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SIM.RI(I)-K3 Comparison of Calibration Coefficients at Radiotherapy Level for Orthovoltage X-ray Beams

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Final Report

Pilot laboratory: NIST

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Abstract

Air-kerma calibration coefficients were compared at the radiotherapy level for orthovoltage x-ray beams in the SIM.RI(I)-K3 comparison for members of the Sistema Interamericano de Metrología (SIM). Five SIM laboratories participated in the comparison: NIST, NRC, ININ, CNEA and LNMRI, the NIST being the pilot laboratory. Results from the comparison are linked to the BIPM.RI(I)-K3 key comparison reference value through the NIST-BIPM comparison made in 2003 and will meet requirements of the Mutual Recognition Arrangement (MRA) to support several CMCs (calibration and measurement capability claims) of the participants. The comparison began in October of 2007 and the measurements were completed in September 2008. The results reveal the degree to which the participating calibration facility can demonstrate proficiency in transferring air-kerma calibrations under the conditions of the said facility at the time of the measurements. The evaluation of the degrees of equivalence was performed as described in the comparison protocol. The comparison of the calibration coefficients for the four chambers is based on the average ratios of the calibration coefficients measured at the NIST and at each participating laboratory.

Key Words: air kerma; free-air ionization chamber; primary standard; reference radiation qualities; x-rays; x-ray calibration; transfer standard;

1. Introduction

The objective of this international comparison SIM.RI(I)-K3 was to compare the calibration coefficients at radiotherapy level for orthovoltage x-ray beams for members of the Sistema Interamericano de Metrología (SIM). The SIM laboratories that participated are the NIST (USA), the NRC (Canada), the CNEA (Argentina), the LNMRI (Brazil), and the ININ (Mexico); see Table 1 for the full institution names and the traceability for each secondary laboratory. Four NIST reference-class transfer ionization chambers of two different models were calibrated by each of the participating laboratories for four tungsten-anode reference radiation qualities of energies between 100 kV and 250 kV. The reference radiation qualities are recommended by the Consultative Committee for Ionizing Radiation (CCRI(I)) [1]. The comparison project was proposed at the SIM MWG6 (Ionizing Radiation) in April 2007 by the CNEA. Results from the comparison are linked to the BIPM.RI(I)-K3 key comparison reference value (KCRV) through the NIST-BIPM comparison made in 2003 [2] and will meet requirements of the Mutual Recognition Arrangement (MRA) to support several CMC (calibration and measurement capability) claims of the participants. The NRC results are superseded by a later direct comparison with the BIPM in 2014. The evaluation of the degrees of equivalence was performed according to the method described by Burns and Allisy-Roberts [3]. The comparison of the calibration coefficients for the four chambers is based on the ratios of average calibration coefficients measured at the NIST and at each participating laboratory.

Table 1. Participants and their Source of Traceability

Participant	Country	Institute	Traceability
NIST	United States	National Institute of Standards and Technology	Maintains primary standard
NRC	Canada	Institute for National Measurement Standards National Research Council of Canada	Maintains primary standard
CNEA	Argentina	Centro Atómico Ezeiza (*National Atomic Energy Commission)*	BIPM
LNMRI	Brazil	Comissão Nacional de Energia Nuclear Laboratório Nacional de Metrologia das Radiações Ionizantes (*National Metrology Laboratory of Ionizing Radiation)*	BIPM
ININ	Mexico	Instituto Nacional de Investigaciones Nucleares (*National Institute for Nuclear Research*)	NIST

2. Procedure

2.1 Object of comparison

Four ionization chambers of two different models, all with volumes of approximately 0.6 cm^3, were calibrated against the national standards for air kerma. The calibration coefficient is $N_{K\text{air}} = K_{\text{air}} / I_{\text{corr}}$, where K_{air} is the air-kerma rate and I_{corr} is the measured ionization current corrected for influence quantities.

2.2 Transfer chambers

The transfer ionization chambers are Farmer-type: two are Exradin A12 and two are PTW 30010[1]. Both are thimble-type, fully guarded chambers. The A12 is made of Shonka air-equivalent plastic, including the electrode. The PTW chamber wall material is graphite with a protective acrylic cover, and the electrode is made of aluminum. The reference point for each chamber is the geometrical center of the volume. The chambers are aligned in the center of the beam with the white or black mark towards the radiation source. The A12 reference point is 12.9 mm from the tip of the chamber (on the chamber axis); the PTW reference point is 13 mm from the chamber tip. The chambers are positioned so that the beam axis is perpendicular to the chamber axis. The signal connection of the chambers is a triaxial BNC plug. The polarizing potential is applied such that the outer wall of the chamber is negative with respect to the collecting center electrode. The equilibrium, build-up caps have been shipped with the chambers for completeness but are not used for the x-ray beams for this comparison. No corrections for ion recombination are applied. A physical description of the transfer chambers follows in Table 2.

