Supplementary comparison of air kerma standards in ^{60}Co and ^{241}Am radiation beams for radiation protection, EURAMET.RI(I)-S19

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Abstract

A supplementary comparison of air kerma standards of five participating laboratories was carried out in ^{241}Am and ^{60}Co radiation beams at radiation protection level, from June 2024 to January 2025. Three of the participating laboratories are secondary standards laboratories (DSA, STUK, and SSM) and NPL and CIEMAT are primary standards laboratories, with NPL providing the reference values for the comparison. The comparison results are published in the BIPM key comparison database (KCDB) under the reference EURAMET.RI(I)-S19. The comparison was made indirectly using two ionization chambers as transfer instruments. The results are analysed and presented in terms of ratios of the calibration coefficients provided by the participants with respect to the comparison reference values.

1. Introduction

The National Metrology Laboratories for dosimetry quantities of Finland (STUK, Radiation and Nuclear Safety Authority), Norway (DSA, Norwegian Radiation and Nuclear Safety Authority), Spain (CIEMAT, Spanish National Metrology Institute for Ionising Radiation), Sweden (SSM, Swedish Radiation Safety Authority) and the United Kingdom of Great Britain and Northern Ireland (NPL, National Physical Laboratory) have performed a comparison in terms of air kerma in ^{241}Am and ^{60}Co radiation fields. NPL and CIEMAT are primary standards laboratories (PSDLs), with NPL providing the reference value. The other participating laboratories are secondary standards laboratories (SSDLs). STUK acted as the measuring pilot laboratory and SSM as the reporting pilot laboratory.

Three transfer chambers, two spherical Exradin A6 ionisation chambers and one PTW TN32003 (10 liter) chamber, were circulated among the participants, and each laboratory reported calibration coefficients and uncertainty budgets for those chambers in terms of air kerma. During the circulation of the chambers, the Exradin A6 XQ152602 chamber was found to be defective. The defect expressed itself as a high and unstable leakage (between 10 - 100 times normal leakage). Therefore, the results from XQ152602 have not been taken into consideration and the results are presented for the other two chambers.

The objective of the comparison is to support the ionising radiation CMCs of SSM, DSA, STUK, and CIEMAT in the dosimetry branch for the quantities of air kerma/rate from a ^{241}Am and ^{60}Co source at radiation protection levels. CIEMAT was not participating in the ^{241}Am comparison.

The detailed technical protocol is available in the KCDB under the reference EURAMET.RI(I)-S19.

2. Comparison procedure

2.1 Participants and measurement schedule

Five participants, listed in table 1, were included in the ^{60}Co comparison and four of them in the ^{241}Am comparison. NPL provided the comparison reference values. STUK and SSM shared responsibilities as pilot laboratories: STUK acting as measuring pilot laboratory and SSM acting as the reporting laboratory. STUK performed measurements at the beginning, in the middle and at the end of the comparison to confirm the stability of the transfer chambers.

Table1. Participants of the comparison, their traceability and the measurement schedule.

Institute, country	Contact person	Comment	Traceability, type of standard	Measuring period
STUK	Jussi Huikari	Pilot, measurements	^{60}Co PTB, secondary ^{241}Am NPL, secondary	June-August 2024
DSA	Per Otto Hetland		^{60}Co IAEA, secondary ^{241}Am VSL (via ISO N-80 X-ray quality), secondary	August-September 2024
NPL	Martin Kelly	Reference value	NPL, primary	October 2024
STUK, stability check				October 2024
SSM	Linda Persson	Pilot, reporting	^{60}Co BIPM, secondary ^{241}Am NPL, secondary	October 2024
CIEMAT	Néstor Armando Cornejo Díaz	Only ^{60}Co	CIEMAT, primary	December 2024
STUK, stability check				13-17 January 2025

2.2 Transfer instruments

Two reference ionisation chambers, Exradin A6 and PTW TN32003, were used as transfer instruments for this comparison. The Exradin A6 chamber is the property of STUK and the PTW TN32003 chamber is the property of SSM, and they had not been calibrated outside STUK and SSM before this comparison. The laboratories used their own electrometers and cables for performing the measurements during the comparison. The technical details of the transfer chambers are presented below (table 2).

Table 2. Technical details of the transfer chambers

Chamber type	**EXRADIN A6 Ref. 92716**	**PTW TN32003**
Serial number	XQ200282	000296
Geometry	spherical	spherical
Wall material	C552	POM (polyoxymethylene)
Wall thickness [mm]	3.0	3.0
External diameter / mm	120	276
Nominal volume / cm^3	800	10000
Reference point for the air kerma measurements	Geometric centre of the chamber	Geometric centre of the chamber
Polarising voltage of the chamber	+400 V on collector (central) electrode, 0 V on chamber wall (collecting negative charge) (if +400 V on collector is not available: -400 V on chamber wall, 0 V on collector electrode)	+400 V on collector (central) electrode, 0 V on chamber wall (collecting negative charge) (if +400 V on collector is not available: -400 V on chamber wall, 0 V on collector electrode)
Connector type	Triax BNC (male) (2 lug)	Triax BNC (male) (2 lug)

2.3 Radiation quality and reference conditions

The radiation qualities used in the comparison are ^{241}Am and ^{60}Co at radiation protection level. The quantity used for the comparison is the air kerma defined according to ICRU85a. The relevant data from ICRU90 has been used for the primary standards from participants in the comparison and for primary standards against which the secondary standards have been calibrated.

The radiation protection level radiation fields for ^{241}Am and ^{60}Co fulfil the standards ISO 4037-1:2019 (Annex B in case of ^{241}Am) and ISO 4037-2:2019. The reference point for the chambers is the geometric centre of the chambers. The chambers were placed free in air with the marking on the stem oriented towards the radiation source. The diameter of the radiation fields can for each participant be found in Appendix 1.

The calibration coefficients for the transfer chambers are corrected to standard conditions of air temperature and pressure; T = 293.15 K and P = 101.325 kPa. The measurements were performed with relative humidity between 38 % and 70 %; therefore, they were not corrected to the reference condition of 50 % RH. Each laboratory was using its own equipment to measure environmental conditions and ensuring traceability for those measurements.

2.4 Reference value

NPL provided the reference values for this comparison as a primary standards laboratory with all relevant CMC entries. All results were compared to these values. STUK and SSM are traceable to NPL for the ^{241}Am air kerma. None of the four laboratories is traceable to NPL for ^{60}Co air kerma.

Realization of the quantity is performed at NPL using their air kerma standards, based on graphite-walled cavity ionisation chambers as described in the respective reports (Bass GA. *et al.* 2019a and Bass GA. *et al.* 2019b).

For ^{60}Co at protection level, CIEMAT has recently implemented its own traceability based on the primary standard for ^{137}Cs (Cornejo, 2022 and Kessler C. *et al.*, 2024) and the use of a beam quality correction factor ($k_{Co,Cs}$) for a well-characterized secondary standard ionization chamber (Cornejo Díaz *et al.* 2024).

For determining calibration coefficients for the transfer chambers, NPL and CIEMAT proceeded as the other laboratories according to section 2.5 excluding the procedure for determining the reference air kerma/ air kerma rate.

2.5 Determination of the calibration coefficient of the transfer chamber

Each laboratory used their own procedure referring to international practices/guidance followed when performing the calibration.
Typically, for air kerma, the SSDLs establish a reference air kerma rate $\dot{K}_{air,lab}$ at their facilities in accordance with their own procedure following an equation such as:

$$\dot{K}_{\mathrm{air},lab} = N_{K,\mathrm{PSDL}} \cdot I_{lab} \qquad (1)$$

where $N_{K,\mathrm{PSDL}}$ is the calibration coefficient of the secondary standard used by a given laboratory in order to establish traceability to a primary standards laboratory for air kerma in ^{241}Am or ^{60}Co beams, and where I_{lab} is the ionisation current measured by the participant with the secondary standard at the reference calibration point. I_{lab} is corrected to standard conditions of air temperature and pressure, and, if needed, for relative humidity. For the other corrections to I_{lab} each laboratory proceeded according to their own procedure and may have included e.g. the electrometer correction factor, correction for leakage, correction for distance, correction for volume etc. All corrections used by the participants are reported in Appendix 1.
Each laboratory positioned the transfer chambers (see table 2) at the reference point, and the calibration coefficient for each transfer chamber, N_K, was calculated as:

$$N_{K,lab} = \frac{\dot{K}_{\mathrm{air},lab}}{I_{M,lab}} \qquad (2)$$

where $\dot{K}_{\mathrm{air},lab}$ is the reference air kerma rate from equation (1), and $I_{M,lab}$ is the ionization current measured by the laboratory with the transfer chamber. Like I_{lab}, $I_{M,lab}$ was corrected to standard conditions of air temperature and atmospheric pressure. The correction for the air relative humidity was not required, according to Section 2.3.

