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Nordic calibration comparison for radiotherapy dosemeters

Cylindrical and plane-parallel ionization chambers

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Abstract

This report describes a calibration comparison for cylindrical and plane-parallel ionization chambers aimed for reference dosimetry in external megavoltage radiotherapy in accordance with the IAEA TRS-398 code of practice. The work has been carried out by Nordic secondary standard dosimetry laboratories (SSDLs) located in the radiation safety authorities in Sweden (SSM), Norway (DSA), Denmark (SIS) and Finland (STUK) in addition to the Technical University of Denmark (DTU). A calibration and communication protocol for the comparison was established prior to the measurements according to international recommendations. Two types of ionization chambers were circulated among the participating laboratories; a cylindrical Farmer-type chamber and a plane-parallel chamber. Both chambers were calibrated by the laboratories for absorbed dose to water in Co-60 gamma beams. Calibrations were carried out using both (i) the laboratories own traceable electrometer systems and (ii) a transfer electrometer that was circulated with the transfer chambers. Correction factors for chamber polarity and recombination were measured, and the transfer electrometer was calibrated by most participating laboratories for charge and/or current measurements at the range relevant for the chamber measurements. All calibration coefficients were in good agreement and well inside the estimated uncertainties. This comparison therefore supports that the calibration capabilities in Nordic countries are consistent for both type of radiotherapy dosemeters and fulfill international requirements. The comparison also demonstrates a well operating and powerful Nordic cooperation in the field of radiation dosimetry.

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1 Introduction

Reference dosimetry for external beam radiotherapy are based on the measurement of absorbed dose to water in well-defined reference conditions using ionization chambers (IAEA TRS 398, 2006; IAEA TRS 469, 2009). Cylindrical ionization chambers are used, for example, in photon beams from megavoltage linear accelerators and plane-parallel ionization chambers are used in electron beams. Ionization chambers are often calibrated in Co-60 beams in national metrology laboratories and corrected to the clinical beams using generic correction factors provided in the IAEA TRS-398 code of practice.

In the Nordic countries practical measurement experience in hospitals arising from inspections and verification measurements as well as in calibration laboratories arising from re-calibrations of ionization chambers indicate that measurement results obtained using plane-parallel ionization chambers vary more than measurement results obtained with cylindrical ionization chambers. This may simply partly reflect the additional complexity associated in vertical beams with the correct positioning of plane-parallel chambers compared with a simple centering procedure for cylindrical chambers as these chambers have their reference point on the central axis. Comparisons for the cylindrical ionization chambers have been performed earlier, e.g. among EURAMET (Csete I et al., 2010) and are nowadays performed regularly for instance by IAEA (IAEA, 2019), but the comparisons for plane-parallel ionization chambers are rare, possible those might not have been available in the European level beforehand. The Nordic secondary standard dosimetry laboratories (SSDLs) located in the radiation safety authorities in Sweden (SSM), Norway (DSA), Denmark (SIS) and Finland (STUK) in addition to the Technical University of Denmark (DTU) therefore decided to carry out a calibration comparison for absorbed dose to water for plane-parallel ionization chambers.

The comparison was organized in two parts. The first round of the comparison was performed in the late 2014. In this comparison a plane-parallel and a cylindrical ionization chamber (and no additional equipment such as cables or electrometer) were circulated and calibration measurements were made in the Nordic SSDLs. In this first round of comparison the results for the cylindrical ionization chamber were in good agreement, but the results for the plane-parallel ionization chamber varied more than expected based on the uncertainty estimates. Eventually, it was concluded that the measurement protocol was not established in sufficient detail and thus, it was decided to perform a second round for the comparison with a better established protocol. The calibration protocol was established in accordance with the international recommendations IAEA TRS 398 and IAEA TRS 469 (IAEA TRS 398, 2006; IAEA TRS 469, 2009).

Two ionization chambers, a cylindrical Farmer-type chamber and a plane-parallel chamber, were circulated among the participating laboratories in accordance with a predefined scheme. The task of the laboratories was to calibrate both chambers for absorbed dose to water in Co-60 gamma beams. The laboratories should use both (i) the laboratories own electrometer systems with full traceability to electrical standards and (ii) a transfer electrometer that was circulated with the transfer chambers. The transfer electrometer was to be used without separate calibration (i.e. without traceability to electrical standards). In this case, the calibration laboratory would effectively calibrate the combined system of ionization chamber and electrometer.