Table 2. Description of the Chambers

Type	Serial number	Sensitive volume (nominal) / cm^3	Outside diameter / mm	Diameter of inner electrode / mm	Chamber voltage / V
A12	XA071361	0.65	7.1	1.0	–300
A12	XA071362	0.65	7.1	1.0	–300
PTW30010	TN30010-0613	0.6	6.95	1.1	–400
PTW30010	TN30010-0614	0.6	6.95	1.1	–400

2.3 Reference radiation qualities

The primary air-kerma determination at the NIST forms the basis of the reference value for the comparison. The measurements were made using the Wyckoff-Attix free-air chamber in the NIST medium-energy calibration facility. The x-ray source at the time of the comparison was a 320 kV x-ray generator with a metal-ceramic x-ray tube. The x-ray generator is a high-frequency, highly stabilized voltage source. The tungsten-anode x-ray tube has a beryllium window of thickness 3 mm and a focal spot 8.0 mm in diameter. The materials used for the filtration and for the measurement of HVL were at least 99.99 % pure with thicknesses known with an uncertainty of 0.01 mm.

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement, nor does it imply that the equipment identified are necessarily the best available for the purpose.

The reference radiation qualities used for the comparison, listed in Table 3, are those recommended by the Consultative Committee for Ionizing Radiation[1] and implemented at the BIPM for the ongoing x-ray comparison series BIPM.RI(I)-K3. NIST conducted a comparison [2] with the BIPM using these reference radiation qualities.

Table 3. Reference Radiation Qualities

Generating tube potential / kV	Half-value layer / mm Cu
100	0.15
135	0.5
180	1.0
250	2.5

2.4 Reference conditions and measurements at the NIST

The reference measurements at the NIST serve to establish the stability of the transfer chambers. Each calibration at the NIST was made by alternating between the transfer chambers and the standard free-air chamber, through the translation of the chambers to the beam center line. Beam alignment on the axis is estimated to be 0.1 mm and reproducible to better than 0.01 mm, as observed by an alignment telescope. The reference plane for all measurements was positioned at 1000 mm from the radiation source at the NIST. The beam diameter in the reference plane was 31 mm. Prior to the comparison the results from the 31 mm diameter beam were verified using a larger diameter beam.

The leakage current was measured before and after each series of ionization-current measurements and a correction made based on the mean of these leakage measurements. For all measurements the leakage current was less than 0.01 % of the ionization current. Each chamber was pre-irradiated for at least 1500 s. The settling time and behavior of both types of chambers appeared to be independent of the beam quality or kerma rate. For all chambers at the NIST an integration time of 60 s was used, and the current measurements were normalized to a temperature and pressure of 295.15 K (22 °C) and 101.325 kPa, respectively. The relative humidity is monitored and recorded and is typically in the range from 30 % to 40 %, however the currents are not corrected for humidity.

The participants were requested to provide the calibration coefficients for the transfer chambers in terms of air kerma per charge in units of Gy/C, referred to standard conditions of air temperature, pressure, and relative humidity of T = 295.15 K (22 °C), P = 101.325 kPa, and h = 50 %.

2.5 Course of comparison

The comparison was based on a star-shaped circulation of the chambers between the NIST and the participants. Table 4 shows the dates and location of the measurements. After completion of the calibrations at each facility, the NIST performed chamber-constancy checks. The initial request was for the chambers to stay at the participant's site for no longer than two weeks and for the results to be reported to the coordinator within four weeks of the calibration. A spreadsheet was provided by the NIST in which information about the radiation qualities at the participant's site and the calibration results were entered. The uncertainties were requested to be given in accordance with the ISO guide to the expression of uncertainties in measurements [4]. In addition to the completed spreadsheet, a complete uncertainty budget for the x-ray qualities included in the comparison was requested by the NIST.

Table 4. Dates of Measurements

Participant	Date chamber at participant	Date chamber at NIST
NRC	November 2007	December 2007
CNEA	February 2008	March 2008
LNMRI	April 2008	June 2008
ININ	June 2008	July 2008

3. Results

The measurements at the NIST were performed during June, July, October, November, and December of 2007, and during March, June, and July of 2008. The geometry and conditions of the air-kerma measurement as noted above remained unchanged for all NIST measurements. The NIST 300 kV primary standard for x-rays was used for each measurement. The mean values of the calibration coefficients measured at the NIST are shown in Table 5, where the stated uncertainties represent the standard deviation of the distribution of the repeat calibrations over the period of the comparison. For each chamber between 20 and 35 calibrations were obtained for each beam quality over the course of the comparison at NIST.

To allow the participants to use their routine "best-practice" setup procedures and geometry, the calibration conditions were not outlined in the technical protocol, which resulted in the use of different conditions at the various calibration facilities. These conditions are compared in Table 6, Table 7, and Table 8. The results for the calibration coefficients at each laboratory are shown in Table 9 through Table 12.