2.6 Ratios of the calibration coefficients

The ratios of the calibration coefficients are evaluated as follows for each participating laboratory, separately for each transfer chamber and beam quality:

$$R_{lab} = \frac{N_{K,lab}}{N_{K,\mathrm{NPL}}} \qquad (3)$$

where $N_{K,lab}$ is the calibration coefficient reported by the participating laboratory for a given transfer chamber and radiation quality, and $N_{K,\mathrm{NPL}}$ is the corresponding calibration coefficient provided by the NPL and adopted as reference in this comparison.

There were two transfer chambers, and for each of the two radiation qualities, the laboratory ratio of the calibration coefficients was calculated as the average of the ratios obtained with each of the transfer chambers:

$$R_{lab} = \frac{1}{2}\sum_{i=1}^{2}\frac{N_{K,lab,i}}{N_{K,\mathrm{NPL},i}} \qquad (4)$$

where $N_{K,lab,i}$ and $N_{K,\mathrm{NPL},i}$ are the calibration coefficients provided by the participating laboratory and the NPL, respectively, for transfer chamber i.

The variance of R_{lab}, denoted as $u_{R,lab}^2$, is calculated as the average of the variances of the calibration coefficient ratios obtained for each transfer chamber i, ($u_{R,lab,i}^2$):

$$u_{R,lab,i}^2 = (u_{lab}^2 + u_{\mathrm{NPL}}^2 - \sum_j f_j^2(u_{lab,j}^2))_i + u_{\mathrm{tr},i}^2 \qquad (5)$$

where u_{lab} is the combined standard uncertainty of the calibration coefficient reported by the participating laboratory; u_{NPL} is the combined standard uncertainty of the NPL's calibration coefficient ($N_{K,\mathrm{NPL}}$); u_{tr} is the uncertainty arising from the transfer chamber stability and f_j are the correlation factors related to the uncertainty components j that are correlated between the participating laboratory and the NPL. The physical constants involved in air kerma determinations by the primary standards laboratories have been considered to be fully correlated (f_j = 1), as well as all of the non-statistical components of u_{NPL} for those participating laboratories traceable to the NPL.

In equation (5), u_{tr} combines the stability of the transfer chambers over the period of the comparison. The measuring pilot laboratory STUK has performed several measurements for the transfer chamber.

The expanded uncertainty of R_{lab} is calculated as: $U_{lab} = 2\ u_{R,lab}$.

2.7 Correlated uncertainties for comparison ratios

Correlated uncertainties were analysed and excluded from the calculation of expanded uncertainties of the ratios of calibration coefficients. STUK and SSM are directly traceable to NPL for ^{241}Am air kerma. The component of the NPL calibration related to the primary standard measurement was removed in all cases where the laboratory is traceable to NPL, i.e. STUK and SSM for ^{241}Am air kerma. For all other cases, the correlated components related to the physical constants were removed.

3. Results

3.1 Transfer chamber stability and recombination

The transfer chambers were calibrated in terms of air kerma in ^{241}Am and ^{60}Co beams by STUK at the beginning, in the middle and at the end of the measurement round. In total, there were 7 (for ^{241}Am) and 10 (for ^{60}Co) stability check measurements for each of the transfer chambers. The standard uncertainty of the mean value for the transfer chamber, u_{tr}, was found to be 0.033% for the Exradin chamber and 0.075% for the PTW chamber, which shows that the chambers were stable during the measurement round.

The pilot laboratory did not apply corrections for lack of saturation of the circulated transfer chambers, using the information provided by the participating laboratories The corrections for lack of saturation are expected to be more significant for the PTW 32003 chamber with 10000 cm^3 collecting volume than for the Exradin A6 chamber (800 cm^3) considering the actual air kerma rates (both chambers are spherical and operated with the same polarizing voltage). For the PTW 32003 chamber, the nominal air kerma rate for a 99 % saturation current is 26 mGy/h, according to the user manual provided by the manufacturer. This value is significantly higher than the maximum value reported by the participants. Furthermore, taking into account previous studies done with the CIEMAT secondary standard ionisation chambers, the corrections for lack of saturation in case of the PTW 32003 chamber varied between 1.0019 and 1.0020 for ^{241}Am and between 1.0019 and 1.0032 for ^{60}Co, with an uncertainty of 0.09 % (k = 1). The impact of the variation of these corrections, due to the volumetric component of the ion recombination (as consequence of air kerma rate variations between laboratories) would be negligible for ^{241}Am and about 0.15 % (maximum variation) in the case of ^{60}Co. An uncertainty component to account for this non-corrected effect was included in the CIEMAT, NPL and SSM uncertainty budgets, for the transfer chambers. STUK and DSA consider the effect negligible.

3.2 Calibration coefficients and uncertainties

The calibration coefficients reported by the participating laboratories and their uncertainties are given in table 3 and 4 below. Detailed uncertainty budgets for each laboratory are given in Appendix 1.

Table 3. Reported calibration coefficients (Gy/C) for transfer chambers in terms of air kerma and their respective relative expanded uncertainties, U, (%), for ^{241}Am radiation quality.

Institute	**EXRADIN A6, Ref. 92716, serial number XQ200282**		**PTW TN32003, serial number 000296**	
	$N_{K,lab}$ **(Gy/C)**	U**(%),** k **= 2**	$N_{K,lab}$ **(Gy/C)**	U**(%),** k **= 2**
STUK	36820	4.33	3020	4.33
DSA	36527	1.74	3008	1.89
NPL	36880	2.04	3035	2.04
SSM	36870	2.10	3042	2.20

Table 4. Reported calibration coefficients (Gy/C) for transfer chambers in terms of air kerma and their respective relative expanded uncertainties, U, (%), for ^{60}Co radiation quality.

Institute	**EXRADIN A6, Ref. 92716, serial number XQ200282**		**PTW TN32003, serial number 000296**	
	$N_{K,lab}$ **(Gy/C)**	U**(%),** k **= 2**	$N_{K,lab}$ **(Gy/C)**	U**(%),** k **= 2**
STUK	36915	1.09	3025	1.09
DSA	36627	1.94	3012	2.33
NPL	36980	1.46	3032	1.46
SSM	36910	1.30	3030	1.40
CIEMAT	36785	1.40	3004	1.47

3.3 Final results of the comparison

The ratios of the calibration coefficients (R_{lab}) and their expanded uncertainties (U_{lab}, k = 2) were calculated according to equations 3-5. The following tables and figures (tables 5 and figure 1; and table 6 and figure 2), summarize the values of R_{lab} and U_{lab} obtained in this comparison by the participating laboratories for both radiation qualities.

Table 5. Ratios of calibration coefficients (R_{lab}) and their expanded uncertainties (U_{lab}) for participating laboratories in terms of air kerma for ^{241}Am radiation quality.

Institute	R_{lab}	U_{lab}, k = 2
STUK	0.997	0.047
DSA	0.991	0.028
NPL*	1.000	0.020
SSM	1.001	0.028

*for NPL, as providing the reference value, the expanded uncertainty is the reported uncertainty from NPL.