The laboratories should also measure correction factors for chamber polarity and recombination, and if possible, the transfer electrometer should be calibrated by the laboratories for charge and/or current measurements at the range relevant for the chamber measurements.

Here in this report, the protocol and results for the second round of Nordic plane-parallel chamber comparison are presented.

2 Comparison procedure

2.1 The object of the comparison

The object of the comparison was to compare and validate the calibration practices of the participating laboratories for quality assurance purposes. Two different types of ionization chambers were used (cylindrical and plane-parallel type) as well as an electrometer and suitable cable and connectors. The comparison could therefore compare the whole measurement chain. The compared quantity was absorbed dose to water using Co-60 gamma radiation. The comparison was primarily motivated by concerns related to the calibration of plane-parallel chambers, as calibration comparisons for these chambers are rare. A cylindrical chamber was included as a control in the comparison.

2.2 Participants and the course of the comparison

Five participants, listed in table 1 below, were included in the comparison. SSM acted as a pilot laboratory for the measurement and owns both ionization chambers used in the comparison. STUK acted as a reporting laboratory for the comparisons, while SIS owns the transfer electrometer used in the comparison.

Table 1. Participating institutes and their traceability for absorbed dose to water in Co-60 gamma beam, in the order of measurements.

SSDL	Institute	Country	Traceability
SSM	Swedish Radiation Safety Authority	Sweden	BIPM
SIS	Danish Health Authority, Radiation Protection	Denmark	PTB
DTU	Technical University of Denmark	Denmark	PTB
STUK	Radiation and Nuclear Safety Authority	Finland	BIPM
DSA	Norwegian Radiation and Nuclear Safety Authority	Norway	BIPM

SSM carried out the first measurements for the comparison in November 2017 and SSM also performed a second set of measurements in April 2018 after the other laboratories had completed their measurements. The chambers remained with each participants 2–3 weeks as a few days were passed for the shipment of the equipment. The results were reported to the coordinator (STUK) using excel-sheet after measurements. A common uncertainty budget template was shared among the participants and the uncertainties U_c were given in accordance with the Guide to the Expression of Uncertainties in measurements with the coverage factor $k = 2$ (JCGM, 2008).

2.3 Radiation quality and reference conditions

The radiation quality used was Co-60. The laboratories measured calibration coefficients for both transfer chambers using (i) the laboratory electrometer system and (ii) the transfer electrometer. The calibration coefficients derived from the two electrometers at each laboratory were reported separately. The calibration coefficients for the transfer chambers were given in terms of absorbed dose to water per charge in units of Gy/C and referred to standard condition of air temperature, pressure and relative humidity; T = 293.15 K, P = 101.325 kPa and 50 % rh. The recommended source to chamber distance in Co-60 beam was 1000 mm and the recommended field size was 10 cm x 10 cm. If possible, the laboratories additionally measured recombination and polarity correction factors for the chambers as well as the electrometer calibration factor (k_{elec} as defined in IAEA TRS-398).

2.4 Transfer instruments

Tables 2 and 3 and figure 1 provide information about the transfer instrumentation (an electrometer, cables and connectors as well as two transfer chambers).

Table 2. Technical data of the additional transfer equipment.

Equipment type	Electrometer	Connectors	Connecting cable
Model	UNIDOS Webline		
Serial number	002023		
Connector type	TNC-F	TNC-M/BNC-banana	TNC-M/TNC-F
Other remarks	To be used with both chambers	15 m, to be used with plane-parallel chamber	10 m, to be used with cylindrical chamber

Table 3. Technical data of the transfer chambers.

Chamber type	**IBA FC65-G**	**PTW Roos TB34001**
Serial number	3738	0706
Geometry	thimble	plane-parallel
Wall material	graphite	1.01 mm PMMA, 0.02 mm graphite, 0.1 mm lacquer
Wall thickness	0.4 mm of outer electrode	132 mg/cm^2
External diameter [mm]	8.6 (stem diameter)	43.95 (total)
Cavity height [mm]	23	5.8
Nominal volume [cm^3]	0.65	0.35
Reference point (on a chamber axis)	13 mm from the distal end of the chamber thimble (w/o build-up cap)	inside of entrance window (at the center of the chamber); 1 mm behind the entrance side according to TRS398
Polarising voltage of a chamber / V	+300 V on collector (central) electrode, 0 V on chamber wall with PTW UNIDOS Webline s/n 002023 -300 V, Medium range	+200 V on collector (central) electrode, 0 V on chamber wall with PTW UNIDOS Webline s/n 002023 -200 V, