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Measurement of air kerma in mammography beams

KEY COMPARISON

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APMP Key Comparison Report of Air Kerma Standards for Mammography X-Rays (APMP.RI(I)-K7)

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Abstract

The APMP/TCRI Dosimetry Working Group initiated the APMP.RI(I)-K7 key comparison of the air kerma standards for mammography X-rays, measurements took place between 2020 and 2023. In total, five institutes took part in the comparison. Two ionization chambers were used as transfer standards circulated among the participants. The results showed that the maximum difference between the participants and the Bureau International des Poids et Mesures (BIPM), evaluated using the comparison data of the linking laboratories of the National Institute of Metrology of China (NIM) and the National Metrology Institute of Japan (NMIJ), was less than 14.8 parts in 10^3 within the expanded uncertainty. This comparison supports the equivalence of the calibration capabilities of the participating laboratories.

1. Introduction

The National Institute of Metrology (NIM) was invited by the TCRI chair in 2020 to act as the coordinator of the APMP.RI(I)-K7 key comparison. Thus, from July 2020, NIM designed and delivered a questionnaire to each member laboratory to gauge their intentions with respect to this comparison. Table 1 gives information for the participating laboratories and contact persons for this APMP.RI(I)-K7 key comparison.

Table 1. Participating laboratories and contact persons for the APMP.RI(I)-K7 comparison

Participant	Institute	Economy	Contact person (E-mail)
1	NIM	China	GUO Siming (gsm@nim.ac.cn)
2	NMISA	South Africa	Sibusiso Jozela (sjozela@nmisa.org)
3	IAEA	International organization	Zakithi Msimang (Z.Msimang@iaea.org)

4	NMIJ	Japan	Takahiro Tanaka (takahiro-tanaka@aist.go.jp)
5	INER	Chinese Taipei	Huang Tseng-Te (huangtt@iner.gov.tw)

2. Procedure and protocol

2.1 Comparison methodology

In this comparison, there was a star-shaped circulation of the transfer chambers among the participants. Before the transfer chambers were delivered to the first participant, they were tested at the NIM to check that the chambers were stable. After being circulated to 1-2 participants, the chambers were sent back to the NIM for stability tests, which included a medium-energy X-rays (60 kV) air kerma measurement. Every participant was asked to provide air kerma calibration coefficients, N_K, and uncertainties $u(N_K)$ for each transfer standard, for each of the four X-ray beam qualities.

Two participating laboratories NIM and NMIJ that had completed the BIPM.RI(I)-K7 comparison with the Bureau International des Poids et Mesures (BIPM) were used to link the results to the BIPM Key Comparison Reference Value.

2.2 Transfer standards

Two ionization chambers were used as transfer instruments for this comparison study. These chambers were calibrated by each of the participating laboratories for several previously selected radiation qualities. The transfer instruments are used for this comparison were: RC6M(#10164), RC6M(#10257).

The main characteristics of the two transfer chambers are listed in Table 2. The collecting voltage stated in the table, consistent with the manufacturer specification, was applied to each chamber, and the equipment was allowed to settle during a warm-up period, according to local procedures, before starting the measurements.

Table 2. Main characteristics of the transfer chamber

Provider	Model	Serial number	Volume (cm^3)	HV (V)	Cable length (m)	Connector type
NIM	RC6M	10164	6	+300	10	TNC
NIM	RC6M	10257	6	+300	10	TNC

2.3 Reference conditions

The reference conditions for the chamber calibrations are as follows:

1). **Distance** from the focal spot to the reference plane (the positioning mark surface of the chamber): **600 mm.**

2). **Field size** at the reference plane: **8 cm in diameter**.

3)**. Air temperature, pressure and relative humidity** of $T = 293.15$ K, $P = 101.325$ kPa and $RH = 50\%$.

4). The calibration coefficients for the transfer chambers should be given in terms of air kerma per charge, in units of $\mathrm{Gy \cdot C^{-1}}$.

The air-kerma calibration coefficient N_K for the chamber is given by the equation: $N_K = \dot{K}/I_{tr}$.

Note: $\dot{K}$ is the air-kerma rate determined by the standard. I_{tr} is the ionization current measured by RC6M or the signal measured by transfer chamber. N_K is the calibration coefficients. All the measurements were corrected for standard environmental conditions of (T=293.15K, P=101.325 kPa and RH= 30%-70%).

The radiation qualities to be used for the comparison are the reference conditions recommended by the CCRI for the Mammography X-ray ranges (25 kV, 28 kV, 30 kV and 35 kV）, which are described in IEC61267 and TRS457. The four radiation qualities for calibration are indicated in Table 3.

Table 3. The radiation qualities for calibration

Radiation qualities(Mo/Mo)	Mo-25	Mo-28	Mo-30	Mo-35
Generating potential / kV	25	28	30	35
Additional filtration	30 μm Mo			
Reference distance / mm	600			

2.4 Schedule

After discussion with all participating laboratories, the comparison was scheduled to commence in November 2021 and was completed in March 2023. The total period for the chambers' delivery and calibration for each participant was about one month. Each participant was expected to measure the transfer chambers for no longer than 15 days. The comparison time schedule is shown in Table 4. Measurements at NIM throughout the comparison were used to assess the stability of the transfer standards which was considered in the data analysis.

Table 4. Schedule for the APMP.RI(I)-K7 comparison

Participant	Measurement period at the laboratory	Date of chambers leaving participant for next participant
Pilot(NIM)	21-Nov-2021 to 9-Dec-2021	10-Dec-2021
NMISA	24-Feb-2022 to 10-Mar-2022	20-Mar-2022
Pilot(NIM)	11-Apr-2022 to 10-May-2022	15-May-2022
IAEA	6-Jun-2022 to 14-Jun-2022	20-Jun-2022
NMIJ	12-Aug-2022 to 26-Aug-2022	30-Aug-2022
Pilot(NIM)	19-Sept-2022 to 10-Oct-2022	11-Oct-2022
INER	20-Oct-2022 to 29-Oct-2022	1-Nov-2022
Pilot(NIM)	1-Feb-2023 to 25-Feb-2023	

2.5 Calibration results and uncertainty evaluations

Participants were requested to submit calibration and uncertainty evaluation results within a month of the calibrations. The format of these results could be identical to that normally used by the participating laboratories. The submission must include at least the air kerma calibration coefficients (Gy C^{-1}) of the transfer chambers, the air kerma rate of the radiation field (mGy s^{-1}), the calibration distance and the expanded uncertainty (with coverage factor k=2) of the calibration coefficients, and measurement conditions. To report the results, a MS-Excel worksheet was provided in which the information about the standard used by the participants was to be supplied.

All the laboratories were required to evaluate the uncertainty of calibration coefficients as Type A and Type B according to the criteria of the "Guide to The Expression of Uncertainty in Measurement” issued by the International Organization for Standardization (ISO)[1].

3. Evaluation of degrees of equivalence

The calculation of the degrees of equivalence follows reference[2-4]. This document describes the calculation of the ratio to the BIPM reference value, taking into account multiple transfer standards and multiple link laboratories. Both linking laboratories conducted indirect comparisons with the BIPM, and for this indirect case:

$$R_i = \frac{N_{K,i}}{N_{K,\mathrm{LINK}}} R_{\mathrm{LINK,BIPM}} = \frac{K_i / I_i}{K_{\mathrm{LINK}}^{\mathrm{reg}} / I_{\mathrm{LINK}}^{\mathrm{reg}}} \frac{K_{\mathrm{LINK}}^{\mathrm{inter}} / I_{\mathrm{LINK}}^{\mathrm{inter}}}{K_{\mathrm{BIPM}} / I_{\mathrm{BIPM}}} \qquad (1)$$

Here $N_{K,i}$ is the transfer chamber calibration coefficient for laboratory i which has been expanded on the right-hand side to its components K_i/I_i, the ratio of the air kerma rate to the ionization current of the transfer standard. The dot above K_i used to denote rate has been omitted to keep the notation simple.

Each linking laboratory has two instances of K_i $/I_i$: one in this regional comparison (superscript ‘reg’) and one in the ongoing BIPM intercomparison (superscript ‘inter’). The $R_{LINK,BIPM}$ is the ratio of the link laboratory in the corresponding BIPM international comparison (superscript ‘inter’), as described in the relevant comparison report for NIM[5] and NMIJ[6]. The linking ratios are given in Table 5.