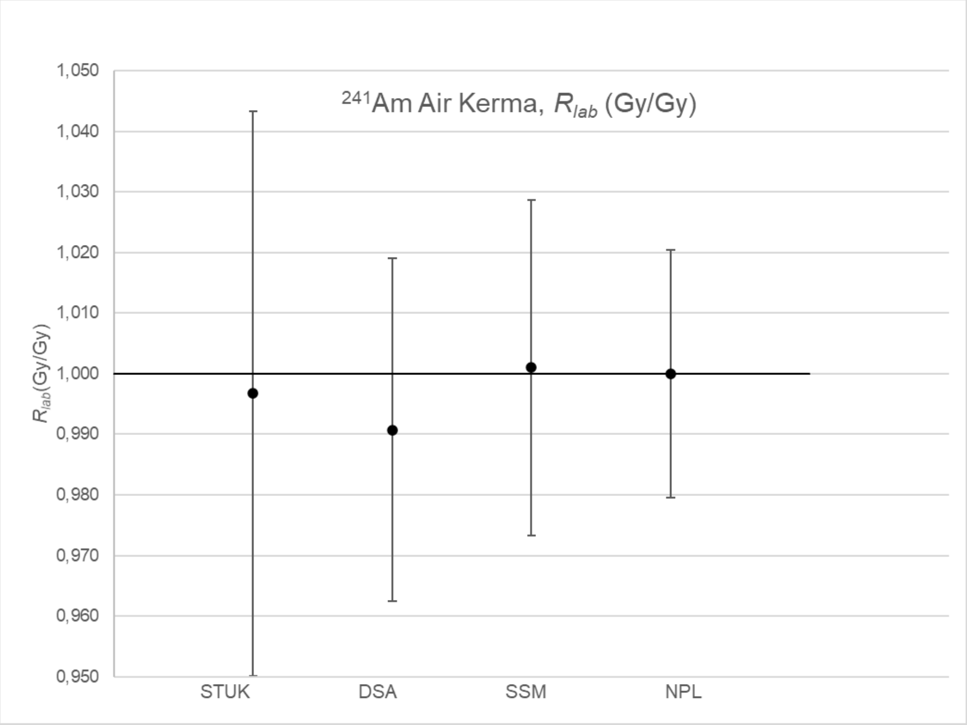

Figure 1. Graphical representation of the results in table 5: Ratios of calibration coefficients (R_{lab}) and their expanded uncertainties (U_{lab}, k = 2) for participating laboratories in terms of air kerma for ^{241}Am radiation quality.

Table 6. Ratios of calibration coefficients (R_{lab}) and their expanded uncertainties (U_{lab}) for participating laboratories in terms of air kerma for ^{60}Co radiation quality.

Institute	R_{lab}	U_{lab}, k = 2
STUK	0.998	0.018
DSA	0.992	0.026
NPL*	1.000	0.015
SSM	0.999	0.020
CIEMAT	0.993	0.020

*for NPL, as providing the reference value, the expanded uncertainty is the reported uncertainty from NPL.

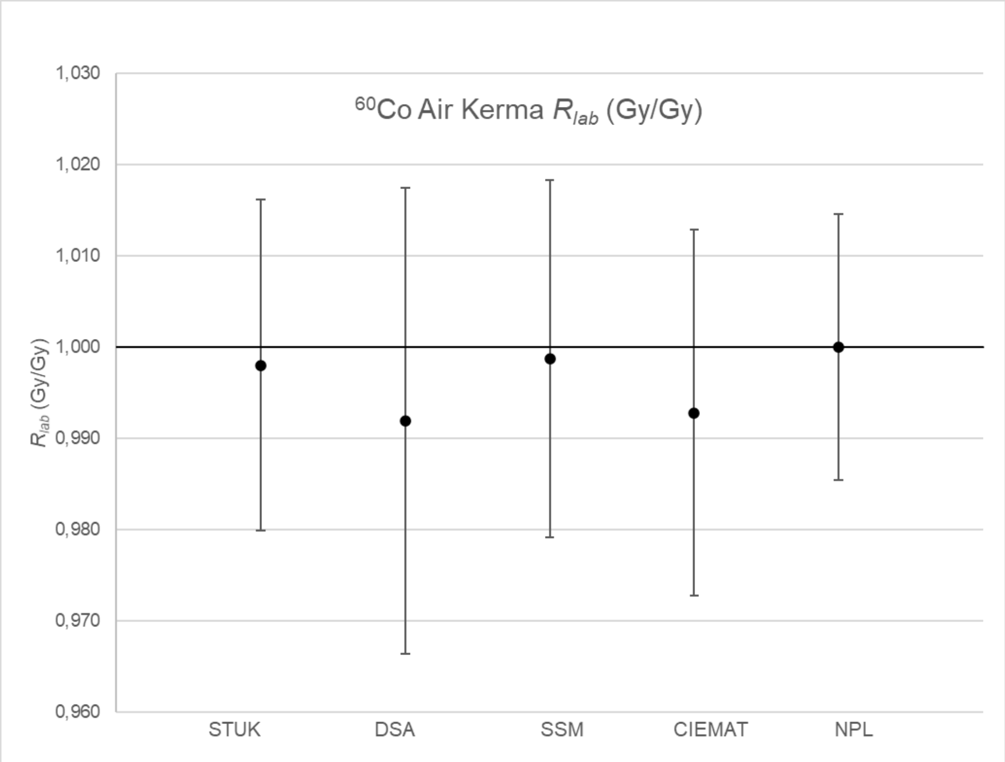

Figure 2. Graphical representation of the results in table 6: Ratios of calibration coefficients (R_{lab}) and their expanded uncertainties (U_{lab}, k = 2) for participating laboratories in terms of air kerma for ^{60}Co radiation quality.

4. Discussion and conclusions

A supplementary comparison in terms of air kerma for ^{241}Am and ^{60}Co radiation has been carried out between five laboratories using two ionisation chambers as transfer standards. The comparison started with three transfer chambers, but one transfer chamber was excluded due to excessive and unpredictable leakage currents. The comparison results of all participating laboratories are in agreement within the expanded uncertainties and support the CMCs of the participating laboratories. The values presented here are in good agreement with earlier comparison results of the participating laboratories.

5. References

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6. Appendix 1

Measurement results, uncertainty budgets and additional information for participating laboratories in the same order as the comparison measurements were performed:

STUK ^{241}Am

Chamber	EXRADIN A6 (XQ200282)	PTW 32003 (000296)
	N_{Kair}	N_{Kair}
Date of measurement	Aug 2024	Aug 2024
Calibration coefficient [Gy/C]	*36820*	3020
U (k = 2) [%]	4,33	4,33
mean ionization current [pA]	-0,032	-0,385
measured leakage current [fA]	-2,0	-12
Environmental conditions (T, p, h), is there correction for humidity?	20 °C, 100.8 kPa, 50% rh, no correction for humidity	20 °C, 100.8 kPa, 50% rh, no correction for humidity
Correction factors: k_{elec}	1,0041	1,0041

Background information	K_{air}
Radiation source	**Am-241**
Irradiator	Custom made
Field size	67 cm (95%)
Dose rate [mGy/s]	1,16E-09
SDD [cm]	200 cm
Reference standard (chamber + traceability)	PTW TM32002-0260, NPL
Electrometer (charge vs current, range + traceability)	Keithley 6517B 4132822, measuring charge, 20 nC, VTT MIKES (Finland 11/21)

Equation/model

NK=K(air)/((Itot-Ileak)*k(kTp)*k(elec))

Computation method (analytic or MC) and program model Analytic

Quantity Kair

Air kerma	Type A	Type B
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,85
Long term stability of reference standard		0,29
Spectral difference of SSDL and PSDL		0,29
Difference in radial non-uniformity of the beam and field size		0,29
Combined uncertainty of reference standard and setup	**0,00**	**0,99**
2 Use of reference standard		
Chamber positioning (distance, orientation)		
Current/charge measurement including leakage	0,05	1,340
Air temperature correction		0,057
Air pressure correction		0,007
Others (e.g. humidity of the measurement environment))		0,06
Combined uncertainty in measuring with reference standard	**0,05**	**1,34**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,05**	**1,666**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,05	1,340
Air temperature correction		0,057

