.35	4.311	0.81	1.0043	0.88

Table 23. Results obtained with the transfer chamber TM34069 S/N 199. (Calibration coefficients N_K are given in units of 10^6 Gy/C)

Quality Code	PTB N_K pre-comp	PTB N_K post-comp	PTB R_K pre / post	PTB N_K mean	PTB $u(N_K)$ %	CPHR N_K	CPHR $u(N_K)$ %	CPHR / PTB R_K	CPHR / PTB $u(R_K)$ %
WMH28	4.281	4.272	0.9981	4.277	0.35	4.196	0.69	0.9812	0.71
WMV28	4.402	4.399	0.9993	4.400	0.35	4.361	0.69	0.9911	0.71
CCRI 25 kV	4.609	4.627	1.0039	4.618	0.35	4.571	0.81	0.9898	0.88
CCRI 50 kVb	4.249	4.252	1.0007	4.251	0.35	4.273	0.81	1.0053	0.88

The pre- and post-comparison calibration coefficients deviate by less than 0.2% for three qualities but by about 0.4% for the CCRI 25 kV quality. The reason for this larger deviation could not be found. A value of 0.2% was considered as an additional contribution to the comparison uncertainty due to the chamber instability during the comparison period.

The ratios R_K(CPHR/PTB) obtained from the two transfer chambers were consistent within about 0.2%. The final results of the comparison for mammographic and low-energy x-ray qualities were calculated as the average ratios of the CPHR and the PTB calibration coefficients obtained with the two transfer chambers and are given in Table 24 and shown in Figure 1. It can be concluded that the level of agreement of the calibration coefficients of both laboratories is within the relative standard uncertainty of the comparison of less than about 1 % except for the quality WMH28 where the relative difference was about 1.9%. Searching for possible reasons of this discrepancy the CPHR found that the operator most probably used an aluminum filter, added in error, which was thicker than 2.0 mm. For this reason, the calibration coefficient was less than expected as the calibration coefficients decrease with increasing Al half-value layer. The CPHR improved their quality assurance procedure to avoid possible errors in adding filters in the future.

Table 24. Comparison results for mammographic and low-energy x-ray qualities

Quality Code	Consistency R_K(S/N 198)/ R_K(S/N 199)	**CPHR / PTB R_K**	**CPHR / PTB $u(R_K)$ / %**	D / u	$D / 2u$
WMH 28	1.0002	**0.9812**	**0.71**	2.64	1.32
WMV28	1.0034	**0.9928**	**0.71**	1.02	0.51
CCRI 25 kV	1.0011	**0.9904**	**0.88**	1.09	0.55
CCRI 50 kVb	0.9990	**1.0048**	**0.88**	0.54	0.27

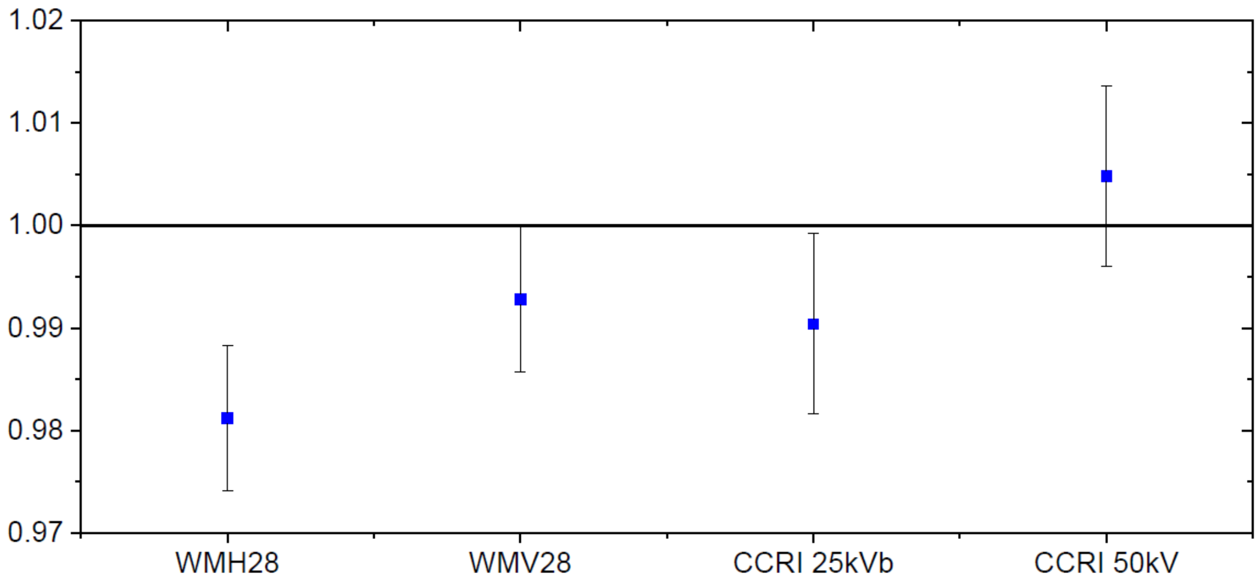

Figure 1. Ratios R_K and their uncertainties for the mammographic and low-energy x-ray qualities