Table 5. Key comparison ratios $R_{\mathrm{LINK,BIPM}}$ of air kerma for mammography x-rays beams for the NIM and NMIJ

Link Laboratory	Year of comparison	$R_{LINK,BIPM}$				Combined standard uncertainty
		Mo-25	*Mo-28*	*Mo-30*	*Mo-35*	
NIM	2018	1.0001	0.9996	1.0000	1.0002	0.0028
NMIJ	2020	0.9945	0.9956	0.9952	0.9957	0.0036

Following [2] the uncertainty in R_i is given by

$$u_{R,i}^2 = \left(u_i^2 + u_{\mathrm{BIPM}}^2 - \sum_j f_j^2 \left(u_{i,j}^2 + u_{\mathrm{BIPM},j}^2 \right) \right) + u_{\mathrm{tr}}^2 + u_{\mathrm{LINK}}^2 \qquad (2)$$

where u_i is the combined standard uncertainty in $N_{K,i}$ (not including a component for the long-term stability of the transfer standards), and u_{BIPM} is the combined standard uncertainty of the BIPM air kerma realization [5,6]. u_{tr} is the uncertainty arising from the transfer chamber; and the u_{LINK} represents the uncertainty arising from the linking mechanism. The summation contains those components $f_j\ u_{i,j}$ and $f_j\ u_{BIPM,j}$ which were correlated between laboratory i and the BIPM, with correlation factor f_j. The other terms are discussed in the following sections.

3.1 Estimates of u_{tr}

The uncertainty u_{tr} arises during the measurement of the transfer standards at each participating laboratory i. As such it is normally included in the estimate of u_i provided by the laboratory and so can be set to zero in Equation (2). However, there is additional information regarding the performance of the transfer standards. The pilot laboratory's stability tests can be used to confirm that the transfer standards are behaving as expected throughout the comparison, and the results included as u_{tr} if the variation is larger than expected.

The variation between the comparison ratios for the multiple transfer standards can be used to provide an alternative estimate of u_{tr}. Following [2] for the general case of n laboratories (i = 1 to n), p transfer chambers (j = 1 to p) and q linking laboratories (k = 1 to q), we obtain npq values $R_{i,j,k}$. For each laboratory, and each chamber, we first calculate the ratio $R_{i,j,k}$ to the BIPM reference value according to Equation (1), for each linking laboratory, resulting in q=2 ratios for each chamber. When the ratios for each linking laboratory are averaged over the p=3 chambers, the ratio of the laboratory dose to the BIPM dose is obtained, for each linking laboratory k:

$$R_{i,k} = \frac{\sum_j R_{i,j,k}}{p} \tag{3}$$

This approach allows us to estimate of the uncertainty arising from the transfer standards, $u_{\mathrm{tr},k}$, from the spread in the results for different chambers:

$$u_{\mathrm{tr}}^2 = \frac{\sum_j \left(R_{i,j,k} - R_{i,k}\right)^2}{p\left(p-1.4\right)} \tag{4}$$

This leads to q=2 values for $u_{\mathrm{tr,k}}$ for each laboratory. The use of p-1.4 rather than the usual p-1 is taken from [2]. We combined the two estimates $u_{tr,k=1}$ and $u_{tr,k=2}$ to obtain u_{tr} from $1/u^2_{tr} = 1/u^2_{tr,k=1} + 1/u^2_{tr,k=2}$. For some laboratories and beam qualities, these estimates were larger than the values determined from the laboratory uncertainty budgets, and so we chose to include the estimates from Equation 4 (for all laboratories).

3.2 Estimates of u_{LINK}

The uncertainty u_{LINK} covers the linking measurements, excluding the uncertainty of the BIPM calibration which is already included in u_{BIPM}. It includes statistical (Type A) uncertainties in K_{air} and I at the link (included twice, once for the BIPM international comparison and once for this regional comparison) and the combined uncertainty in the BIPM determination of current. The estimates for each link can be combined:

$$u^{2}_{LINK,combined} = \sum_{k} \frac{\mu^{2}_{LINK,k}}{q^{2}} \tag{5}$$

An alternative estimate of u_{LINK} can be obtained from the variation between the ratios calculated for the different linking laboratories. Still following [1], we average over the q=2 links to obtain the final result, R_{i}, as the unweighted mean of $R_{i,k}$:

$$R_{i} = \frac{R_{i,\mathrm{NIM}} + R_{i,\mathrm{NMIJ}}}{2} \tag{6}$$

And calculate the corresponding uncertainty:

$$u^{2}_{\mathrm{LINK}} = \frac{\sum_{k} \left(R_{i,k} - R_{i}\right)^{2}}{q\left(q-1.4\right)} \tag{7}$$

The best estimate of u_{LINK} is derived from Equation (5) or (7), whichever is the large. In this way, differences in the results for the two linking laboratories are taken into account if they are larger than expected from the statistical uncertainties included in Equation (5).

4. Results and discussion

4.1 Transfer chamber stability

The results of the transfer chamber constancy tests made in the 60 kV X-ray reference beam at the NIM are given in Figure 1. The standard deviation of the chamber response was 0.21% and 0.15% for the 10164 and 10257, respectively. From these values and the trend on the graphs, we conclude the transfer chambers behaved normally during this comparison.

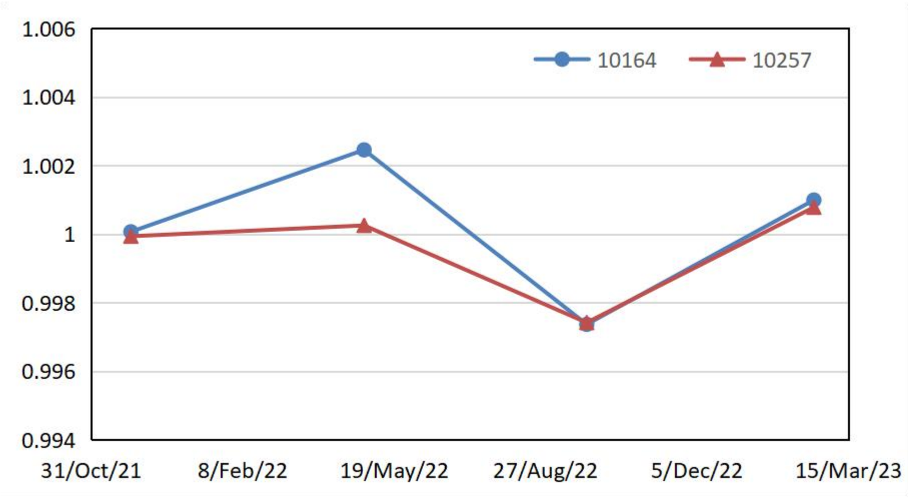

Figure 1. Stability results of transfer chamber measurements made at the NIM

4.2 Calibration coefficients and uncertainties

The calibration coefficients and uncertainty for transfer chambers are given in Table 6. Each laboratory chose to report the same relative uncertainty for two chambers.

Table 6. Reported Mo-25、28、30、35 calibration coefficients of the transfer chambers for the APMP RI(I)-K7 key comparison

Lab i	N_K/ Gy µC^{-1}								$u_i(N_K)$ (%)
	Radcal RC6M-10164				Radcal RC6M-10257				
	Mo-25	Mo-28	Mo-30	Mo-35	Mo-25	Mo-28	Mo-30	Mo-35	
NIM	4.742	4.737	4.738	4.738	4.663	4.660	4.665	4.663	0.47
NMISA	4.764	4.758	4.758	4.754	4.666	4.657	4.660	4.657	0.63
IAEA	4.743	4.737	4.736	4.734	4.663	4.659	4.660	4.660	0.59
NMIJ	4.744	4.743	4.742	4.743	4.662	4.661	4.659	4.661	0.53
INER	4.760	4.752	4.756	4.743	4.656	4.673	4.670	4.647	0.59

In the following analysis we have chosen to include the link laboratories NIM and NMIJ in the graphs and tables, even though the degrees of equivalence are not changed for the link laboratories. The ratio R_{NIM} has been evaluated using NMIJ as the link, and likewise R_{NMIJ} has been evaluated using NIM as the link, while all the other laboratories use the average of both. R_i and u_{LINK} were determined as shown in table 7 and table 8 based on the results of the 2 chambers. The u_{LINK} was estimated according to equation (7).

Table 7. R_i of the participating laboratories, calculated from the calibration coefficients of the two ionization chambers

Lab i	R_i							
	Radcal RC6M-10257				Radcal RC6M-10164			
	Mo-25	Mo-28	Mo-30	Mo-35	Mo-25	Mo-28	Mo-30	Mo-35
NIM	0.9949	0.9954	0.9964	0.9963	0.9941	0.9945	0.9944	0.9947
NMISA	0.9981	0.9970	0.9971	0.9968	1.0018	1.0013	1.0013	1.0009
IAEA	0.9973	0.9975	0.9972	0.9975	0.9974	0.9970	0.9967	0.9966
NMIJ	0.9997	0.9998	0.9988	0.9996	1.0005	1.0007	1.0008	1.0012
INER	0.9960	1.0003	0.9994	0.9946	1.0009	1.0002	1.0009	0.9986