Air pressure correction		0,007
Difference in radial non-uniformity of the beam and field size		0,29
Decay of Am-241		
Others (e.g. humidity in measurement environment)		0,06
Combined uncertainty in measuring with transfer chamber	**0,05**	**1,38**
Relative combined standard uncertainty (1+2+3)	**0,07**	**2,16**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**2,164**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**4,33**	
Confidence level (%)	95,3	

STUK ^{60}Co

Chamber	**EXRADIN A6 (XQ200282)**	**PTW 32003 (000296)**
	N_{Kair}	N_{Kair}
Date of measurement	Aug 2024	Aug 2024
Calibration coefficient [Gy/C]	*3,692E+04*	3,025E+03
***U* (*k* = 2) [%]**	**1,09**	**1,09**
mean ionization current [pA]	-100,30	-302,48
measured leakage current [fA]	-2,0	-12
Environmental conditions (T, p, h), is there correction for humidity?	20 °C, 100.8 kPa, 50% rh, no correction for humidity	20 °C, 100.8 kPa, 50% rh, no correction for humidity
Correction factors: k_{elec}	1,0041	1,0041

Background information	K_{air}
Radiation source	Co-60
Irradiator	Gemini
Field size	A6: 30 cm (98%) PTW: 60 cm (98%)
A6 Dose rate [mGy/s]	3,70E-06
A6 SDD [cm]	200 cm
PTW Dose rate [Gy/s]	9,15E-07
PTW SDD [cm]	400 cm
Reference standard (chamber + traceability)	PTW TM32002-0260, PTB
Electrometer (charge vs current, range + traceability)	Keithley 6517B 4132822, measuring charge, 20 nC, VTT MIKES (Finland, 11/21)

Equation/model
NK=K(air)/((Itot-Ileak)*k(kTp)*k(elec))

Computation method (analytic or MC) and program model — Analytic

Quantity — Kair

Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,375
Long term stability of reference standard		0,29
Spectral difference of SSDL and PSDL		0,03
Difference in radial non-uniformity of the beam and field size		0,06
Combined uncertainty of reference standard and setup	**0,00**	**0,478**
2 Use of reference standard		
Chamber positioning (distance, orientation)		
Current/charge measurement including leakage	0,05	0,124
Air temperature correction		0,06
Air pressure correction		0,01
Others (e.g. humidity of the measurement environment))		0,06
Combined uncertainty in measuring with reference standard	**0,05**	**0,15**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,05**	**0,501**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,05	0,124
Air temperature correction		0,057
Air pressure correction		0,007
Difference in radial non-uniformity of the beam and field size		0,06
Decay of Co-60		
Others (e.g. humidity in measurement environment)		0,06
Combined uncertainty in measuring with transfer chamber	**0,05**	**0,20**
Relative combined standard uncertainty (1+2+3)	**0,07**	**0,539**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,544**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,09**	
Confidence level (%)	95,3	

DSA ^{241}Am

Chamber	EXRADIN A6 (XQ200282)	PTW 32003 (000296)
	N_{Kair}	N_{Kair}
Date of measurement	04.09.2024 to 05.09.2024	2024-09-09
Calibration coefficient [µGy/nC]	*36,53*	3,008
U (k = 2) [%]	1,74	1,89
mean ionization current [A]	*-1,112E-12*	*-2,107E-12*
measured leakage current [A]	*-1,3E-14*	*-3,3E-14*
Environmental conditions (T, p, h), is there correction for humidity?	04.09: T=294.60 K, P=100.83 kPa, h=65%, no correction for humidity	09.09: T=294.15 K, P=98.38 kPa, h=68%, no correction for humidity
Environmental conditions (T, p, h), is there correction for humidity?	05.09: T=294.25 K, P=101.39 kPa, h=63%, no correction for humidity	09.09: T=294.17 K, P=98.28 kPa, h=70%, no correction for humidity
Correction factors: k_{elec}	Ref: 1.0009, UUT: 1.001	Ref: 1.0009, UUT: 1.001
Correction factors: kTP	04.09: Mean 1.010	09.09: Mean 1.033
Correction factors: kTP	05.09: Mean 1.003	09.09: Mean 1.035

Background information	K_{air}
Radiation source	**Am-241**
Irradiator	DIR101, Veenstra
Field size	24 cm for Exradin A6 chambers, 60 cm for the PTW chamber
Dose rate [µGy/h] 100.0 cm	145
Dose rate [µGy/h] 250.0 cm	22,4
SDD [cm]	100.0 for Exradin A6 chambers, 250.0 for the PTW chamber
Reference standard (chamber + traceability)	Exradin A6 XQ102232, VSL 2016, for N-80
Electrometer (charge vs current, range + traceability)	Keithley 6517A 0863876 and Keithley 6517A 0925329, measuring current, calibrated in-house and traceable to Justervesenet
other remarks	All currents and dose rates are referenced to 01.09.2024

Exradin A6 XQ200282

Quantity Kair

Air kerma	Type A	Type B
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,80
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,10
Combined uncertainty of reference standard and setup	**0,00**	**0,84**
2 Use of reference standard		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,10	
Air temperature correction		0,06
Air pressure correction		0,02

Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,14**	**0,07**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,14**	**0,84**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,10	
Air temperature correction		0,06
Air pressure correction		0,02
Difference in radial non-uniformity of the beam and field size		
Decay of Am-241		0,00
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,14**	**0,07**
Relative combined standard uncertainty (1+2+3)	**0,20**	**0,84**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,865**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,74**	
Confidence level (%)	95,3	

PTW TN32003, 000296

Quantity Kair

Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,80
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,10
Combined uncertainty of reference standard and setup	**0,00**	**0,84**
2 Use of reference standard		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,40	
Air temperature correction		0,06
Air pressure correction		0,02
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,41**	**0,07**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,41**	**0,84**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,06	
Air temperature correction		0,06
Air pressure correction		0,02
Difference in radial non-uniformity of the beam and field size		
Decay of Am-241		0,00
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,12**	**0,07**

Relative combined standard uncertainty (1+2+3)	**0,43**	**0,84**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,945**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,89**	
Confidence level (%)	95,3	

DSA ^{60}Co

Chamber	**EXRADIN A6 (XQ200282)**	**PTW 32003 (000296)**
	N_{Kair}	N_{Kair}
Date of measurement	04.09.2024 to 05.09.2024	09.09.2024 to 10.09.2024
Calibration coefficient [µGy/nC]	*36,63*	3,012
***U* (*k* = 2) [%]**	1,94	2,33
mean ionization current [pA]	*-1,267E-13*	*-2,509E-13*
measured leakage current [fA]	*-1,1E-14*	*-3,1E-14*
Environmental conditions (T, p, h), is there correction for humidity?	04.09: T=294.59 K, P=100.85 kPa, h=65%, no correction for humidity	09.09: T=294.17 K, P=98.34 kPa, h=69%, no correction for humidity
Environmental conditions (T, p, h), is there correction for humidity?	05.09: T=294.34 K, P=101.36 kPa, h=64%, no correction for humidity	10.09: T=294.64 K, P=97.66 kPa, h=47%, no correction for humidity
Correction factors: k_{elec}	Ref: 1.0009, UUT: 1.001	Ref: 1.0009, UUT: 1.001
Correction factors: kTP	04.09: Mean 1.010	09.09: Mean 1.034
Correction factors: kTP	05.09: Mean 1.004	10.09: Mean 1.043

Background information	K_{air}
Radiation source	**Co-60**
Irradiator	DIR101, Veenstra
Field size	24 cm for Exradin A6 chambers, 60 cm for the PTW chamber
Dose rate [µGy/h] 100.0 cm	15,3
Dose rate [µGy/h] 250.0 cm	2,4
SDD [cm]	100.0 for Exradin A6 chambers, 250.0 for the PTW chamber
Reference standard (chamber + traceability)	Exradin A6 XQ102232, IAEA 2023, for S-Cs and S-Co
Electrometer (charge vs current, range + traceability)	Keithley 6517A 0863876 and Keithley 6517A 0925329, measuring current, calibrated in-house and traceable to Justervesenet
other remarks	All currents and dose rates are referenced to 01.09.2024