Table 5. Mean values ($\overline{N}_{\mathrm{K,NIST}}$) and relative standard deviations of the calibration coefficients measured at the NIST during the comparison

	PTW SN613		PTW SN614		Exradin SN71361		Exradin SN71362	
Tube voltage / kV	Mean N_K / 10^7 Gy C^{-1}	Std Dev / %	Mean N_K / 10^7 Gy C^{-1}	Std Dev / %	Mean N_K / 10^7 Gy C^{-1}	Std Dev / %	Mean N_K / 10^7 Gy C^{-1}	Std Dev / %
100	4.805	0.095	4.797	0.050	4.250	0.193	4.329	0.147
135	4.808	0.087	4.801	0.053	4.269	0.178	4.331	0.151
180	4.828	0.091	4.825	0.068	4.299	0.204	4.354	0.177
250	4.841	0.098	4.846	0.065	4.332	0.145	4.380	0.126

Table 6. Half-value layers of the reference radiation qualities maintained by each participant

Tube voltage / kV	1st HVL / mm Cu NIST	NRC	CNEA	LNMRI	ININ
100	0.15	4.022 (mm Al)	0.14	0.15	0.149
135	0.5	0.488	0.50	0.50	0.496
180	1	0.991	1.00	1.01	1.003
250	2.5	2.53	2.50	2.48	2.502

Table 7. Beam geometry used at each facility

	NIST	NRC	CNEA	LNMRI	ININ
Calibration distance / mm	1000	987.7	863	1000	1000
Beam diameter / mm	31	89	80	77	83

Table 8. Average air-kerma rates used at each facility

	Average Air-kerma Rate / Gy s^{-1}				
Tube voltage / kV	NIST	NRC	CNEA	LNMRI	ININ
100	1.0E-03	9.2E-04	5.2E-04	5.0E-04	9.2E-04
135	9.6E-04	9.3E-04	8.0E-04	5.1E-04	9.4E-04
180	1.2E-03	1.0E-03	8.9E-04	5.0E-04	1.2E-03
250	1.5E-03	8.1E-04	6.7E-04	5.1E-04	1.4E-03

Table 9. Calibration coefficient for the Exradin SN71361 from all participants

Tube voltage / kV	Exradin SN71361 Calibration Coefficients / 10^7 Gy C^{-1}			
	NRC	CNEA	LNMRI	ININ
100	4.237	4.202	4.210	4.139
135	4.265	4.279	4.248	4.189
180	4.291	4.325	4.284	4.230
250	4.320	4.362	4.328	4.269

Table 10. Calibration coefficient for the Exradin SN71362 from all participants

Tube voltage / kV	Exradin SN71362 Calibration Coefficients / 10^7 Gy C^{-1}			
	NRC	CNEA	LNMRI	ININ
100	4.310	4.279	4.278	4.212
135	4.321	4.335	4.304	4.248
180	4.339	4.372	4.334	4.291
250	4.362	4.404	4.371	4.319

Table 11. Calibration coefficient for the PTW SN613 from all participants

Tube voltage / kV	PTW 613 Calibration Coefficients / 10^7 Gy C^{-1}			
	NRC	CNEA	LNMRI	ININ
100	4.788	4.778	4.752	4.769
135	4.805	4.826	4.778	4.759
180	4.814	4.852	4.804	4.765
250	4.828	4.885	4.836	4.789

Table 12. Calibration coefficient for the PTW SN614 from all participants

Tube voltage / kV	PTW 614 Calibration Coefficients / 10^7 Gy C^{-1}			
	NRC	CNEA	LNMRI	ININ
100	4.778	4.767	4.749	4.744
135	4.794	4.834	4.779	4.745
180	4.807	4.857	4.805	4.766
250	4.826	4.891	4.838	4.786

4. Summary

The NIST results from Table 5 are sufficiently stable to determine differences between the N_K values. The low standard deviations, resulting from multiple measurement sets during the course of the comparison, represent the combined effects of the stability of the chambers and the reproducibility of the calibration process at the NIST. Despite the differences at each laboratory reported in Tables 6 through 8, the conditions permit a comparison of N_K values. Differences in the beam qualities and scatter conditions used at each laboratory are not analyzed for this comparison.

The results for the NIST in the BIPM key comparison database (KCDB), based on the NIST/BIPM comparison of 2003 [5], are updated for the re-evaluation of the BIPM international standards for air kerma in x-rays made in 2009 [6]. For consistency, therefore, the N_K values supplied by the CNEA and the LNMRI, as shown in Tables 9 to 12, must also be updated for this change, since both NMIs are traceable to the BIPM. It is these updated results that are used for Table 13, which shows for each quality the ratios of each calibration coefficient taken from Table 9 through Table 12 relative to the NIST mean value found in Table 5. Table 14 provides the results for the most recent NIST/BIPM comparison [2], updated for the BIPM 2009 revision [6]; it is these results that form the basis of the degrees of equivalence for the present comparison. Table 15 lists the product of the ratios of the calibration coefficients for each chamber to the NIST mean value and the NIST/BIPM 2003 comparison result. Table 16 gives the typical uncertainty components reported by each laboratory, as Type A and Type B. The combined standard uncertainty is listed for all participants. Figure 1 through Figure 4 compares the data from Table 15, showing the results for each chamber as a function of kV.

After the results of the comparison were revealed to the participants, the ININ reported some errors they made with their data calculations. According to the ININ the errors are with the ININ N_K calculations. The errors made were as follows: the reference temperature for the response of the transfer chambers was taken to be 293.15 K (20 °C) instead of 295.15 K (22 °C), and the correction factors $k_{\mathrm{PT,MC}}$ given in references [7,8] were not applied. ININ reported that the correction factor $k_{\mathrm{PT,MC}}$ should be applied in addition to the standard k_{PT} correction because the SSDL-ININ is located 3000 meters above the sea level. The ININ also identified changes to their values of the relative standard uncertainty related to their errors, including an additional uncertainty for the Exradin chambers for the correction k_{PT}. As the CIPM guidance document [9] for comparisons does not in general allow any changes, except for trivial transcription or arithmetic mistakes, to submitted data after the results have been disclosed, the requested changes by the ININ could not be included in this report. It is suggested that that the ININ support their CMCs by undertaking a subsequent bilateral comparison, using their recent (2012) traceability to the BIPM.

