EURAMET Project 1285

Comparisons of air kerma and absorbed dose to water standards in ^{60}Co radiation beams for radiotherapy

Identifier in Appendix B of the BIPM key comparison database (BIPM KCDB):

EURAMET.RI(I)-K1.1
EURAMET.RI(I)-K4.1

Final Report

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Abstract

The air kerma and absorbed dose to water standards for ^{60}Co radiotherapy beams of 6 EURAMET NMIs were compared by circulating 2 transfer standards. The schedule for the measurements lasted from March 2013 to February 2015. The participants determined the calibration coefficients for the 2 transfer standards in both radiation quantities mentioned above. The comparison results are given in terms of air kerma and absorbed dose to water for both transfer standards as the ratio of the participants' calibration coefficients to the respective average values over all participants. Two participating NMIs, BEV and METAS, measured the transfer standards twice and three times, respectively. Hence, submeans were calculated and propagated as their respective repeated measurements are correlated.

The results are also linked to the BIPM.RI(I)-K1 and BIPM.RI(I)-K4 key comparisons through the linking laboratories BEV, LNE-LNHB and VSL for the air kerma and BEV, LNE-LNHB and METAS for the absorbed dose to water standards.

1. Introduction

The comparisons for air kerma (EURAMET.RI(I)-K1.1) and for absorbed dose to water (EURAMET.RI(I)-K4.1), both quantities being measured in ^{60}Co radiotherapy beams, took place in parallel as foreseen in the technical-protocol of the comparison (Appendix A).

The comparisons aimed for supporting the calibration and measurement capabilities (CMC) of the participants for the quantities mentioned above in the context of the CIPM - Mutual Recognition Arrangement (CIPM-MRA) [1-5].

In order to do so, transfer standards for air kerma and absorbed dose to water were circulated among the participants. The circulating items were two ionization chambers and one dedicated electrometer. The participants determined the calibration coefficients of the transfer standards $N(K_{Air})$ and $N(D_W)$ through comparison with their national standards in their respective ^{60}Co beams [6]. The calibration coefficients were corrected for reference conditions as well as for leak current, ion recombination and the electrometer range used. But no correction for polarity effects were applied as the ionization chambers were measured with a unique electrometer and a fixed configuration concerning the polarity and the voltage level.

Detailed uncertainty budgets for the calibration coefficient determinations were given by the participants according to [7].

The linking laboratories BEV, LNE-LNHB and VSL for the air kerma and BEV, LNE-LNHB, and METAS for the absorbed dose to water standards allow discussing the results in terms of degree of equivalence with respect to the BIPM.RI(I)-K1 and BIPM.RI(I)-K4 key comparisons [9-15].

2. Participants

The participating institutes and their contact persons are listed in Table 1.

Table 1: List of the contact persons of all participants at the present date. In brackets the respective contact persons are stated at the time of the measurements.

	Contact person	**Country**	**Institute**	**E-mail address**
1	Dr. Christian Kottler (Dr. Anton Steiner)	Switzerland	METAS	christian.kottler@metas.ch
2	Dipl. Ing. Andreas Steurer	Austria	BEV	Andreas.Steurer@bev.gv.at
3	Dr. Frank Delaunay	France	LNE-LNHB	Franck.DELAUNAY@cea.fr
4	Dr. Jacco de Pooter	Netherlands	VSL	JdPooter@vsl.nl
5	Ms. Cristina García Mulas (Dr. Paz Avilés Lucas)	Spain	CIEMAT	cristina.garcia@ciemat.es
6	Dr. Liviu-Cristian Mihailescu	Belgium	SCK-CEN	lmihaile@sckcen.be

3. Procedure

3.1 Outline of the comparison

The calibration of two transfer standards against the national standards of air kerma and of absorbed dose to water in ^{60}Co radiotherapy beams were carried out. The ionization chambers were measured sequentially each with the likewise circulating electrometer. The chambers were placed free in air and in water for the air kerma and absorbed dose to water measurements, respectively. The absorbed dose to water measurements were performed at the depth of 5 g·cm-2. For the reference distances in the ^{60}Co beams those values were applied, where the conventional true values of air kerma and absorbed dose to water rates are established by the corresponding national standards. The calibration coefficients were calculated from $N(K_{\mathrm{Air}}) = \acute{K}_{\mathrm{Air}}/I_{\mathrm{corr}}$ and $N(D_{\mathrm{W}}) = \acute{D}_{\mathrm{W}}/I_{\mathrm{corr}}$. I_{corr} is the measured ionization current corrected to reference conditions (pressure, temperature and relative humidity) as well as for leak current and ion recombination . $\acute{K}_{\mathrm{Air}}$ and $\acute{D}_{\mathrm{W}}$ are the established air kerma and absorbed dose to water rates of the ^{60}Co sources under reference conditions [6].

3.2 Description of the transfer instruments

The electrometer was a PTW UNIDOS webline T10022, S/N 000308. The ionization chambers were a PTW T30006, S/N 036, waterproof and a PTW T30004, S/N 286, not waterproof. Technical data are given in Table 2.

Table 2: Technical data of the circulated ionization chambers

Type, serial number	Nom. N(D_W) (Gy·µC-1)	Nominal volume (cm-3)	Collecting Voltage (V)	Wall material	Water-proof	Wall thickness (g·cm-2)	inner Diam. of head (mm)	Stem diameter/ length (mm)
PTW T30006, S/N 036	50	0.6	+400	PMMA	Yes	0.0565	6.1	12.6/132.6
PTW T30004, S/N 286	50	0.6	+400	Graphite	No	0.0785	6.1	12.6/132.6

Each chamber has its own build-up cap made in POM for the calibration in terms of air kerma. For the absorbed dose to water calibration the waterproof chamber PTW T30006 did not need a PMMA sleeve in the water phantom whereas the PTW 30004 chamber was protected with its PMMA sleeve (wall thickness of the sleeve 1.1 mm).