Exradin A6 XQ200282

Quantity	Kair	
Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		

Calibration coefficient by PSDL		0,40
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,05
Difference in radial non-uniformity of the beam and field size		0,10
Combined uncertainty of reference standard and setup	**0,00**	**0,43**
2 Use of reference standard		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,60	
Air temperature correction		0,06
Air pressure correction		0,02
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,61**	**0,07**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,61**	**0,432**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,60	
Air temperature correction		0,06
Air pressure correction		0,02
Difference in radial non-uniformity of the beam and field size		
Decay of Co-60		0,00
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,61**	**0,07**
Relative combined standard uncertainty (1+2+3)	**0,86**	**0,44**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,965**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,94**	
Confidence level (%)	95,3	

PTW TN32003, 000296

Quantity	Kair	
Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,40
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,05
Difference in radial non-uniformity of the beam and field size		0,10
Combined uncertainty of reference standard and setup	**0,00**	**0,43**
2 Uncertainty in the determination of kerma at 2.5 m based on historical data and measurements at other distances and interpolation		
		1,00

Combined uncertainty in measuring with reference standard	**0,00**	**1,00**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,00**	**1,087**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)	0,10	
Current/charge measurement including leakage	0,40	
Air temperature correction		0,06
Air pressure correction		0,02
Difference in radial non-uniformity of the beam and field size		
Decay of Co-60		0,00
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,41**	**0,07**
Relative combined standard uncertainty (1+2+3)	**0,41**	**1,09**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**1,165**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**2,33**	
Confidence level (%)	95,3	

NPL ^{241}Am

Chamber	EXRADIN A6 (XQ200282)	PTW 32003 (000296)
	N_{Kair}	N_{Kair}
Date of measurement	04-Oct-24	04-Oct-24
Calibration coefficient [Gy/C]	*3,688E+04*	3,035E+03
U (k = 2) [%]	2,04	2,04
mean ionization current [pA]	-1,845	-5,743
measured leakage current [fA]	-9	36
Environmental conditions (T, p, h), is there correction for humidity?	T= 293.22 K (20.07C), p= 101.94 kPa, rh=50.2%, no correction for humidity	T= 293.22 K (20.07C), p= 101.94 kPa, rh=50.2%, no correction for humidity
Correction factors: k_{elec}	1,00	1,00

Background information	K_{air}	K_{air}
Radiation source	**Am-241**	**Am-241**
Irradiator	Mainance	Mainance
Field size (cm)	38,0	76,0
Dose rate [uGy/h]	242,9	62,56
SDD [cm]	100	200
Reference standard (chamber + traceability)	2551/053 via specially constructed graphite walled ionization chamber to NPL 300 kV PS FAC	2551/053 via specially constructed graphite walled ionization chamber to NPL 300 kV PS FAC
Electrometer (charge vs current, range + traceability)	Keithley 6517B measuring current, 20pA range, internal UKAS calibration	Keithley 6517B measuring current, 20pA range, internal UKAS calibration
other remarks- SNR	0,47%	-0,63%

Table 1 **Uncertainties in the primary standard factor**

Symbol	Quantity, source of uncertainty	Type A	Type B
$U_{FAC\text{-}METS}$	Uncertainties in the 300 kV primary standard FAC correction factors, measurement, and calibration of a medium energy transfer standard	-	0,66
$u_c(K_a)$	Combined standard uncertainty	0,66	

Table 2 **Uncertainties in the calibration of the low energy transfer standard**

Symbol	Quantity, source of uncertainty	Type A	Type B
$U_{METS\text{-}LETS}$	ME TS standard measurement uncertainty	-	0,66
k_{elec}	Electrometer current calibration (pA/'pA')	-	0,30
k_{res}	Electrometer resolution (nA)	-	0,03
k_{ion}	Ion recombination correction	0,05	-
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
$R_{angular}$	Angular response change	0,03	-
R	Repeatability	0,30	-

Interpolation of calibration factors and weighting for Am-241 spectra from N serires of x-ray qualities	Interpolation	-	0,2
$u_c(K_a)$	Combined standard uncertainty	0,82	

Table 3 **Uncertainties in calibration of a secondary standard**

Symbol	Quantity, source of uncertainty	Type A	Type B
K_a	Air kerma rate	-	0,82
k_{elec}	Electrometer current calibration (nA/'nA')	-	0,15
k_{res}	Electrometer resolution (nA)	-	0,03
$I_{leakage}$	Leakage current (A)	0,50	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
k_{dist}	Distance from source	-	0,05
k_{orient}	Orientation of chamber	-	0,01
R	Repeatability	0,50	-
$u_c(K_a)$	Combined standard uncertainty	1,10	
U	Expanded uncertainty (k=2)	2,19	

NPL ^{60}Co

Chamber	**EXRADIN A6 (XQ200282)**	**PTW 32003 (000296)**
	N_{Kair}	***N_{Kair}***
Date of measurement	04-Oct-24	04-Oct-24
Calibration coefficient [Gy/C]	*3,698E+04*	*3,032E+03*
***U* (*k* = 2) [%]**	1,46	1,46
mean ionization current [pA]	-57,45	-702,15
measured leakage current [fA]	3	63
Environmental conditions (T, p, h), is there correction for humidity?	T= 292.81 K (19.66C), p= 102.0 kPa, rh=50.6%, no correction for humidity	T= 292.76 K (19.61C), p= 102.0 kPa, rh=50.6%, no correction for humidity
Correction factors: k_{elec}	1,00	1,00

Background information	**K_{air}**
Radiation source	Co-60
Irradiator	Mainance
Field size (cm)	48,9
Dose rate [mGy/h]	7,58
SDD [cm]	300,00
Reference standard (chamber + traceability)	NPL primary standard via a specially constructed graphite walled transfer standard chamber
Electrometer (charge vs current, range + traceability)	Keithley 6517B, measuring current, 200pA/2nA range, internal UKAS calibration
other remarks	

Table 1	**Uncertainties in the primary standard factor**		
Symbol	Quantity, source of uncertainty	Type A	Type B
$\bar{S}_{air}^{graphite} \cdot k_{fl}$	Mass stopping power ratio (graphite to air) x fluence perturbation correction	-	0,08
$(\mu_{en}/\rho)_{graphite}^{air}$	Mass energy absorption coefficient ratio (air to graphite)	-	0,10
k_{wall}	Wall correction	-	0,10
$u_c(\tilde{F})$	Standard uncertainty	0,11	0,16
$u_c(\tilde{F})$	Combined standard uncertainty	0,20	
k_{an} x k_{rn}	Product of axial uniformity and radial uniformity correction factors	0,16	0,10
k_{stem}	Stem scatter correction	0,01	0,05
k_{pol}	Polarity correction	0,01	-
$u_c(F)$	Combined standard uncertainty	0,28	
(W_{air}/e)*	Energy per ion pair (J/C)	-	0,35
g	Fraction of energy lost by bremsstrahlung	-	0,02
k_h	Humidity correction	-	0,05
ρ_{air}	Density of dry air (kg/m^3)	-	0,01
V	Volume of cavity (cm^3)	-	0,01
$u_c(N_k)$	Combined standard uncertainty	0,28	

*Due to correlated uncertainties between the stopping power ratio and W_{air}/e, the uncertainty in W_{air}/e has been included in the combined uncertainty for the product $\bar{S}_{air}^{graphite} \cdot k_{fl}$

Table 2	**Uncertainties in the primary standard measurement**		
Symbol	Quantity, source of uncertainty	Type A	Type B
N_k	Total primary standard correction	-	0,28
k_{elec}	Electrometer current calibration (pA/'pA')	-	0,30
k_{res}	Electrometer resolution (nA)	-	0,03
k_{ion}	Ion recombination correction	0,05	-
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
$R_{angular}$	Angular response change	0,03	-
R	Repeatability	0,30	-
$u_c(K_a)$	Combined standard uncertainty	0,53	

Table 3	**Uncertainties in the calibration of the NPL transfer standard**		
Symbol	Quantity, source of uncertainty	Type A	Type B
K_a	Air kerma rate	-	0,53
k_{elec}	Electrometer current calibration (nA/'nA')	-	0,15
k_{res}	Electrometer resolution (nA)	-	0,03
k_{ion}	Ion recombination correction	0,05	-
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
k_{dist}	Distance from source	-	0,05
k_{orient}	Orientation of chamber	-	0,01
R	Repeatability	0,30	-
$u_c(N_k)$	Combined standard uncertainty	0,64	

Table 4 **Uncertainties in calibration of a secondary standard**

Symbol	Quantity, source of uncertainty	Type A	Type B
K_a	Air kerma rate	-	0,64
k_{elec}	Electrometer current calibration (nA/'nA')	-	0,15
k_{res}	Electrometer resolution (nA)	-	0,03
$I_{leakage}$	Leakage current (A)	0,10	-
p	Pressure (kPa)	0,02	-
T	Temperature (K)	0,04	-
k_{dist}	Distance from source	-	0,05
k_{orient}	Orientation of chamber	-	0,01
R	Repeatability	0,30	-
$u_c(K_a)$	Combined standard uncertainty	0,73	
U	Expanded uncertainty (k=2)	1,46	

SSM ^{241}Am

Chamber	EXRADIN A6 (XQ200282)	PTW 32003 (000296)
	N_{Kair}	N_{Kair}
Date of measurement	2024-11-15	2024-11-15
Calibration coefficient [Gy/C]	36870	3042
U (k = 2) [%]	2,1	2,2
mean ionization current [pA]	-1,08	-3,24
measured leakage current [fA]	2,3	-14,9
Environmental conditions (T, p, h), is there correction for humidity?	T=21,45°C, p=101,62 kPa, rh=44% no correction for humidity	T=21,48°C, p=101,34 kPa, rh=44% no correction for humidity
Correction factors: k_{elec}	1,00	1,00

Background information	K_{air}	
Radiation source	**Am-241**	
Irradiator	Veenstra DIR101	
Field size	FWHM= 40 cm	FWHM= 80 cm
Dose rate [mGy/s]	3,987E-05	9,854E-06
SDD [cm]	100	200
Reference standard (chamber + traceability)	Exradin A6 XQ023361, NPL 2020100174	
Electrometer (charge vs current, range + traceability)	Keysight B2987A-MY54321271, current measurements, 2E-12 och 2E-11 range, RISE 04/24	
other remarks	radiation field: ISO 4037	

Equation/model

$\Delta K_{1m}=\delta N_{k,PSDL}*\Delta I*\Delta k_{T,p}*\delta T*\delta k_{pos.jonk.1m,inmätning}*\delta k_{rek,1m}*\delta E_{PSDL}*\delta T_{1/2}*\delta k_{spridd}*\delta k_{fält}*\delta k_{stab}*\delta k_{spek}$

$\Delta K_{2m}=\delta N_{k,PSDL}*\Delta I*\Delta k_{T,p}*\delta T*\delta k_{pos.jonk.2m,inmätning}*\delta k_{rek,2m}*\delta E_{PSDL}*\delta T_{1/2}*\delta k_{spridd}*\delta k_{fält}*\delta k_{stab}*\delta k_{spek}$

$\Delta N_{k,1m}=\Delta K_{1m}*\delta k_{fält,instr,1m}*\delta k_{pos.instr,1m}*\Delta ITrans*\Delta k_{T,p}*\delta T*\delta A*\delta RH*\delta k_{pos.källa}*\delta M_{1m}*\delta T_{1/2}$

$\Delta N_{k,2m}=\Delta K_{2m}*\delta k_{fält,instr,2m}*\delta k_{pos.instr,2m}*\Delta ITrans*\Delta k_{T,p}*\delta T*\delta A*\delta RH*\delta k_{pos.källa}*\delta M_{Am,2m}*\delta T_{1/2}$

Computation method (analytic or MC) and program model analytic

Chamber EXRADIN A6 (XQ200282)

Quantity Kair

Air kerma	Type A	Type B
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,85
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,01
Combined uncertainty of reference standard and setup	**0,00**	**0,88**
2 Use of reference standard		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,340	0,020
Air temperature and pressure correction		0,04
Scattering		0,10

Uncertainty in half-life		0,14
Recombination		0,01
Temperature gradients		0,06
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,34**	**0,22**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,34**	**0,907**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,03	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life		0,14
Temperature gradients		0,06
Difference in radial non-uniformity of the beam and field size		0,30
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,03**	**0,37**
Relative combined standard uncertainty (1+2+3)	**0,34**	**0,98**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**1,038**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**2,08**	
Confidence level (%)	95,3	

Camber PTW 32003 (000296)

Quantity	Kair	
Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL		0,85
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,01
Combined uncertainty of reference standard and setup	**0,00**	**0,88**
2 Use of reference standard		
Chamber positioning (distance, orientation)		0,06
Current/charge measurement including leakage	0,500	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life		0,14
Recombination		0,01
Temperature gradients		0,06
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,50**	**0,20**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,50**	**0,901**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,06

Current/charge measurement including leakage	0,16	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life		0,14
Temperature gradients		0,06
Difference in radial non-uniformity of the beam and field size		0,20
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,16**	**0,28**
Relative combined standard uncertainty (1+2+3)	**0,53**	**0,94**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**1,081**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**2,17**	
Confidence level (%)	95,3	

SSM ^{60}Co

Chamber	**EXRADIN A6 (XQ200282)**	**PTW 32003 (000296)**
	N_{Kair}	N_{Kair}
Date of measurement	2024-11-15	2024-11-15
Calibration coefficient [Gy/C]	36910	3030
***U* (*k* = 2) [%]**	1,3	1,4
mean ionization current [pA]	-0,063	-0,192
measured leakage current [fA]	-2,0	-15,8
Environmental conditions (T, p, h), is there correction for humidity?	T=21,50°C, p=101,77 kPa, rh=44% no correction for humidity	T=21,41°C, p=100,37 kPa, rh=43% no correction for humidity
Correction factors: k_{elec}	1,00	1,00
Background information	K_{air}	
Radiation source	Co-60	
Irradiator	Veenstra DIR101	
Field size	FWHM= 40 cm	FWHM= 80 cm
Dose rate [mGy/s]	2,346E-06	5,832E-07
SDD [cm]	100	200
Reference standard (chamber + traceability)	Exradin A6 XQ040063, BIPM 2016	
Electrometer (charge vs current, range + traceability)	Keysight B2987A-MY54321271, current measurements, 2E-12 range, RISE 04/24	
other remarks	radiation field: ISO 4037	

Equation/model

$\Delta K_{1m}=\delta N_{k,PSDL}*\Delta I*\Delta k_{T,p}*\delta T*\delta k_{pos.jonk.1m,\text{inmätning}}*\delta k_{rek,1m}*\delta E_{PSDL}*\delta T_{1/2}*\delta k_{spridd}*\delta k_{\text{fält}}*\delta k_{stab}*\delta k_{spek}$

$\Delta K_{2m}=\delta N_{k,PSDL}*\Delta I*\Delta k_{T,p}*\delta T*\delta k_{pos.jonk.2m,\text{inmätning}}*\delta k_{rek,2m}*\delta E_{PSDL}*\delta T_{1/2}*\delta k_{spridd}*\delta k_{\text{fält}}*\delta k_{stab}*\delta k_{spek}$

$\Delta N_{k,1m}=\Delta K_{1m}*\delta k_{\text{fält},instr,1m}*\delta k_{pos.instr,1m}*\Delta ITrans*\Delta k_{T,p}*\delta T*\delta A*\delta RH*\delta k_{pos.\text{källa}}*\delta M_{1m}*\delta T_{1/2}$

$\Delta N_{k,2m}=\Delta K_{2m}*\delta k_{fält,instr,2m}*\delta k_{pos.instr,2m}*\Delta ITrans*\Delta k_{T,p}*\delta T*\delta A*\delta RH*\delta k_{pos.källa}*\delta M_{Am,2m}*\delta T_{1/2}$