5.2 Transfer chambers PTW 23361

The pre- and post-comparison calibration coefficients deviate in general by less than about 0.2%. This value was considered as an additional contribution to the comparison uncertainty due to the chamber instability. The final results of the comparison for these radiation qualities were calculated as the average ratios of the CPHR and PTB calibration coefficients obtained with the two transfer chambers and are given in Table 28 and shown in Figure 2.

It can be concluded that the level of agreement of the calibration coefficients of both laboratories is generally within about the relative standard uncertainty of the comparison of about 0.7 % for the diagnostic and therapy qualities and of about 0.9% for the radiation protection qualities.

Table 25. Air kerma rates used for the calibrations at PTB and CPHR

Quality Code	PTB $\dot{K}_a$ / mGy/min	CPHR $\dot{K}_a$ /mGy/min
RQR3	6.57	18.56
RQR5	6.15	31.6
RQR9	6.53	71.68
RQT8	6.55	23.62
RQT9	6.42	32.77
RQT10	6.44	50.13
F100	6.44	48.74
F135	6.50	47.22
N60	0.44	0.208
N100	0.45	0.051
N150	0.44	0.399

Table 26. Results obtained with the transfer chamber TM23361 S/N 712. (Calibration coefficients N_K are given in units of 10^5 Gy/C)

Quality Code	PTB N_K pre-comp	PTB N_K post-comp	PTB R_K pre / post	PTB N_K mean	PTB $u(N_K)$ %	CPHR N_K	CPHR $u(N_K)$ %	CPHR / PTB R_K	CPHR / PTB $u(R_K)$ %
RQR3	8.884	8.888	1.0004	8.886	0.34	8.947	0.62	1.0069	0.64
RQR5	8.802	8.805	1.0004	8.804	0.34	8.830	0.62	1.0030	0.64
RQR9	8.803	8.802	0.9999	8.802	0.34	8.827	0.62	1.0028	0.64
RQT8	8.794	8.794	1.0001	8.794	0.34	8.862	0.62	1.0078	0.64
RQT9	8.823	8.820	0.9997	8.821	0.34	8.902	0.62	1.0091	0.64
RQT10	8.841	8.840	0.9999	8.841	0.34	8.935	0.62	1.0106	0.64
F100	8.798	8.794	0.9995	8.796	0.34	8.810	0.63	1.0015	0.65
F135	8.819	8.814	0.9994	8.817	0.34	8.904	0.63	1.0099	0.65
N60	8.647	8.676	1.0034	8.662	0.34	8.730	0.84	1.0079	0.86
N100	8.964	8.968	1.0004	8.966	0.34	8.930	0.84	0.9959	0.86
N150	8.820	8.830	1.0012	8.825	0.34	8.819	0.84	0.9993	0.86

Table 27. Results obtained with the transfer chamber TM23361 S/N 713. (Calibration coefficients N_K are given in units of 10^5 Gy/C)

Quality Code	PTB N_K pre-comp	PTB N_K post-comp	PTB R_K pre / post	PTB N_K mean	PTB $u(N_K)$ %	CPHR N_K	CPHR $u(N_K)$ %	CPHR / PTB R_K	CPHR / PTB $u(R_K)$ %
RQR3	8.897	8.883	0.9985	8.890	0.34	8.925	0.62	1.0040	0.64
RQR5	8.812	8.803	0.9990	8.807	0.34	8.812	0.62	1.0006	0.64
RQR9	8.812	8.802	0.9989	8.807	0.34	8.810	0.62	1.0003	0.64
RQT8	8.804	8.797	0.9992	8.800	0.34	8.858	0.62	1.0065	0.64
RQT9	8.834	8.827	0.9992	8.830	0.34	8.903	0.62	1.0082	0.64
RQT10	8.860	8.852	0.9991	8.856	0.34	8.946	0.62	1.0102	0.64
F100	8.805	8.794	0.9988	8.800	0.34	8.810	0.63	1.0011	0.65
F135	8.833	8.824	0.9990	8.828	0.34	8.882	0.63	1.0061	0.65
N60	8.654	8.677	1.0026	8.666	0.34	8.716	0.84	1.0058	0.86
N100	8.984	8.979	0.9994	8.982	0.34	8.955	0.84	0.9970	0.86
N150	8.846	8.852	1.0006	8.849	0.34	8.877	0.84	1.0031	0.86