The chambers were measured with the accompanying electrometer in the already predefined configuration for the two chambers (*Collecting voltage +400 V, mode ∫Current dt, Range LOW/MEDIUM (to be selected), Integration time 60 s resp. 120 s at SCK-CEN*). The chambers were aligned in the beam with the black line on their stem facing the radiation source. For the air kerma measurement the marking on the build-up cap was also adjusted on the beam axis. These markings being perpendicular to each other their intersection locates uniquely the reference point of the chambers. For the absorbed dose to water measurement the chamber was aligned with respect to the reference point as stated by the manufacturer (at 13 mm apart from the tip).

Since the ^{60}Co dose rates among the different irradiation facilities varied between 0.1 Gy·min-1 to 1.2 Gy·min-1, the participants used different ranges of the electrometer for optimum measurements, i.e. the most appropriate one. The corresponding electrometer correction factors are given in Appendix B of the technical-protocol of the comparison (Appendix A). Each laboratory had to use its own temperature and pressure measurement equipment.

3.3 Reference conditions

The chambers were placed in the usual reference conditions in the ^{60}Co beams where the conventional true values of air kerma and absorbed dose to water rates are established by the corresponding national standards. For each participant, the applied source-chamber distance (SCD, the distance between the chamber reference point and the reference point of the ^{60}Co source) was 100 cm along the central beam axis and a 10 cm x 10 cm beam cross section perpendicular to the beam axis at this SCD was used. This is achieved if the photon fluence rate at the mid-point of each side of the square is 50 % of the photon fluence rate at the center of the field. For the determination of $N(K_{Air})$ the chambers were placed free in air, for $N(D_W)$ the reference points of the chambers were placed at the depth of 5 g·cm-2 in water.

The calibration coefficients of the ionization chambers $N(K_{Air})$ and $N(D_W)$ were reported in terms of air kerma and absorbed dose to water per unit charge in the units of Gy/µC. The reported values are corrected for air and/or water temperature, air pressure and relative humidity in order to comply with the standard conditions of T = 293,15 K, P = 101,325 kPa and H = 50 %rh [6]. No correction for humidity was required for measurements in the range 20 % < H < 80 %. If outside this range then all ion chamber measurements were to be corrected to H = 50 %rh, but in practice no participant had to apply a correction.

The calibration coefficients of the chambers were corrected further for leak current and ion recombination but not for polarity effects. The correction for ion recombination was determined from adequate measurements according to the procedure normally used in the respective laboratory (e.g. two voltage method).

3.4 Course of the comparison

To ensure the highest possible reliability of the comparison result, a partly star-shaped circulation scheme of the transfer instruments between METAS and the other participants was chosen, i.e., measurements were performed at METAS at the beginning, at the end and also in the middle of that sequence. Furthermore, BEV decided to participate twice within that sequence, once before and once after the replacement of their ^{60}Co source. Each participant paid for the transportation and insurance for sending the instruments to the next institute.

The transfer standards stayed at the participant's site for 4 weeks at most. The results were reported to METAS within 3 months of the measurements. Each participant delivered detailed uncertainty budgets for the calibration coefficient determinations of the transfer instruments in accordance with the ISO Guide to the expression of uncertainties in measurements (GUM 1995 [7]).

The comparison measurement period lasted from March 2013 to February 2015. The detailed schedule is given in Table 3.

Table 3: Schedule for the circulation of the transfer standards

	Participant	Measurement period
1	METAS	March/Mai 2013
2	LNE-LNHB	July 2013
3	BEV	August 2013
4	METAS	January 2014
5	SCK-CEN	March 2014
6	VSL	June 2014
7	CIEMAT	July 2014
8	BEV	September 2014
9	METAS	December 2014/January/February 2015

Transportation time for the instruments from one participant to next was estimated being one week by door-to-door delivery. The participants communicated about transportation details by e-mail. The exact addresses for delivering the equipment to the different participants were given in Appendix C of the technical-protocol of the comparison (Appendix A).

3.5 Calibration coefficient determination

The participants proceeded their usual way to determine the calibration coefficients of the transfer standards. Descriptions of the procedures applied were reported to METAS.

As an example, the procedure used at METAS is as follows:

At METAS the ionization chambers are connected to the electrometer at least two hours before doing any measurements. Due to the actual strength of the METAS Cobalt source (~1 Gy·min-1) the electrometer mode is set to *" ∫Current dt, Range Medium, Integration time 60 s "* with a collecting voltage of +400 V. The measurement sequence is as follows: First, ten leak current measurements are acquired each with 60 s integration time, followed by the opening of the source and a 10 Gy pre-irradiation period. Thereafter, twenty-five irradiation measurements each with 60 s integration time are performed. After these measurements, the irradiation is stopped and a five minute waiting time is allowed for before a second series of ten leak current measurements is taken. Air and/or water temperature and air pressure are measured at halftime of each 60 s integration period. The air density correction k_{TP} is, thus, applied to each acquired charge value. The calculated correction for ion recombination k_S is also applied to each charge value. The mean of the leak current measurements before and after the irradiation is subtracted from the mean of the irradiation measurements. Finally, the electrometer range correction k_{EM}, based on an electrical calibration of the electrometer done at METAS, is applied. The corresponding factors were given in Appendix B of the technical-protocol of the comparison (Appendix A).

Apart from minor differences, e.g., pre-irradiation time, number of integration cycles, etc., the procedures used by the other participants are essentially identical.