Table 8. The average R_i and the u_{LINK}

	Ri				u_{LINK}(%)
	Mo-25	Mo-28	Mo-30	Mo-35	
NIM	0.9945	0.9949	0.9954	0.9955	0.33
NMISA	0.9999	0.9992	0.9992	0.9988	
IAEA	0.9974	0.9972	0.9970	0.9971	
NMIJ	1.0001	1.0003	0.9998	1.0004	
INER	0.9985	1.0003	1.0001	0.9966	

The uncertainty in the ratio to the BIPM Key Comparison Reference Value has been calculated following [1] from the uncertainty budgets of the participants, that of the BIPM and those of the linking comparison ratios. The results are given in Table 9. For this analysis we have used the uncertainty budgets which were submitted prior to the changes made following ICRU Report 90.

Table 9. Final result of the ratio $R_{i,\mathrm{BIPM}}$ and combined relative standard uncertainty u_{Ri} (Equation 2).

Participant	u_i(%)	u_{BIPM}(%)	u_c^* (%)	u_{tr} (%)	u_{LINK}(%)	$u_{R,i}$ (%)
NIM	0.47	0.39	0.31	0.14	0.33	**0.48**
NMISA	0.63	0.39	0.64	0.14	0.33	**0.74**
IAEA	0.59	0.39	0.47	0.14	0.33	**0.60**
NMIJ	0.53	0.39	0.39	0.14	0.33	**0.54**
INER	0.59	0.39	0.42	0.14	0.33	**0.55**

$$* u_{\mathrm{c}} = \sqrt{u_i^2 + u_{\mathrm{BIPM}}^2 - \sum_j f_j^2 \left(u_{i,j}^2 + u_{\mathrm{BIPM},j}^2\right)}$$

4.3 Degrees of equivalence

The ratios $R_{\mathrm{i,NIM}}$ and $R_{\mathrm{i,NMIJ}}$ obtained using Equation (3) are the unweighted mean for the two chambers. These are then averaged to get the final comparison result R_{i} for each laboratory relative to the Mo-25, Mo-28, Mo-30, Mo-35 kV beams.

The degree of equivalence, D_i, for each of n participating laboratories $i = 1$ to n (excluding the linking laboratories) is defined as the difference $D_i = R_i - 1$, and its expanded ($k = 2$) uncertainty $U_i = 2u_{R,i.}$, expressed in mGy/Gy.

The largest discrepancy between any of the laboratories and the BIPM is less than 0.5 % and in no case, the degree of equivalence is larger than the expanded uncertainty.

Table 10. Degrees of Equivalence for the APMP.R(I)-K7 comparison.

	Mo-25		Mo-28		Mo-30		Mo-35	
Lab i	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
	(mGy/Gy)		(mGy/Gy)		(mGy/Gy)		(mGy/Gy)	
NMISA	-0.1	14.8	-0.8	14.8	-0.8	14.8	-1.2	14.8
IAEA	-2.6	12.0	-2.8	12.0	-3.0	12.0	-2.9	12.0
INER	-1.5	11.0	0.3	11.0	0.1	11.2	-3.4	11.0

5. Conclusion

The key comparison APMP.RI(I)-K7 for the determination of air kerma in mammography x-ray beams has been carried out among 5 laboratories. Two chambers transfer standards were used among the laboratories and each laboratory was asked to provide calibration coefficients and associated uncertainties. The stabilities of the chambers were measured at NIM before and after the comparison and they were both shown to be well-behaved. The comparison results showed the calibration capabilities of all participating laboratories to be in general agreement within the stated uncertainties. Consequently, participants have been able to verify their measurement capabilities as well as strengthen technical cooperation and exchange ideas with other laboratories in the process of achieving a link to the BIPM.

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[8] IAEA TRS 457 Dosimeter in Diagnostic Radiology：An International Code of Practice

Appendix A

NIM Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		0.01
W/e		0.35
initial ionization and Energy dependence of Wair		0.06
scattered radiation		0.10
fluorescence		
electron loss		0.02
ion recombination	0.02	0.01
polarity correction	0.01	0.01
air attenuation kPa		0.15
electric field distortion		0.01
transmission through edges of diaphragm	0.02	0.03
scattering from diaphragm		
transmission through walls of standard		0.01
humidity		0.03
bremsstrahlung loss		0.01
measurement of air kerma rate		
temperature		0.04
pressure		0.01
volume	0.01	0.12
current measurement	0.02	0.01
position		0.10
Quadratic sum	0.04	0.43
Combined standard uncertainty	0.43	