Table 28. Comparison results for diagnostic, radiation protection and medium-energy x-ray qualities

Quality Code	Consistency R_K(S/N 712)/ R_K(S/N 713)	**CPHR / PTB R_K**	**CPHR / PTB $u(R_K)$ %**	D / u	$D / 2u$
RQR3	1.0029	**1.0054**	**0.64**	0.84	0.42
RQR5	1.0024	**1.0018**	**0.64**	0.27	0.14
RQR9	1.0025	**1.0016**	**0.64**	0.24	0.12
RQT8	1.0012	**1.0071**	**0.64**	1.11	0.55
RQT9	1.0009	**1.0086**	**0.64**	1.34	0.67
RQT10	1.0004	**1.0104**	**0.64**	1.62	0.81
F100	1.0004	**1.0013**	**0.65**	0.20	0.10
F135	1.0038	**1.0080**	**0.65**	1.22	0.61
N60	1.0021	**1.0068**	**0.86**	0.80	0.40
N100	0.9989	**0.9965**	**0.86**	0.41	0.21
N150	0.9962	**1.0012**	**0.86**	0.14	0.07

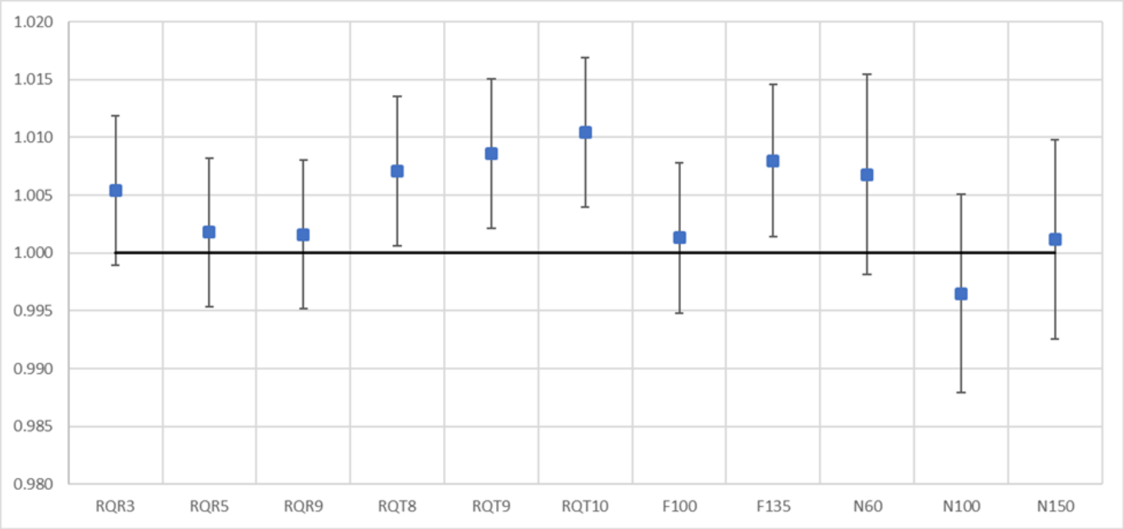

Figure 2. Ratios R_K and their uncertainties for the diagnostic, radiation protection and medium-energy x-ray qualities

5.3 Transfer chambers PTW 30009

The pre- and post-comparison calibration coefficients deviate by less than about 0.2%. This value was considered as an additional contribution to the comparison uncertainty due to the chamber instability. The final results of the comparison for these radiation qualities were calculated as the average ratios of the CPHR and PTB calibration coefficients obtained with the two transfer chambers and are given in Table 32 and shown in Figure 3.

It can be concluded that the level of agreement of the calibration coefficients in terms of air kerma-length product of both laboratories is well within the relative standard uncertainty of the comparison of about 1 %.

Table 29. Air kerma rates used for the calibrations at PTB and CPHR

Quality Code	PTB $\dot{K}_a$ / mGy/min	CPHR $\dot{K}_a$ /mGy/min
RQT8	21.9	23.4
RQT9	21.8	32.6
RQT10	21.6	49.8

Table 30. Results obtained with the transfer chamber TM30009 S/N 1287 (Calibration coefficients N_{KL} are given in units of 10^5 Gy m / C)

Quality Code	PTB N_{KL} pre-comp	PTB N_{KL} post-comp	PTB R_{KL} pre / post	PTB N_{KL} mean	PTB $u(N_{KL})$ %	CPHR N_{KL}	CPHR $u(N_{KL})$ %	CPHR / PTB R_{KL}	CPHR / PTB $u(R_{KL})$ %
RQT8	8.076	8.082	1.0008	8.079	0.69	8.150	0.82	1.0088	1.05
RQT9	8.150	8.157	1.0008	8.154	0.69	8.178	0.82	1.0030	1.05
RQT10	8.265	8.277	1.0015	8.271	0.69	8.308	0.82	1.0045	1.05