3.6 Handling the results

METAS measured the transfer standards first in March/May 2013. The reports on these measurements were sent to the EURAMET TC-IR Chair and to the CCRI(I) Executive Secretary on June 7th, 2013, before any further participant delivered its measurement results. This procedure was a measure of confidence as to ensure the impartiality of METAS as pilot laboratory.

The participants sent their results with detailed description of the procedure applied and with the corresponding uncertainty budget established to the pilot laboratory by e-mail within 3 months after having completed the measurements. Upon reception, the pilot laboratory checked the data basically for consistency and typing errors. Once having all data at hand, METAS started evaluating the results.

3.7 Evaluation of the data

METAS has explored different ways to analyze the comparison data as developed in detail in Appendix B *Data Analysis*.

The arithmetic mean taken over all participants' results, the mean taken over the linking laboratories' results, the mean taken over the participants' results weighted by their respective uncertainties as well as the mean taken over all participants' results with submeans for BEV and METAS being calculated and propagated give basically similar outputs. The variations of the deviations from the corresponding means are for all participants lower than the laboratory's uncertainty u(k=1) for the air kerma and dose to water. For the analysis of this comparison’s results, the means was applied, which takes the mean over all participants' results with submeans for BEV and METAS (see section 4.2).

In order to detect eventual drifts of the transfer standards throughout the circulation, the individual data from BEV and METAS were evaluated because these laboratories performed more than one measurement during the comparison sequence (see section 3.4). Whereas the data form BEV indicate no drift at all, the data from METAS indicate a slight drift. Nevertheless, the values of the calibration coefficients resulting from the three measurements done at METAS agree well within the stated standard uncertainty for both transfer standards as well as for K_{Air} and D_W. Therefore, the presumable drift is considered negligible.

The respective repeated measurements at BEV and METAS are fully correlated. Thus, in order to give the same weight to all participants the mean over all participants' results with submeans for BEV and METAS being calculated and propagated for both transfer standards and radiation quantities are proposed to define the base lines against which the participants' calibration coefficients are compared as follows:

$R(K_{Air})_{Lab\ i,\ mean} = N(K_{Air})_{Lab\ i} / N(K_{Air})_{mean}$ and $R(D_W)_{Lab\ i,\ mean} = N(D_W)_{Lab\ i} / N(D_W)_{mean}$ in terms of air kerma and absorbed dose to water respectively.

The degree of equivalence for entries in the BIPM key comparison data base in terms of air kerma and in terms of absorbed dose to water was established by linking the ratios as defined above to the BIPM.RI(I)-K1 and BIPM.RI(I)-K4 key comparisons respectively through laboratories having participated in one or both comparison exercises [9-15]. Thus, the linking factor $Q(X)_{Lab\ i} = R(X)_{Lab\ i,\ mean} / R(X)_{Lab\ i,\ BIPM}$ can be defined with $R(X)_{Lab\ i,\ BIPM}$ being the result from the corresponding CCRI(I) key comparison and (X) standing for either (K_{Air}) or (D_W).

The linking laboratories refer strictly to the same primary standards for the present and for the BIPM.RI(I)-K1 and BIPM.RI(I)-K4 comparisons.

3.8 Publication of the results

The final report of the EURAMET project 1285 will be submitted to the EURAMET TC-IR Chair and the KCWG of CCRI(I). The approved report will finally be submitted for publication to the *Technical Supplement* of *Metrologia*.

4. Results

4.1 Data reported

All the calibration coefficient data $N(K_{Air})_{Lab\ i}$ and $N(D_W)_{Lab\ i}$ with their respective uncertainties as reported by the participants are given for both chambers chronologically in Table 4. The ion recombination and the electrometer correction factors k_S and k_{EM} used and reported by the participants are also given together with the declared electrometer range indication.

Table 4: Calibration coefficient data $N(K_{Air})_{Lab\,i}$ and $N(D_W)_{Lab\,i}$

Co-60 Air Kerma calibration factor for chamber PTW 30004 #286

Lab i	meas. Period	$N(K_{Air})_{Lab\,i}$		u(k=1)	unit	k_S	k_{EM}	electrometer range
METAS	15.05.2013	47.87	±	0.21	Gy·µC^{-1}	1.0010	1.0006	medium
LNE-LNHB	18.07.2013	47.87	±	0.17	Gy·µC^{-1}	1.0005	1.0005	medium
BEV	15.08.2013	48.23	±	0.12	Gy·µC^{-1}	1.0001	0.9999	low
METAS	30.01.2014	47.88	±	0.21	Gy·µC^{-1}	1.0010	1.0006	medium
SCK-CEN	13.03.2014	47.77	±	0.27	Gy·µC^{-1}	1.0001	0.9999	low
VSL	19.06.2014	47.77	±	0.12	Gy·µC^{-1}	1.0005	0.9999	low
CIEMAT	14.07.2014	47.97	±	0.12	Gy·µC^{-1}	1.0006	1.0006	medium
BEV	22.09.2014	48.21	±	0.12	Gy·µC^{-1}	1.0001	0.9999	low
METAS	07.01.2015	48.06	±	0.21	Gy·µC^{-1}	1.0010	1.0006	medium

Co-60 Air Kerma calibration factor for chamber PTW 30006 #036

Lab i	meas. Period	$N(K_{Air})_{Lab\,i}$		u(k=1)	unit	k_S	k_{EM}	electrometer range
METAS	16.05.2013	47.85	±	0.21	Gy·µC^{-1}	1.0010	1.0006	medium
LNE-LNHB	01.07.2013	47.88	±	0.17	Gy·µC^{-1}	1.0010	1.0005	medium
BEV	15.08.2013	48.21	±	0.12	Gy·µC^{-1}	1.0002	0.9999	low
METAS	30.01.2014	47.92	±	0.21	Gy·µC^{-1}	1.0010	1.0006	medium
SCK-CEN	13.03.2014	47.86	±	0.27	Gy·µC^{-1}	1.0001	0.9999	low
VSL	19.06.2014	47.76	±	0.12	Gy·µC^{-1}	1.0005	0.9999	low
CIEMAT	14.07.2014	47.95	±	0.12	Gy·µC^{-1}	1.0008	1.0006	medium
BEV	22.09.2014	48.20	±	0.12	Gy·µC^{-1}	1.0001	0.9999	low
METAS	21.12.2014	48.02	±	0.21	Gy·µC^{-1}	1.0010	1.0006	medium