Computation method (analytic or MC) and program model analytic

Chamber EXRADIN A6 (XQ200282)

Quantity Kair

Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL	0,11	0,13
Long term stability of reference standard		0,10
Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,01
Combined uncertainty of reference standard and setup	**0,11**	**0,26**
2 Use of reference standard		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,40	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life Co-60		0,00
Recombination		0,01
Temperature gradients		0,06
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,40**	**0,17**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,41**	**0,311**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,12
Current/charge measurement including leakage	0,02	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life Co-60		0,00
Temperature gradients		0,06
Difference in radial non-uniformity of the beam and field size		0,30
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,02**	**0,35**
Relative combined standard uncertainty (1+2+3)	**0,42**	**0,47**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,624**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,25**	
Confidence level (%)	95,3	

Chamber PTW 32003 (000296)

Quantity Kair

Air kerma	**Type A**	**Type B**
	Uncertainty (%)	
1 Reference standard, set-up and radiation field		
Calibration coefficient by PSDL	0,11	0,13
Long term stability of reference standard		0,10

Spectral difference of SSDL and PSDL		0,20
Difference in radial non-uniformity of the beam and field size		0,01
Combined uncertainty of reference standard and setup	**0,11**	**0,26**
2 Use of reference standard		
Chamber positioning (distance, orientation)		0,06
Current/charge measurement including leakage	0,50	0,020
Air temperature and pressure correction		0,04
Scattering		0,10
Uncertainty in half-life Co-60		0,00
Recombination		0,01
Temperature gradients		0,06
Others (e.g. humidity of the measurement environment))		0,02
Combined uncertainty in measuring with reference standard	**0,50**	**0,14**
Combined uncertainty in air kerma determination, K_{std} (1+2)	**0,51**	**0,294**
3 Use of transfer chamber		
Chamber positioning (distance, orientation)		0,06
Current/charge measurement including leakage	0,04	0,020
Air temperature and pressure correction		0,04
Scattering		0,30
Uncertainty in half-life Co-60		0,02
Temperature gradients		0,06
Difference in radial non-uniformity of the beam and field size		0,20
Others (e.g. humidity in measurement environment)		0,02
Combined uncertainty in measuring with transfer chamber	**0,04**	**0,37**
Relative combined standard uncertainty (1+2+3)	**0,51**	**0,48**
***U*, Total relative measurement uncertainty for the air kerma calibration coefficient, 1σ**	**0,700**	
***U*, Relative expanded measurement uncertainty, *k* = 2**	**1,40**	
Confidence level (%)	95,3	

CIEMAT ^{60}Co

Chamber	**EXRADIN A6 (XQ200282)**	**PTW 32003 (000296)**
Quantity	$\boldsymbol{N_{K\mathrm{air}}}$	$\boldsymbol{N_{K\mathrm{air}}}$
Date of measurements	27/11/2024 - 19/12/2024	02/12/2024 - 18/12/2024
Calibration coefficient [Gy/C]	**3,6785E+04**	**3,0042E+03**
U (k = 2) [%]	**1,40**	**1,47**
Mean ionization current [pA]	-4,059	-12,32
measured leakage current [fA]	2,00	5,00
Environmental conditions (T, p, h), is there correction for humidity?	T = 292,22 K (19,07 ºC), P = 94,69 kPa, h = 41,2 %. No correction applied for humidity.	T = 291,69 K (18,54 ºC), P = 94,46 kPa, h = 38,5 %. No correction applied for humidity.
Correction factors: k_{elec}	1,001 (HIGH, uncertainty included)	1,001 (HIGH, uncertainty included)
Other remarks:	-	-

Background information	$\boldsymbol{K_{\mathrm{air}}}$	
Radiation source	Co-60	
Irradiator	NI-646 (Nuclear Ibérica)	
Field size	Diameter: 36,8 cm	Diameter: 73,7 cm
Air Kerma rate [mGy/s]	1,4932E-04	3,6999E-05
SDD [cm]	150	300
Reference standard (chamber + traceability)	Graphite chambers CS-001 and SP-001 and secondary standards: 1-PTW 32005 (00047) and 2-PTW 32002 (00345). Traceability: CIEMAT	Graphite chambers CS-001 and SP-001 and secondary standards: 1-PTW 32005 (00047), 2-PTW 32002 (00345) and 3-PTW 32003 (00134). Traceability: CIEMAT
Electrometer (charge vs current, range + traceability)	PTW UNIDOS - T10002-20641 (Charge mode, range HIGH (22 nC), VSL (Nederlands 05/2024))	PTW UNIDOS - T10002-20641 (Charge mode, range HIGH (22 nC), VSL (Nederlands 05/2024))

Primary Reference (Measurement. Volume 188, 110374 (2022)) for 137-Cs with a beam quality correction factor ($k_{\mathrm{Co,Cs}}$) applied to the calibration coefficient of the secondary standard PTW 32002 (CIEMAT Report: DT-LMRI-2402).

$$\dot{K}_{\mathrm{air}} = \frac{I}{\rho_0 \cdot V_{\mathrm{col}}} \cdot \left(\frac{\overline{W}}{e}\right)_{\mathrm{air}} \cdot \left(\frac{\bar{S}_{\mathrm{el}}}{\rho}\right)_{\mathrm{c,air}} \cdot \left(\frac{\bar{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{air,c}} \cdot \frac{1}{(1-\bar{g}_{\mathrm{air}})} \cdot \prod_i k_i$$

$$\left\{\prod_i k_i = k_{PT} \cdot k_{\mathrm{h}} \cdot k_{\mathrm{dec}} \cdot k_{\mathrm{att}} \cdot k_{\mathrm{pos}} \cdot k_{\mathrm{pol}} \cdot k_{s} \cdot k_{\mathrm{st}} \cdot k_{\mathrm{wall}} \cdot k_{\mathrm{an}} \cdot k_{\mathrm{rn}} \cdot k_{\mathrm{SA}}\right\}$$

$$N_{K,\mathrm{Co}} = N_{K,\mathrm{Cs}} \, . \, k_{\mathrm{Co,Cs}}$$

EXRADIN A6 (XQ200282)

Table 1: Laboratory reference		
Quantity: Air Kerma rate (137-Cs)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Physical constants		
ρ_0 (dry air density)	-	0,01
$(\bar{W}/e)_{\mathrm{air}} \cdot (\bar{S}_{\mathrm{el}}/\rho)_{\mathrm{c,air}}$	-	0,13
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{air,c}}$ / $(1-\bar{g}_{\mathrm{air}})$	-	0,10
Quadratic summation	**0,00**	**0,16**
Chamber volume and Correction factors		
V_{col} (Chamber collection volume)	-	0,10
k_{PT} (air pressure and temperature)	-	0,07
k_{h} (humidity)	-	0,03
k_{dec} (source decay)	-	0,01
k_{att} (air attenuation)	-	0,03
k_{pos} (chamber positioning)	-	0,06
k_{pol} (effect of the polarizing voltage)	-	0,01
k_{s} (recombination losses)	0,01	0,02
k_{st} (stem scattering)	0,03	-
k_{wall} (wall effect)	0,01	0,10
k_{an} (axial non-uniformity)	0,05	0,03
k_{rn} (radial non-uniformity)	0,06	0,08
k_{SA} (Spencer-Attix theory)	-	0,10
Quadratic summation	**0,08**	**0,22**
Ionization current measurements		
Electrometer resolution	-	0,01
Leakage current	-	0,03
N_{el} (Electrometer calibration factor)	-	0,10
$f_{\text{non-lin}}$ (Linearity correction of the electrometer response)	-	
f_{tem} (rate of the electrometer timer)	-	0,10
Repeatability	0,02	
Quadratic summation	**0,02**	**0,14**
Reference Air Kerma rate		
Quadratic summation	**0,09**	**0,31**
Relative combined standard uncertainty, $u(\dot{K}_{\mathrm{air}})$	**0,32**	