Table 13. The ratios of each calibration coefficient taken from Table 9 through Table 12 relative to the NIST mean value found in Table 5.

Chambers	NRC	CNEA[a]	LNMRI[a]	ININ
100 kV				
PTWSN613	0.9969	0.9922	0.9868	0.9925
PTWSN614	0.9965	0.9916	0.9878	0.9890
Exradin SN71361	0.9976	0.9865	0.9884	0.9739
Exradin SN71362	0.9956	0.9863	0.9860	0.9730
135 kV				
PTWSN613	1.0004	0.9992	0.9893	0.9898
PTWSN614	0.9977	1.0023	0.9909	0.9883
Exradin SN71361	0.9979	0.9978	0.9906	0.9813
Exradin SN71362	0.9975	0.9964	0.9893	0.9808
180 kV				
PTWSN613	0.9963	0.9993	0.9895	0.9870
PTWSN614	0.9969	1.0010	0.9903	0.9878
Exradin SN71361	0.9979	1.0004	0.9909	0.9839
Exradin SN71362	0.9968	0.9985	0.9898	0.9855
250 kV				
PTWSN613	0.9977	1.0016	0.9916	0.9893
PTWSN614	0.9967	1.0018	0.9910	0.9876
Exradin SN71361	0.9972	0.9995	0.9917	0.9855
Exradin SN71362	0.9954	0.9980	0.9906	0.9861

[a] The ratios for the CNEA and the LNMRI include the change due to the BIPM 2009 [6].

Table 14. Results $R_K = N_{K,NIST}/N_{K,BIPM}$ of the comparison of the NIST and BIPM air kerma standards, from Burns and O'Brien (2006), updated for the BIPM 2009 revision [6] and used here as a link to the KCRV

Tube Voltage / kV	$N_{K,NIST}/N_{K,BIPM}$	Standard Relative Uncertainty / %
100	1.0030	0.36
135	1.0020	0.36
180	1.0021	0.36
250	1.0004	0.36

Table 15. The product of the ratios of the calibration coefficients for each chamber to the NIST mean value, from Table 5, and the NIST/BIPM 2003 comparison result

	$R_K\ N_{K,LAB}\ /\ \overline{N}_{K,NIST}$			
Chambers	NRC	CNEA	LNMRI	ININ
100 keV				
PTWSN613	0.9999	0.9952	0.9898	0.9955
PTWSN614	0.9995	0.9945	0.9908	0.9920
Exradin SN71361	1.0006	0.9895	0.9914	0.9768
Exradin SN71362	0.9986	0.9892	0.9890	0.9759
135 keV				
PTWSN613	1.0006	0.9994	0.9895	0.9900
PTWSN614	0.9979	1.0025	0.9911	0.9885
Exradin SN71361	0.9981	0.9980	0.9908	0.9815
Exradin SN71362	0.9977	0.9966	0.9895	0.9810
180 keV				
PTWSN613	0.9984	1.0014	0.9915	0.9891
PTWSN614	0.9990	1.0031	0.9924	0.9899
Exradin SN71361	1.0000	1.0025	0.9930	0.9860
Exradin SN71362	0.9989	1.0006	0.9919	0.9876
250 keV				
PTWSN613	0.9981	1.0020	0.9920	0.9897
PTWSN614	0.9971	1.0022	0.9914	0.9880
Exradin SN71361	0.9976	0.9999	0.9921	0.9859
Exradin SN71362	0.9958	0.9984	0.9910	0.9865

Table 16. Uncertainty components of all participants

Source of Uncertainty	Standard relative uncertainty (%) for the transfer chamber[a]									
	NIST		NRC		CNEA		LNMRI		ININ	
Reference Chamber	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
Air-Kerma standard (BIPM-NIST 2003)	0.230	0.270								
Reference chamber										
N_k			0.01	0.16		0.220		0.208		0.500
Long-term stability			0.01	0.02		0.200		0.450	0.040	
Positioning			0.02	0.01		0.030		0.115		0.002
Current/charge			0.03	0.03	0.070		0.015	0.071	0.049	0.250
Temperature/ pressure			0.02	0.20		0.110		0.123	0.060	0.060
Transfer chamber										
Positioning		0.01	0.020	0.020		0.030		0.115		0.002
Temperature/ pressure	0.01	0.07	0.050	0.100		0.110		0.123	0.070	0.060
Current/charge	0.03	0.06	0.030	0.030	0.120		0.015	0.071	0.061	0.25
Quadratic sum	0.232	0.285	0.075	0.280	0.139	0.338	0.021	0.559	0.127	0.618
Combined standard uncertainty	0.368		0.290		0.366		0.559		0.631	

[a]The values are shown as provided by participants. Resolution below 0.01% is not meaningful, but provided as documentation. The third digit, when given, is not significant but provided for rounding purposes.

5. Degrees of Equivalence

5.1 Explanation of approach

The formulation to link the SIM.RI(I)-K3 to the BIPM.RI(I)-K3 comparison is taken directly from Burns and Allisy-Roberts (2007). For each lab *i*, with respect to the key-comparison reference value, we form

$$R_i = \frac{N_{\mathrm{K},i}}{N_{\mathrm{K,LINK}}} \frac{K_{\mathrm{LINK}}}{K_{\mathrm{BIPM}}}\,, \qquad (1a)$$

with its variance

$$u_{R,i}^2 = \left(u_i^2 + u_{\mathrm{BIPM}}^2 - \sum_n f_n^2 (u_{i,n}^2 + u_{\mathrm{BIPM},n}^2) \right) + u_{\mathrm{stab}}^2 + u_{\mathrm{LINK}}^2 , \tag{1b}$$

where LINK represents the NIST as linking laboratory and the *f*s are the coefficients of the component correlations between lab *i* and the BIPM. The uncertainties associated with the stability of the NIST calibrations was evaluated according to Eq. (3b), below, using the standard deviations of the NIST calibrations listed in Table 5; the results are listed in Table 22. The value of u_{LINK}, 0.26 %, was evaluated by combining in quadrature the total Type A uncertainties (without rounding) for the NIST and the BIPM given in Table 18. The degree of equivalence for lab *i* is $D_i = R_i - 1$, and its expanded uncertainty is $U_i = 2u_{R,i}$.

For pair-wise degrees of equivalence,

$$D_{i,j} = D_i - D_j , \tag{2a}$$

with variance

$$u_{i,j}^2 = \left(u_i^2 + u_j^2 - \sum_n f_n^2 (u_{i,n}^2 + u_{j,n}^2) \right) + 2u_{\mathrm{stab}}^2 . \tag{2b}$$

Using multiple transfer instruments (designated by subscript *p*),

$$R_i = \frac{\sum_p \frac{R_{i,p}}{u_{\mathrm{stab},p}^2}}{\sum_p \frac{1}{u_{\mathrm{stab},p}^2}} , \tag{3a}$$

and

$$\frac{1}{u_{\mathrm{stab}}^2} = \sum_p \frac{1}{u_{\mathrm{stab},p}^2} . \tag{3b}$$

5.2 Implementation for the primary laboratories

Burns and O’Brien (2006) established from the NIST/BIPM 2003 comparison results, duplicated in Table 14, a relative uncertainty for the ratio of calibration coefficients of 0.37 % and updated by the BIPM 2009 revision to 0.36 % [5,6]. From their table of the standard uncertainties of the standards, reproduced here in Table 17, the Type A relative uncertainty for the NIST standard is 0.23 % and for the BIPM standard is 0.05 %. The uncertainty u_{LINK} used in Eq. (1b) combines in quadrature these Type A uncertainties for the standards with those given in Table 18 for the calibration of the transfer chamber during the NIST/BIPM comparison, for a combined total of 0.26 %.

Table 17. Relative standard uncertainties (%) associated with the standards, from Burns and O'Brien (2006)

Component	NIST		BIPM	
	Type A	Type B	Type A	Type B
Ion current	0.15	0.06	0.03	0.02
Volume	0.04	0.01	0.01	0.05
Positioning		0.01	0.01	0.01
Corrections (exc. k_h)	0.16	0.22	0.04	0.12
Humidity k_h		0.03		0.03
Physical constants		0.15		0.15
$\dot{K}_{LAB}$	0.23	0.27	0.05	0.20

Table 18. Relative standard uncertainties (%) associated with the calibration of the transfer ionization chamber, from Burns and O'Brien (2006)

Component	NIST		BIPM	
	Type A	Type B	Type A	Type B
$\dot{K}_{LAB}$	0.23	0.27	0.05	0.20
Ion current	0.12	0.06	0.03	0.02
Positioning		0.01	0.01	0.01
$N_{K,LAB}$	0.26	0.28	0.06	0.20

The uncertainties for two correction factors used for the calculation of air-kerma by the primary standards, those for electron loss and for photon scatter, were reduced by half to account for correlation between the BIPM and the NIST values; this practice is common to all comparisons in the BIPM.RI(I)-K3 series. Additionally, correlation removes humidity and physical constants from the uncertainty of primary comparisons. Uncertainties are listed in Table 19 and Table 20 for the participating primary laboratories and for the BIPM, the latter included for use in the calculation of the uncertainties of the secondary laboratories that are traceable to the BIPM. It should be emphasized that the BIPM did not participate in this comparison, but it is a goal of this comparison to evaluate the results relative to the key comparison reference value, which is the BIPM standard.

Table 19. Uncertainties (%) for the participating primary laboratories and for the BIPM. Correlation in the physical constants has been removed.

Component	NIST		NRC		BIPM	
	Type A	Type B	Type A	Type B	Type A	Type B
Ion current	0.15	0.06	0.03	0.03	0.03	0.02
Volume	0.04	0.01	0.01	0.04	0.01	0.05
Positioning		0.01	0.02	0.01	0.01	0.01
Corrections (excl. k_h)	0.16	0.21	0.02	0.19	0.04	0.11
$\dot{K}_{LAB}$	0.22	0.22	0.04	0.20	0.05	0.12

Table 20. Uncertainty (%) for the transfer chamber calibrations at the participating primary laboratories and the values for the BIPM (for traceability of the secondary laboratories). Correlation in the physical constants has been removed.

Component	NIST		NRC		BIPM	
	Type A	Type B	Type A	Type B	Type A	Type B
$\dot{K}_{LAB}$	0.22	0.22	0.04	0.20	0.05	0.12[a]
Ion current	0.03	0.06	0.03	0.03	0.03	0.02
Positioning		0.01	0.02	0.02	0.01	0.01
T-P corrections	0.01	0.07	0.05	0.10		
$N_{K,LAB}$	0.23	0.24	0.07	0.23	0.06	0.12[b]
u_{LAB} / %	0.33		0.24		0.13 (p)[c], 0.08 (s)[c]	

[a] For labs traceable to the BIPM, this component is set to zero.
[b] For labs traceable to the BIPM, this becomes 0.02.
[c] (p) pertains to primary labs; (s) pertains to secondary labs traceable to the BIPM.

Note that the NIST uncertainty for ion current in Table 20 is reduced from that in Table 18, due to changes in correlations and the inclusion of the statistics associated with the air density. Note further that the value in Table 20, u_{NIST} = 0.33 %, is slightly different from u_{NIST} = 0.36 % that one gets from Burns and O'Brien (2006) and updated [6] for N_K; this is due to the elimination of correlated components and from the reduction of the uncertainty for ion current from Table 19 to Table 20. The choice made is to use the values of u_{LAB} in Table 20 as appropriate in Eqs. (1b) and (2b), and as described earlier u_{LINK} = 0.26 % in Eq. (1b).

5.3 Implementation for the secondary labs

For the secondary laboratories, the Type A uncertainties from the primary standard and calibration of the secondary laboratory's reference chamber are used. The self-reported uncertainties for the calibration of the transfer chamber are listed in Table 21.

Table 21. Uncertainty (%) for transfer chamber calibrations at the secondary laboratories[a]

Component	CNEA		LNMRI		ININ	
	Type A	Type B	Type A	Type B	Type A	Type B
$\dot{K}_{STD}$	0.05		0.05		0.05	
$N_{K,STD}$	0.06		0.06		0.06	
Ion current	0.12		0.015	0.071	0.061	0.250
Positioning		0.03		0.115		0.002
T/P corrections		0.11		0.123	0.070	0.060
$N_{K,LAB}$	0.160	0.257	0.083	0.519	0.150	0.364
u_{LAB} / %	0.303		0.525		0.393	

[a]The values are shown as provided by participants. Resolution below 0.01% is not meaningful, but provided as documentation. The third digit, when given, is not significant but provided for rounding purposes.

The values obtained by evaluating Eq. (3a) are listed in Table 22. The NIST R_K values are those listed in Table 14, originally from Burns and O'Brien (2006) and updated by the BIPM 2009 revision [5,6]. From Eq. (3b), u_{stab} values have been evaluated and are listed in Table 22.

Table 22. Weighted averages of the calibration coefficients.

Tube Voltage (kV)	u_{stab}	$R_i = R_K N_{K,LAB} / \overline{N}_{K,NIST}$				
		NIST	NRC	CNEA	LNMRI	ININ
100 kV	0.00041	1.0030	0.9995	0.9940	0.9905	0.9907
135 kV	0.00042	1.0020	0.9985	1.0011	0.9906	0.9879
180 kV	0.00050	1.0021	0.9987	1.0021	0.9920	0.9889
250 kV	0.00047	1.0004	0.9972	1.0014	0.9915	0.9880

Table 23. Degrees of equivalence, D, and associated expanded uncertainties, U (for k = 2), both in mGy/Gy.

		Ref		NIST		NRC		CNEA		LNMRI		ININ	
	R_i	D_i	U_i	$D_{i,j}$	$U_{i,j}$	$D_{i,j}$	$U_{i,j}$	$D_{i,j}$	$U_{i,j}$	$D_{i,j}$	$U_{i,j}$	$D_{i,j}$	$U_{i,j}$
100kV													
NIST	1.003	3.0	8.5			3.5	7.7	9.0	14.8	12.5	12.7	12.3	13.7
NRC	0.9995	-0.5	6.7	-3.5	7.7			5.5	13.8	9.1	11.5	8.9	15.6
CNEA	0.9940	-6.0	14.3	-9.0	14.8	-5.5	13.8			3.5	17.1	3.3	20.1
LNMRI	0.9905	-9.5	12.1	-12.5	12.7	-9.1	11.5	-3.5	17.1			-0.2	18.6
ININ	0.9907	-9.3	16.0	-12.3	13.7	-8.9	15.6	-3.3	20.1	0.2	18.6		
135 kV													
NIST	1.0002	0.2	8.5			1.7	7.7	-0.9	14.8	9.6	12.7	12.3	13.7
NRC	0.9985	-1.5	6.7	-1.7	7.7			-2.6	13.8	7.9	11.5	10.7	15.6
CNEA	1.0011	1.1	14.3	0.9	14.8	2.6	13.8			10.5	17.1	13.2	20.1
LNMRI	0.9906	-9.4	12.1	-9.6	12.7	-7.9	11.5	-10.5	17.1			2.7	18.6
ININ	0.9879	-12.1	16.0	-12.3	13.7	-10.7	15.6	-13.2	20.1	-2.7	18.6		
180 kV													
NIST	1.0021	2.1	8.6			3.4	7.8	0.0	14.8	10.1	12.7	13.2	13.7
NRC	0.9987	-1.3	6.8	-3.4	7.8			-3.3	13.9	6.8	11.6	9.8	15.7
CNEA	1.0021	2.1	14.3	0.0	14.8	3.3	13.9			10.1	17.1	13.2	20.1
LNMRI	0.9920	-8.0	12.1	-10.1	12.7	-6.8	11.6	-10.1	17.1			3.0	18.6
ININ	0.9889	-11.1	16.1	-13.2	13.7	-9.8	15.7	-13.2	20.1	-3.0	18.6		
250 kV													
NIST	1.0004	0.4	8.5			3.2	7.8	-1.0	14.8	8.9	12.7	12.4	13.7
NRC	0.9972	-2.8	6.8	-3.2	7.8			-4.2	13.8	5.7	11.6	9.2	15.6
CNEA	1.0014	1.4	14.3	1.0	14.8	4.2	13.8			9.9	17.1	13.4	20.1
LNMRI	0.9915	-8.5	12.1	-8.9	12.7	-5.7	11.6	-9.9	17.1			3.6	18.6
ININ	0.9880	-12.0	16.1	-12.4	13.7	-9.2	15.6	-13.4	20.1	-3.6	18.6		

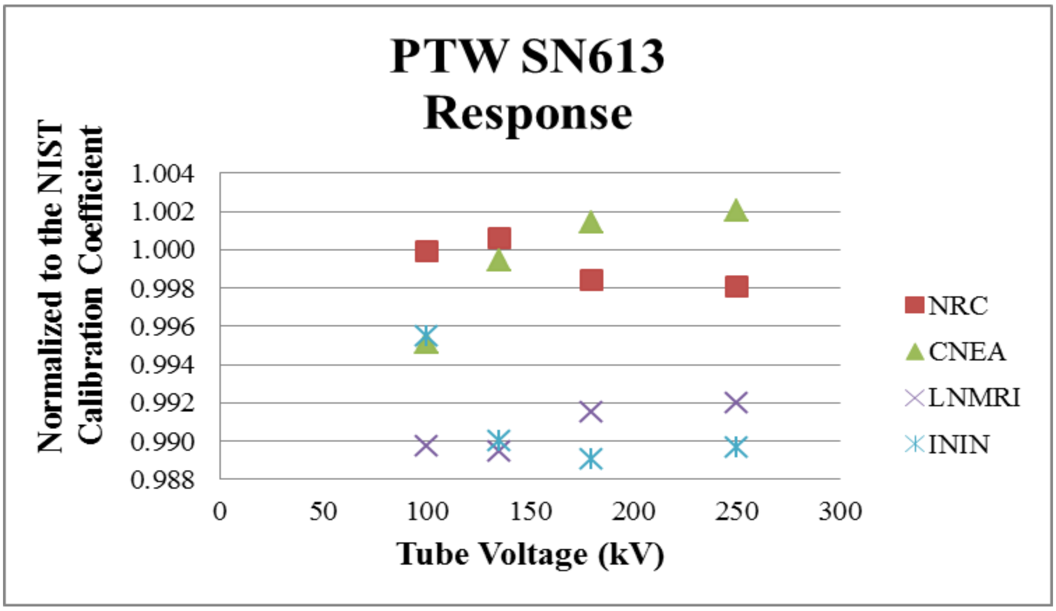

Figure 1. Relative calibration coefficients measured with the PTW SN613 for all participants as a function of the tube voltage, normalized to the NIST average, as shown in Table 15.

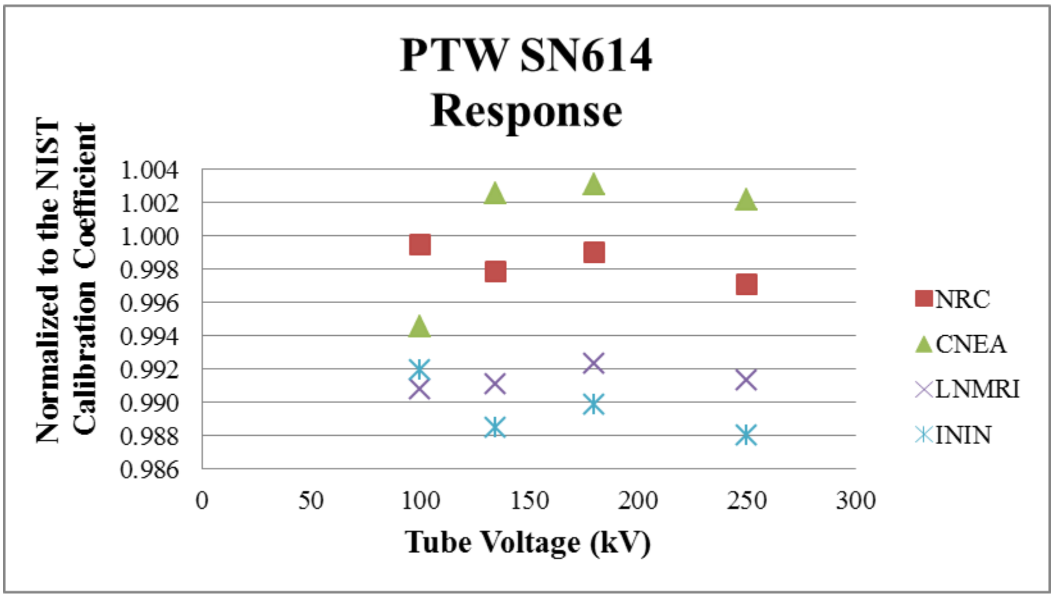

Figure 2. Relative calibration coefficients measured with the PTW SN614 as a function of the tube voltage, normalized to the NIST average, as shown in Table 15.