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
temperature	0.01	0.04
pressure	0.01	0.01
humidity		
current measurement	0.01	0.01
monitor normalization	0.10	
air kerma		
short-term reproducibility		
position	0.01	0.10
Quadratic sum	0.10	0.11
Combined standard uncertainty	0.46	

NMISA Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		0.01
W/e		0.35
initial ionization and Energy dependence of Wair		
scattered radiation		
fluorescence		
electron loss		
ion recombination		
polarity correction		
air attenuation kPa		
electric field distortion		
transmission through edges of diaphragm		
scattering from diaphragm		
Chamber calibration (Nk)		0.50
Charge measurements	0.02	
Temperature calibration		0.17
Pressure calibration	0.01	
Electrometer resolution		0.02
Beam Stability		0.25
Chamber position		0.10
Barometer Res		0.01
Thermometer resolution		0.01
Electrometer charge Calibration (Kelec)		0.05
Quadratic sum	0.02	0.60
Combined standard uncertainty	0.60	

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
temperature		0.34
pressure	0.01	
humidity		
current measurement		
monitor normalization		
air kerma		
short-term reproducibility		
position		0.20
Quadratic sum	0.01	0.40
Combined standard uncertainty	0.72	

IAEA Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		
W/e		
initial ionization and Energy dependence of Wair		
scattered radiation		
fluorescence		
electron loss		
ion recombination		
polarity correction		
air attenuation kPa		
electric field distortion		
transmission through edges of diaphragm		
scattering from diaphragm		
transmission through walls of standard		
humidity		
bremsstrahlung loss		
measurement of air kerma rate		
Calibration from BIPM/PSDL		0.41
Long term stability of the secondary standard		0.29
Spectral difference PSDL/IAEA		0.17
Current measurement - Ref. Std.	0.05	0.10
Temperature and pressure correction - Ref. Std.		0.05
Current measurement - Monitor	0.05	0.10
Temperature and pressure correction - Monitor		0.05
Quadratic sum	0.07	0.55
Combined standard uncertainty	0.54	

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
Current measurement - User Chamber	0.05	0.10
Temperature and pressure correction - User Chamber		0.05
Current measurement - Monitor	0.05	0.10
Temperature and pressure correction - Monitor		0.05
Difference in radial non-uniformity of the beam		0.09
Chamber positioning		0.01
Quadratic sum	0.07	0.18
Combined standard uncertainty	0.59	

NMIJ Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		0.01
W/e		0.35
initial ionization and Energy dependence of Wair		0.15
scattered radiation		0.14
fluorescence		
electron loss		0.01
ion recombination		0.02
polarity correction		0.03
air attenuation kPa		0.15
electric field distortion		0.01
transmission through edges of diaphragm		0.01
scattering from diaphragm		0.02
transmission through walls of standard		0.01
humidity		0.02
bremsstrahlung loss		0.01
measurement of air kerma rate		
temperature		0.02
pressure		0.05
volume		0.12
current measurement	0.02	0.04
position		0.05
Quadratic sum	0.02	0.46
Combined standard uncertainty	0.46	

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
temperature		0.03
pressure		0.05
humidity		0.05
current measurement	0.11	0.04
monitor normalization		
Field inhomogeneity		0.06
Scattering photons		0.20
position		0.05
Quadratic sum	0.11	0.23
Combined standard uncertainty	0.53	

INER Uncertainty budget

Uncertainty associated with the standard

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
dry air density		0.01
W/e		0.35
initial ionization and Energy dependence of Wair		0.08
scattered radiation		0.07
fluorescence		
electron loss		0.07
ion recombination	0.18	
polarity correction		
air attenuation kPa		0.07
electric field distortion		
transmission through edges of diaphragm		
scattering from diaphragm		
transmission through walls of standard		
humidity		0.1
bremsstrahlung loss		
measurement of air kerma rate		
temperature		0.02
pressure		0.05
volume		0.12
current measurement		0.24
position		0.03
Quadratic sum	0.18	0.48
Combined standard uncertainty	0.52	

Uncertainty associated with the calibration of the transfer chambers

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
temperature		0.02
pressure		0.05
humidity		
current measurement	0.27	
monitor normalization		
air kerma		
short-term reproducibility		
position		0.03
Quadratic sum	0.27	0.07
Combined standard uncertainty	0.59	