Co-60 Dose to Water calibration factor for chamber PTW 30004 #286

Lab i	meas. Period	$N(D_W)_{Lab\,i}$		u(k=1)	unit	k_S	k_{EM}	electrometer range
METAS	08.03.2013	51.96	±	0.24	Gy·µC^{-1}	1.0010	1.0006	medium
LNE-LNHB	01.07.2013	52.04	±	0.16	Gy·µC^{-1}	1.0004	1.0005	medium
BEV	15.08.2013	52.24	±	0.20	Gy·µC^{-1}	1.0002	0.9999	low
METAS	27.01.2014	52.01	±	0.24	Gy·µC^{-1}	1.0010	1.0006	medium
SCK-CEN	13.03.2014	52.08	±	0.34	Gy·µC^{-1}	1.0001	0.9999	low
VSL	19.06.2014	51.91	±	0.21	Gy·µC^{-1}	1.0005	0.9999	low
CIEMAT	14.07.2014	52.28	±	0.19	Gy·µC^{-1}	1.0006	1.0006	medium
BEV	22.09.2014	52.19	±	0.20	Gy·µC^{-1}	1.0001	0.9999	low
METAS	25.02.2015	52.21	±	0.24	Gy·µC^{-1}	1.0010	1.0006	medium

Co-60 Dose to Water calibration factor for chamber PTW 30006 #036

Lab i	meas. Period	$N(D_W)_{Lab\ i}$		u(k=1)	unit	k_S	k_{EM}	electrometer range
METAS	06.03.2013	51.99	±	0.24	$Gy·µC^{-1}$	1.0010	1.0006	medium
LNE-LNHB	01.07.2013	52.11	±	0.16	$Gy·µC^{-1}$	1.0008	1.0005	medium
BEV	15.08.2013	52.22	±	0.20	$Gy·µC^{-1}$	1.0002	0.9999	low
METAS	28.01.2014	52.13	±	0.24	$Gy·µC^{-1}$	1.0010	1.0006	medium
SCK-CEN	13.03.2014	52.13	±	0.34	$Gy·µC^{-1}$	1.0001	0.9999	low
VSL	19.06.2014	52.00	±	0.21	$Gy·µC^{-1}$	1.0005	0.9999	low
CIEMAT	14.07.2014	52.33	±	0.19	$Gy·µC^{-1}$	1.0008	1.0006	medium
BEV	22.09.2014	52.16	±	0.20	$Gy·µC^{-1}$	1.0001	0.9999	low
METAS	24.02.2015	52.22	±	0.24	$Gy·µC^{-1}$	1.0010	1.0006	medium

4.2 Result of the comparison

Table 5 below gives the comparison results $R(K_{Air})_{Lab\ i,\ mean} = N(K_{Air})_{Lab\ i} / N(K_{Air})_{mean}$ for air kerma and $R(D_W)_{Lab\ i,\ mean} = N(D_W)_{Lab\ i} / N(D_W)_{mean}$ for absorbed dose to water for each chamber in alphabetical order of the participants. The standard uncertainties u(k=1) on $R(K_{Air})_{Lab\ i,\ mean}$ and $R(D_W)_{Lab\ i,\ mean}$ are calculated from the uncertainties on the reported values $N(K_{Air})_{Lab\ i}$ and $N(D_W)_{Lab\ i}$ combined with the standard deviations on the corresponding mean and in accordance to the propagation of uncertainties on a ratio.

In order to account for the correlation between the respective repeated measurements at BEV and METAS the mean over all participants' results is calculated taking into account only the submeans for BEV and METAS. This manner to proceed gives all participants the same weight. Although SCK-CEN is a secondary standard laboratory with traceability to VSL, their respective measurements are considered as independent in the present context.

Deviations from unity for $R(K_{Air})_{Lab\ i,\ mean}$ and $R(D_W)_{Lab\ i,\ mean}$ constitute a measure of the quality of the reported results. If the usual extended 95 % confidence level uncertainties U(k=2) are considered, the deviations from unity of all participants' results are found within the resulting standard uncertainty interval "1±U(k=2)", with the exception of the two values for $R(K_{Air})_{BEV,\ mean}$, which are just slightly outside the corresponding interval. The summary of the results are shown in Figure 1.

Table 5: Comparison results $R(K_{Air})_{Lab\ i,\ mean}$ and $R(D_W)_{Lab\ i,\ mean}$ and corresponding standard uncertainties u(k=1) in alphabetical order of the participants