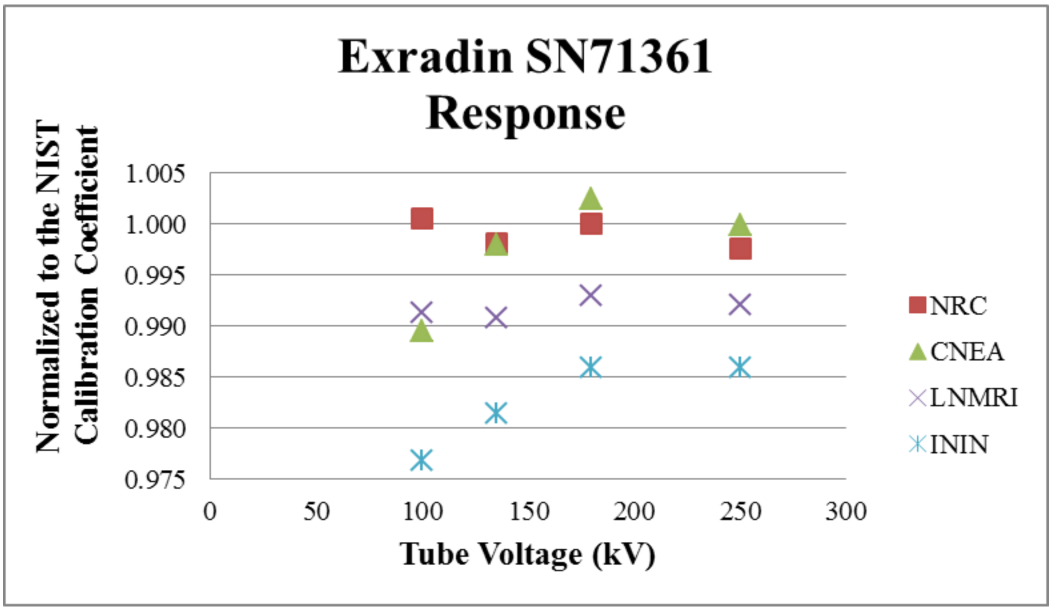

Figure 3. Relative calibration coefficients measured with the Exradin SN 71361 as a function of the tube voltage, normalized to the NIST average, as shown in Table 15.

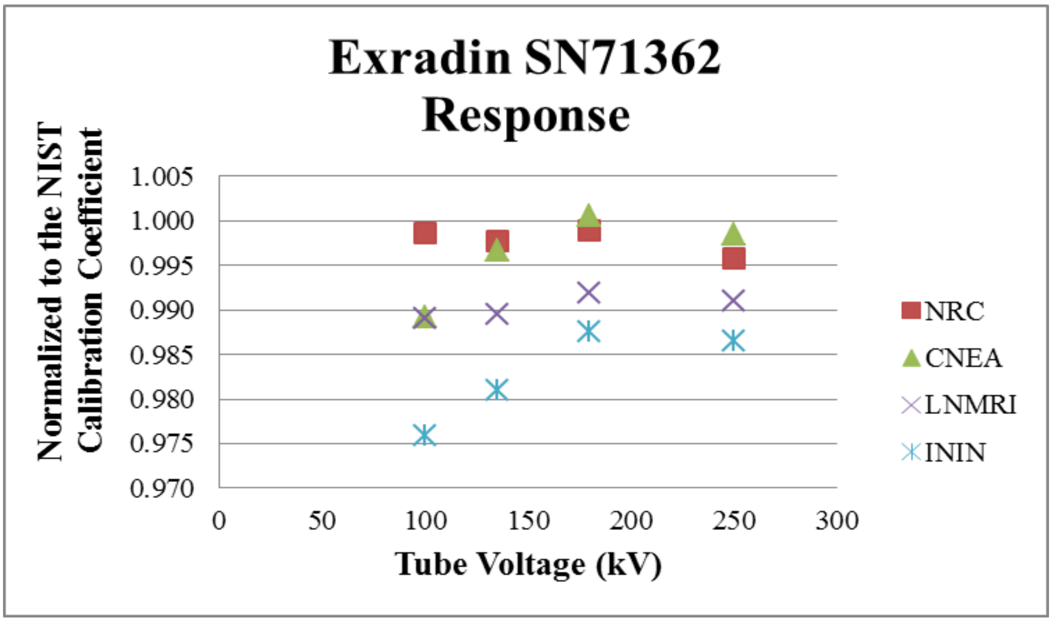

Figure 4. Relative calibration coefficients measured with the Exradin SN 71362 as a function of the tube voltage, normalized to the NIST average, as shown in Table 15.

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