Table 2: Uncertainties in the calibration of the CIEMAT secondary standard 1 (30 cm^3)		
Quantity: $N_{K,\,Cs}$ (Gy/C)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Reference air kerma rate	0,09	0,31
Measured current (including leakage)	0,01	0,12
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,03	-
Quadratic summation	**0,09**	**0,36**
Relative combined standard uncertainty, $u\,(N_{K,\,Cs})$	**0,37**	

Table 3: Uncertainties in the calibration of the CIEMAT secondary standard 2 (1000 cm^3)		
Quantity: Air Kerma rate (Obtained with the secondary standard 1)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the secondary standard 1, $N_{K,\,Cs}$	0,09	0,36
Measured current (including leakage correction)	0,02	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,02	-
Quadratic summation	**0,10**	**0,40**
Relative combined standard uncertainty, $u\,(\dot{K}_{\mathrm{air}})$	**0,41**	
Quantity: $N_{k,\,Co} = N_{K,\,Cs}\ x\ k_{Co,Cs}$ (Gy/C)		
Air kerma rate	0,10	0,40
Beam Quality correction factor, $k_{Co,Cs}$	-	0,40
Measured current (including leakage correction)	0,01	0,12
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,09	-
Quadratic summation	**0,13**	**0,59**
Relative combined standard uncertainty, $u\,(N_{K,\,Co})$	**0,61**	

Measurements in 60-Co beam		
Table 4: Uncertainties in the calibration of the transfer chamber (EXRADIN A6 (XQ200282))		
Quantity: Air Kerma rate (Obtained with the secondary standard 2)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the secondary standard 2, $N_{K,\,\mathrm{Co}}$	0,13	0,59
Measured current (including leakage correction)	0,02	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,08
Radial non-uniformity correction	-	0,10
Repeatability	0,06	-
Quadratic summation	**0,15**	**0,62**
Relative combined standard uncertainty, $u(\dot{K}_{air})$	**0,64**	
Quantity: $N_{K,\,\mathrm{Co}}$ (Gy/C)		
Air kerma rate	0,15	0,62
Measured current (including leakage correction)	0,02	0,12
Ion recombination	-	0,15
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,08
Radial non-uniformity	-	0,15
Repeatability	0,11	-
Quadratic summation	**0,18**	**0,67**
Relative combined standard uncertainty (1 σ), $u(N_{K,\,\mathrm{Co}})$	**0,70**	
Relative expanded uncertainty (k = 2), $U(N_{K,\,\mathrm{Co}})$	**1,40**	
Coverage probability (%)	**95**	

PTW 32003 (000296)

Table 1: Laboratory reference		
Quantity: Air Kerma rate (137-Cs)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Physical constants		
ρ_0 (dry air density)	-	0,01
$(\bar{W}/e)_{\mathrm{air}} \cdot (\bar{S}_{\mathrm{el}}/\rho)_{\mathrm{c,air}}$	-	0,13
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{air,c}}$ / $(1-\bar{g}_{\mathrm{air}})$	-	0,10
Quadratic summation	**0,00**	**0,16**
Chamber volume and Correction factors		
V_{col} (Chamber collection volume)	-	0,10
k_{PT} (air pressure and temperature)	-	0,07
k_{h} (humidity)	-	0,03
k_{dec} (source decay)	-	0,01
k_{att} (air attenuation)	-	0,03
k_{pos} (chamber positioning)	-	0,06
k_{pol} (effect of the polarizing voltage)	-	0,01
k_{s} (recombination losses)	0,01	0,02
k_{st} (stem scattering)	0,03	-
k_{wall} (wall effect)	0,01	0,10
k_{an} (axial non-uniformity)	0,05	0,03
k_{rn} (radial non-uniformity)	0,06	0,08
k_{SA} (Spencer-Attix theory)	-	0,10
Quadratic summation	**0,08**	**0,22**
Ionization current measurements		
Electrometer resolution	-	0,01
Leakage current	-	0,03
N_{el} (Electrometer calibration factor)	-	0,10
$f_{\mathrm{non\text{-}lin}}$ (Linearity correction of the electrometer response)	-	
f_{tem} (rate of the electrometer timer)	-	0,10
Repeatability	0,02	
Quadratic summation	**0,02**	**0,14**
Reference Air Kerma rate		
Quadratic summation	**0,09**	**0,31**
Relative combined standard uncertainty, $u(\dot{K}_{\mathrm{air}})$	**0,32**	

Table 2: Uncertainties in the calibration of the CIEMAT secondary standard 1 (30 cm^3)		
Quantity: $N_{k,\ Cs}$ (Gy/C)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Reference air kerma rate	0,09	0,31
Measured current (including leakage correction)	0,01	0,12
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,03	-
Quadratic summation	**0,09**	**0,36**
Relative combined standard uncertainty, $u\,(N_{K,\ Cs})$	**0,37**	

Table 3: Uncertainties in the calibration of the CIEMAT secondary standard 2 (1000 cm^3)		
Quantity: Air Kerma rate (Obtained with the secondary standard 1)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the secondary standard 1, $N_{K,\ Cs}$	0,09	0,36
Measured current (including leakage correction)	0,02	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,02	-
Quadratic summation	**0,10**	**0,40**
Relative combined standard uncertainty, $u\,(\dot{K}_{air})$	**0,41**	
Quantity: $N_{k,\ Co} = N_{K,\ Cs} \times k_{Co,Cs}$ (Gy/C)		
Air kerma rate	0,10	0,40
Beam Quality correction factor, $k_{Co,Cs}$	-	0,40
Measured current (including leakage correction)	0,01	0,12
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,06
Radial non-uniformity correction	-	0,10
Repeatability	0,09	-
Quadratic summation	**0,13**	**0,59**
Relative combined standard uncertainty, $u\,(N_{K,\ Co})$	**0,61**	

Measurements in 60-Co beam		
Table 4: Uncertainties in the calibration of the CIEMAT secondary standard 3 (10000 cm^3)		
Quantity: Air Kerma rate (Obtained with the secondary standard 2)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the transfer standard 2, $N_{K,\,Co}$	0,13	0,59
Measured current (including leakage correction)	0,02	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,08
Radial non-uniformity correction	-	0,10
Repeatability	0,06	-
Quadratic summation	**0,15**	**0,62**
Relative combined standard uncertainty, $u(\dot{K}_{air})$	**0,64**	
Quantity: $N_{k,\,Co}$ (Gy/C)		
Air kerma rate	0,15	0,62
Measured current (including leakage correction)	0,01	0,12
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,08
Radial non-uniformity	-	0,10
Repeatability	0,12	-
Quadratic summation	**0,19**	**0,65**
Relative combined standard uncertainty (1 σ), $u(N_{K,\,Co})$	**0,67**	

Table 5: Uncertainties in the calibration of the transfer chamber PTW 32003 (000296)		
Quantity: Air Kerma rate (Obtained with the secondary standard 3)		
Uncertainty components	**Type A**	**Type B**
	Uncertainty (%)	
Calibration coefficient of the secondary standard 3, $N_{K, Co}$	0,19	0,65
Measured current (including leakage correction)	0,03	0,11
Recombination correction	-	0,05
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,04
Radial non-uniformity correction	-	0,05
Repeatability	0,05	-
Quadratic summation	**0,20**	**0,66**
Relative combined standard uncertainty, $u(\dot{K}_{air})$	**0,69**	
Quantity: $N_{K, Co}$ (Gy/C)		
Air kerma rate	0,20	0,66
Measured current (including leakage correction)	0,01	0,12
Ion recombination	-	0,15
Atmospheric pressure correction	-	0,03
Air temperature correction	-	0,02
Humidity	-	0,03
Chamber positioning	-	0,04
Radial non-uniformity	-	0,10
Repeatability	0,08	-
Quadratic summation	**0,21**	**0,70**
Relative combined standard uncertainty (1 σ), $u(N_{K, Co})$	**0,73**	
Relative expanded uncertainty (k = 2), $U(N_{K, Co})$	**1,47**	
Coverage probability (%)	**95**	