Co-60 Air Kerma calibration factor for chamber PTW 30004 #286

Lab i	$N(K_{Air})_{Lab\ i}$		u(k=1)	unit	$R(K_{Air})_{Lab\ i,\ mean} = N(K_{Air})_{Lab\ i} / N(K_{Air})_{mean}$	standard uncertainty on $R(K_{Air})_{Lab\ i,\ mean}$ u(k=1)
BEV mean	48.22	±	0.12	$Gy \cdot \mu C^{-1}$	1.0062	0.0029
CIEMAT	47.97	±	0.12	$Gy \cdot \mu C^{-1}$	1.0009	0.0029
LNE-LNHB	47.87	±	0.17	$Gy \cdot \mu C^{-1}$	0.9989	0.0038
METAS mean	47.94	±	0.21	$Gy \cdot \mu C^{-1}$	1.0003	0.0046
SCK-CEN	47.77	±	0.27	$Gy \cdot \mu C^{-1}$	0.9968	0.0058
VSL	47.77	±	0.12	$Gy \cdot \mu C^{-1}$	0.9968	0.0029
$N(K_{AIR})_{mean}$	47.92			$Gy \cdot \mu C^{-1}$		
stdev mean	0.07			$Gy \cdot \mu C^{-1}$		

experimental standard deviation of the mean

Co-60 Air Kerma calibration factor for chamber PTW 30006 #036

Lab i	$N(K_{Air})_{Lab\ i}$		u(k=1)	unit	$R(K_{Air})_{Lab\ i,\ mean} = N(K_{Air})_{Lab\ i} / N(K_{Air})_{mean}$	standard uncertainty on $R(K_{Air})_{Lab\ i,\ mean}$ u(k=1)
BEV mean	48.20	±	0.12	$Gy \cdot \mu C^{-1}$	1.0057	0.0028
CIEMAT	47.95	±	0.12	$Gy \cdot \mu C^{-1}$	1.0004	0.0028
LNE-LNHB	47.88	±	0.17	$Gy \cdot \mu C^{-1}$	0.9990	0.0038
METAS mean	47.93	±	0.21	$Gy \cdot \mu C^{-1}$	1.0000	0.0046
SCK-CEN	47.86	±	0.27	$Gy \cdot \mu C^{-1}$	0.9986	0.0058
VSL	47.76	±	0.12	$Gy \cdot \mu C^{-1}$	0.9964	0.0028
$N(K_{AIR})_{mean}$	47.93			$Gy \cdot \mu C^{-1}$		
stdev mean	0.06			$Gy \cdot \mu C^{-1}$		

experimental standard deviation of the mean

Co-60 Dose to Water calibration factor for chamber PTW 30004 #286

Lab i	$N(D_W)_{Lab\ i}$		u(k=1)	unit	$R(D_W)_{Lab\ i,\ mean} = N(D_W)_{Lab\ i} / N(D_W)_{mean}$	standard uncertainty on $R(D_W)_{Lab\ i,\ mean}$ u(k=1)
BEV mean	52.22	±	0.20	$Gy \cdot \mu C^{-1}$	1.0023	0.0040
CIEMAT	52.28	±	0.19	$Gy \cdot \mu C^{-1}$	1.0035	0.0038
LNE-LNHB	52.04	±	0.16	$Gy \cdot \mu C^{-1}$	0.9989	0.0032
METAS mean	52.06	±	0.24	$Gy \cdot \mu C^{-1}$	0.9992	0.0048
SCK-CEN	52.08	±	0.34	$Gy \cdot \mu C^{-1}$	0.9997	0.0066
VSL	51.91	±	0.21	$Gy \cdot \mu C^{-1}$	0.9964	0.0042
$N(D_W)_{mean}$	52.10			$Gy \cdot \mu C^{-1}$		
stdev mean	0.05			$Gy \cdot \mu C^{-1}$		

experimental standard deviation of the mean

Co-60 Dose to Water calibration factor for chamber PTW 30006 #036

Lab i	$N(D_W)_{Lab\ i}$		u(k=1)	unit	$R(D_W)_{Lab\ i,\ mean} = N(D_W)_{Lab\ i} / N(D_W)_{mean}$	standard uncertainty on $R(D_W)_{Lab\ i,\ mean}$ u(k=1)
BEV mean	52.19	±	0.20	Gy·µC^{-1}	1.0009	0.0040
CIEMAT	52.33	±	0.19	Gy·µC^{-1}	1.0035	0.0037
LNE-LNHB	52.11	±	0.16	Gy·µC^{-1}	0.9993	0.0032
METAS mean	52.11	±	0.24	Gy·µC^{-1}	0.9994	0.0048
SCK-CEN	52.13	±	0.34	Gy·µC^{-1}	0.9997	0.0065
VSL	52.00	±	0.21	Gy·µC^{-1}	0.9972	0.0041
$N(D_W)_{mean}$	52.14			Gy·µC^{-1}		
stdev mean	0.04			Gy·µC^{-1}		

experimental standard deviation of the mean

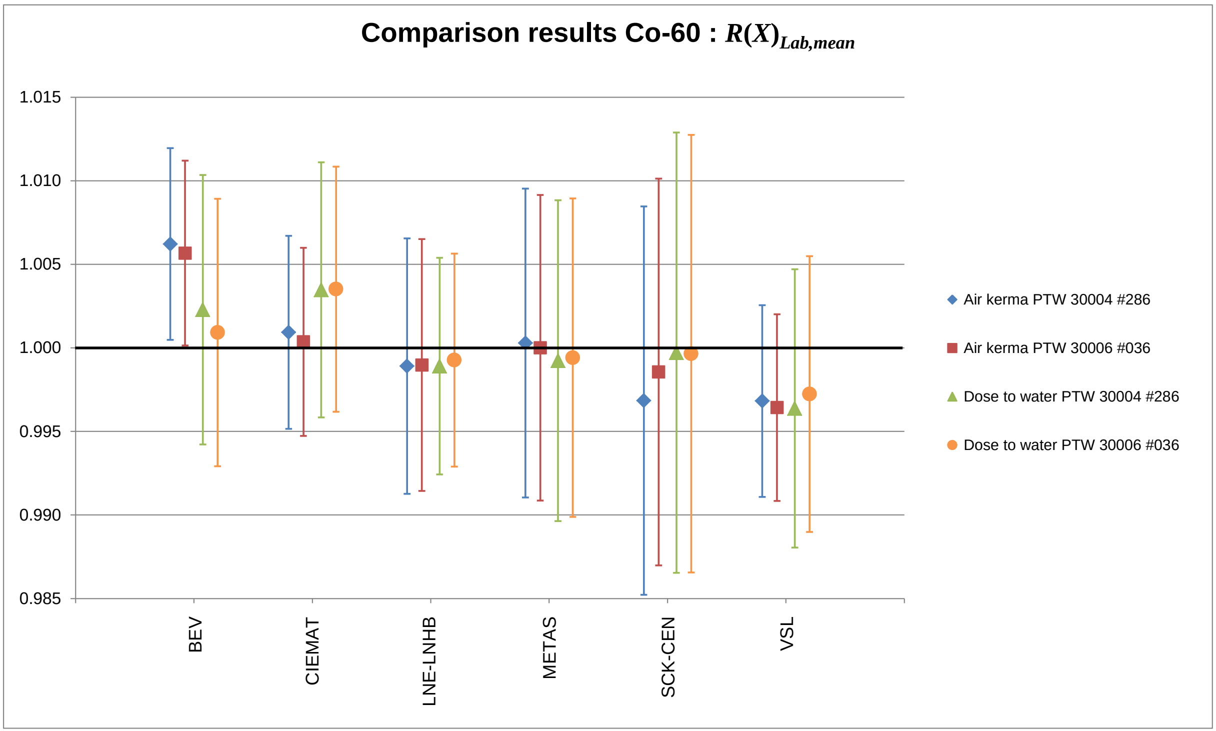

Figure 1: Comparison results $R(K_{Air})_{Lab\ i,\ mean}$ and $R(_{DW})_{Lab\ i,\ mean}$ and corresponding standard uncertainties u(k=2) for both ionization chambers given in alphabetical order of the participants

4.3 Link with BIPM.RI(I)-K1 and BIPM.RI(I)-K4

In order to link the actual comparison results with the corresponding key comparisons BIPM.RI(I)-K1 and BIPM.RI(I)-K4 linking factors $Q(X)_{Lab\ i} = R(X)_{Lab\ i,\ mean} / R(X)_{Lab\ i,\ BIPM}$ are defined, $R(X)_{Lab\ i,\ BIPM}$ being the result from the corresponding CCRI(I) key comparison for Lab i and (X) standing for either (K_{Air}) or (D_W). $Q(X)_{Lab\ i}$ corresponds to the virtual ratio of $N(X)_{BIPM} / N(X)_{mean}$. It is calculated via each linking laboratory Lab i and these values should, accounting the uncertainties, be in agreement with each other. Furthermore, the standard uncertainties from the corresponding BIPM.RI(I)-K1 and BIPM.RI(I)-K4 results are combined according to GUM to give the standard uncertainty on $R(X)_{Lab\ i,\ BIPM\ mean}$ (for both chambers and both radiation quantities individually).

As several linking labs participated in the present comparison exercise mean linking factors $Q(X)_{mean}$ relative to BIPM.RI(I)-K1 for the air kerma and relative to BIPM.RI(I)-K4 for the dose to water measurements are calculated for both chambers and both radiation quantities.

Table 6: Linking factors $Q(K_{Air})_{mean}$ and $Q(D_W)_{mean}$

Linking factor to BIPM.RI(I)-K1 for Co-60 Air Kerma calibration for chamber PTW 30004 #286

Lab i	$Q(K_{Air})_{Lab\ i}$: $R(K_{Air})_{Lab\ i,\ mean}$ / $R(K_{Air})_{Lab\ i,\ BIPM}$	u(k=1)	$R(K_{Air})_{Lab\ i,\ BIPM}$: results from BIPM.RI(I)-K1	u(k=1)	Year
LNE-LNHB	0.9995	0.0042	0.9994	0.0018	2013
BEV mean	1.0028	0.0035	1.0034	0.0021	2009
VSL	0.9983	0.0036	0.9985	0.0022	2005
$Q(K_{Air})_{mean}$	1.0002	standard uncertainty on $R(K_{Air})_{Lab\ i,\ BIPM\ mean}$		0.0020	
stdev mean	0.0013	experimental standard deviation of the mean			

Linking factor to BIPM.RI(I)-K1 for Co-60 Air Kerma calibration for chamber PTW 30006 #036

Lab i	$Q(K_{Air})_{Lab\ i}$: $R(K_{Air})_{Lab\ i,\ mean}$ / $R(K_{Air})_{Lab\ i,\ BIPM}$	u(k=1)	$R(K_{Air})_{Lab\ i,\ BIPM}$: results from BIPM.RI(I)-K1	u(k=1)	Year
LNE-LNHB	0.9996	0.0042	0.9994	0.0018	2013
BEV mean	1.0023	0.0035	1.0034	0.0021	2009
VSL	0.9979	0.0036	0.9985	0.0022	2005
$Q(K_{Air})_{mean}$	0.9999	standard uncertainty on $R(K_{Air})_{Lab\ i,\ BIPM\ mean}$		0.0020	
stdev mean	0.0013	experimental standard deviation of the mean			

Linking factor to BIPM.RI(I)-K4 for Co-60 Dose to Water calibration for chamber PTW 30004 #286

Lab i	$Q(D_W)_{Lab\ i}$: $R(D_W)_{Lab\ i,\ mean}$ / $R(D_W)_{Lab\ i,\ BIPM}$	u(k=1)	$R(D_W)_{Lab\ i,\ BIPM}$: results from BIPM.RI(I)-K4	u(k=1)	Year
METAS mean	0.9991	0.0071	1.0001	0.0052	2013
LNE-LNHB	1.0018	0.0051	0.9971	0.0039	2013
BEV mean	1.0027	0.0060	0.9996	0.0044	2009
$Q(D_W)_{mean}$	1.0012	standard uncertainty on $R(K_{Air})_{Lab\ i,\ BIPM\ mean}$		0.0046	
stdev mean	0.0010	experimental standard deviation of the mean			