Table 31. Results obtained with the transfer chamber TM30009 S/N 1288 (Calibration coefficients N_{KL} are given in units of 10^5 Gy m / C)

Quality Code	PTB N_{KL} pre-comp	PTB N_{KL} post-comp	PTB R_{KL} pre / post	PTB N_{KL} mean	PTB $u(N_{KL})$ %	CPHR N_{KL}	CPHR $u(N_{KL})$ %	CPHR / PTB R_{KL}	CPHR / PTB $u(R_{KL})$ %
RQT8	8.078	8.095	1.0021	8.086	0.69	8.157	0.82	1.0088	1.05
RQT9	8.152	8.167	1.0018	8.160	0.69	8.198	0.82	1.0047	1.05
RQT10	8.269	8.280	1.0013	8.274	0.69	8.314	0.82	1.0048	1.05

Table 32. Comparison results of air kerma-length product for diagnostic x-ray qualities

Quality Code	Consistency R_K(S/N 1287)/ R_K(S/N 1288)	**CPHR / PTB R_{KL}**	**CPHR / PTB $u(R_{KL})$ / %**	D / u	D / 2u
RQT8	1.0000	**1.0088**	**1.05**	0.84	0.42
RQT9	0.9983	**1.0038**	**1.05**	0.37	0.18
RQT10	0.9997	**1.0046**	**1.05**	0.44	0.22

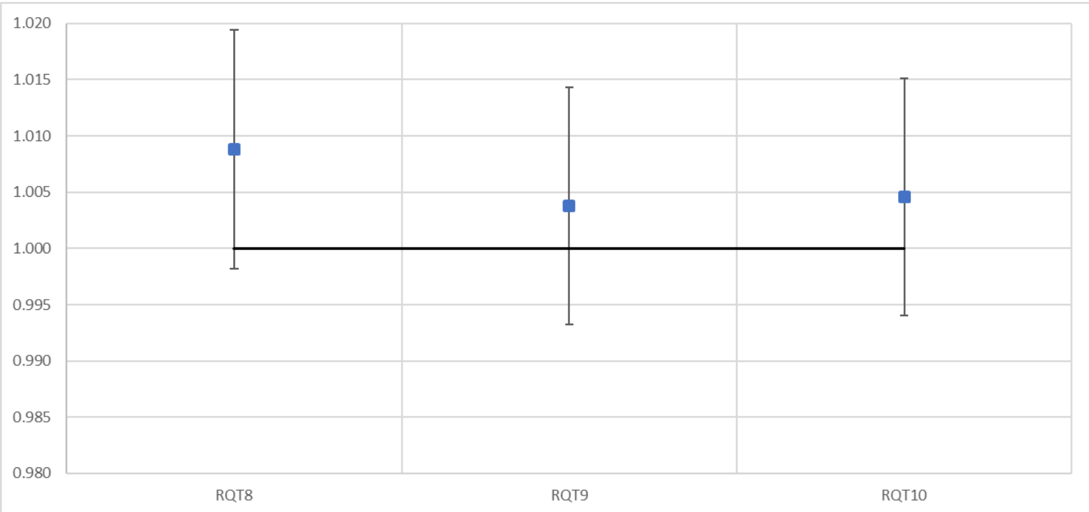

Figure 3. Ratios R_{KL} and their uncertainties for the diagnostic x-ray qualities

6. Summary and conclusion

A comparison of the air kerma standards for selected x-radiation qualities used in radiation protection, general diagnostic radiology, computed tomography, mammography and radiation therapy was performed between the PTB, Germany, and the CPHR, Cuba. Two plane-parallel (PTW 34069), two cylindrical (PTW 23361) and two pencil-type (PTW 30009) ionisation chambers provided by the PTB and 15 radiation qualities according to CCRI low- and medium-energy x-rays, IEC 61267 and ISO 4037 in the range of tube voltages between 25 kV and 150 kV were selected for the comparison. The calibration coefficients were determined for the transfer chambers at the CPHR in the period January to September 2017 and before (November 2016) and after (January 2018) at the PTB. The comparison results for the selected beam qualities expressed as the ratio of calibration coefficients were in the range (0.98-1.01). Most of the results are consistent within the standard uncertainty of the comparison (12 out of 18) which ranged between 0.6 % and 1 %. Five results were within the extended (*k*=2) standard uncertainty and one result deviated relatively by 1.9%. It was found that a wrong filtration was used at CPHR for the corresponding WMH28 mammographic radiation quality. A corrective action was taken to avoid this error in future.

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