Linking factor to BIPM.RI(I)-K4 for Co-60 Dose to Water calibration for chamber PTW 30006 #036

Lab i	$Q(D_W)_{Lab\ i}$: $R(D_W)_{Lab\ i,\ mean}$ / $R(D_W)_{Lab\ i,\ BIPM}$	u(k=1)	$R(D_W)_{Lab\ i,\ BIPM}$: results from BIPM.RI(I)-K4	u(k=1)	Year
METAS mean	0.9993	0.0070	1.0001	0.0052	2013
LNE-LNHB	1.0022	0.0051	0.9971	0.0039	2013
BEV mean	1.0013	0.0060	0.9996	0.0044	2009
$Q(D_W)_{mean}$	1.0009	standard uncertainty on $R(K_{Air})_{Lab\ i,\ BIPM\ mean}$		0.0046	
stdev mean	0.0011	experimental standard deviation of the mean			

The standard deviations on the $Q(X)_{mean}$ constitute the standard uncertainty contributions linking the actual comparison results with the corresponding key comparisons BIPM.RI(I)-K1 and BIPM.RI(I)-K4. As can be seen in the Table 6, the linking factors $Q(X)_{Lab\ i}$ mutually agree very well, if the usual extended 95 % confidence level uncertainties U(k=2) are considered.
In 2017 VSL has participated in BIPM.RI(I)-K4. The resulting degrees of equivalence of that comparison (0.9960), agrees very well with the degrees of equivalence linked to BIPM.RI(I)-K4 reported in Table 7 (0.9952 and 0.9963 for the PTW 30004 #286 and PTW 30006 #036 respectively) and can be considered as an independent verification of the applied linking method.

4.4 Degrees of equivalence

The mean linking factors $Q(X)_{mean}$ allow for the calculation of virtual ratios "$N(X)_{Lab\ i}$ / $N(X)_{BIPM}$" by dividing the actual comparison results $R(X)_{Lab\ i,\ mean}$ through the corresponding $Q(X)_{mean}$ for each chamber in each radiation quantity; (X) standing for either (K_{Air}) or (D_W).
Further, following the BIPM.RI(I) comparison publications [9-15] a degree of equivalence linked to BIPM.RI(I)-K1 and BIPM.RI(I)-K4 among the actual calibration coefficient data $N(X)_{Lab\ i}$ may be calculated as "$(N(X)_{Lab\ i}$ / $N(X)_{BIPM})$ - 1" expressed in "mGy·Gy-1" (Table 7).

Table 7: Degrees of equivalence for the results reported above

Co-60 Air Kerma calibration for chamber PTW 30004 #286

Lab i	"$N(K_{Air})_{Lab\ i}$ / $N(K_{Air})_{BIPM}$"	Degree of Equivalence with its uncertainty U(k=2) as linked to BIPM.RI(I)-K1			
BEV mean	1.0060	6.0	±	7.5	$mGy \cdot Gy^{-1}$
CIEMAT	1.0007	0.7	±	7.6	$mGy \cdot Gy^{-1}$
LNE-LNHB	0.9987	-1.3	±	9.1	$mGy \cdot Gy^{-1}$
METAS mean	1.0001	0.1	±	10.5	$mGy \cdot Gy^{-1}$
SCK-CEN	0.9966	-3.4	±	12.6	$mGy \cdot Gy^{-1}$
VSL	0.9966	-3.4	±	7.5	$mGy \cdot Gy^{-1}$

Co-60 Air Kerma calibration for chamber PTW 30006 #036

Lab i	"$N(K_{Air})_{Lab\ i}$ / $N(K_{Air})_{BIPM}$"	Degree of Equivalence with its uncertainty U(k=2) as linked to BIPM.RI(I)-K1			
BEV mean	1.0058	5.8	±	7.3	$mGy{\cdot}Gy^{-1}$
CIEMAT	1.0004	0.4	±	7.4	$mGy{\cdot}Gy^{-1}$
LNE-LNHB	0.9991	-0.9	±	8.9	$mGy{\cdot}Gy^{-1}$
METAS mean	1.0001	0.1	±	10.3	$mGy{\cdot}Gy^{-1}$
SCK-CEN	0.9986	-1.4	±	12.5	$mGy{\cdot}Gy^{-1}$
VSL	0.9965	-3.5	±	7.4	$mGy{\cdot}Gy^{-1}$

Co-60 Dose to Water calibration for chamber PTW 30004 #286

Lab i	"$N(D_W)_{Lab\ i}$ / $N(D_W)_{BIPM}$"	Degree of Equivalence with its uncertainty U(k=2) as linked to BIPM.RI(I)-K4			
BEV mean	1.0011	1.1	±	11.4	$mGy{\cdot}Gy^{-1}$
CIEMAT	1.0023	2.3	±	11.1	$mGy{\cdot}Gy^{-1}$
LNE-LNHB	0.9977	-2.3	±	10.4	$mGy{\cdot}Gy^{-1}$
METAS mean	0.9980	-2.0	±	12.6	$mGy{\cdot}Gy^{-1}$
SCK-CEN	0.9985	-1.5	±	15.5	$mGy{\cdot}Gy^{-1}$
VSL	0.9952	-4.8	±	11.6	$mGy{\cdot}Gy^{-1}$

Co-60 Dose to Water calibration for chamber PTW 30006 #036

Lab i	"$N(D_W)_{Lab\ i}$ / $N(D_W)_{BIPM}$"	Degree of Equivalence with its uncertainty U(k=2) as linked to BIPM.RI(I)-K4			
BEV mean	1.0000	0.0	±	11.3	$mGy{\cdot}Gy^{-1}$
CIEMAT	1.0026	2.6	±	10.9	$mGy{\cdot}Gy^{-1}$
LNE-LNHB	0.9983	-1.7	±	10.2	$mGy{\cdot}Gy^{-1}$
METAS mean	0.9985	-1.5	±	12.5	$mGy{\cdot}Gy^{-1}$
SCK-CEN	0.9987	-1.3	±	15.3	$mGy{\cdot}Gy^{-1}$
VSL	0.9963	-3.7	±	11.5	$mGy{\cdot}Gy^{-1}$

Ideally, for the linking laboratories, the values of $N(D_W)_{Lab\ i}$ / $N(D_W)_{BIPM}$ should give the same results than those obtained during their comparison with the BIPM ($R(X)_{Lab\ i,\ BIPM}$ in Table 6). The reported 95 % confidence level uncertainties U(k=2) are calculated from the standard uncertainties on the comparison results $R(X)_{Lab\ i,\ mean}$ combined with the standard deviations on $Q(X)_{mean}$ according to the propagation of uncertainties on a ratio, then square summed with the corresponding pooled uncertainties on $R(K_{Air})_{Lab\ i,\ BIPM\ mean}$ and completed by an overall coverage factor of 2.

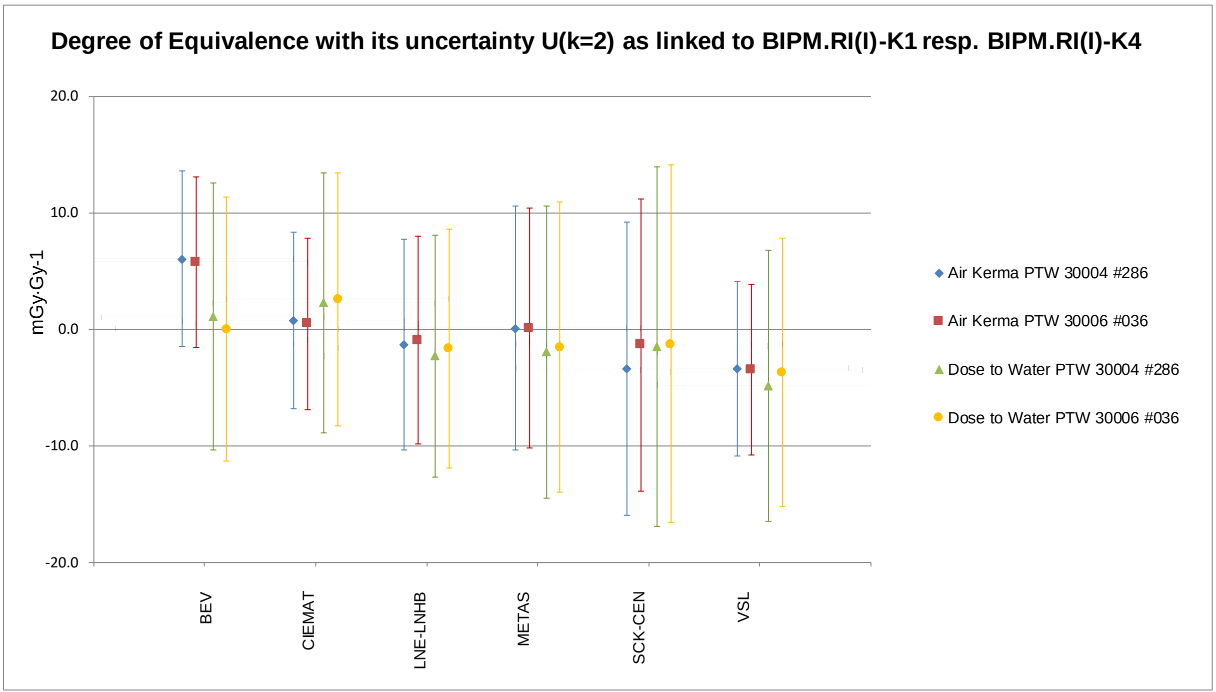

Figure 2: Degree of Equivalence as linked to BIPM.RI(I)-K1 and BIPM.RI(I)-K4 with corresponding extended uncertainties U(k=2) for both ionization chambers given in alphabetical order of the participants

5. Conclusion

The air kerma and absorbed dose to water standards for ^{60}Co radiotherapy beams of 6 NMIs, all members of EURAMET, have been compared by circulating 2 transfer standards.

The comparison results are evaluated in terms of air kerma and absorbed dose to water for both transfer standards as the ratio of the participants' calibration coefficients to the corresponding arithmetic mean over all participants' results with submeans propagated for the two BEV and three METAS measurements as their respective repeated measurements are correlated. The results are found within the resulting expanded uncertainties "1±U(k=2)" with the exception of the values $R(K_{Air})_{Lab\ i,\ mean}$ from BEV. Therefore, this comparison of air kerma and absorbed dose to water in ^{60}Co can be used to support the calibration and measurement capabilities (CMC) of the participants in the context of the CIPM - Mutual Recognition Arrangement (CIPM-MRA) [1-5]. Nevertheless, this report does not state if the claimed uncertainties correspond to those in the published CMS's. This goes beyond the protocol of this comparison.

Further, the results are linked to the CCRI(I) key comparisons BIPM.RI(I)-K1 and BIPM.RI(I)-K4 through the linking laboratories BEV, LNE-LNHB and VSL for the air kerma and through BEV, LNE-LNHB and METAS for the absorbed dose to water standards. A degree of equivalence calculation for the actual comparison results is proposed according to the BIPM.RI(I) comparison publications [9-15]

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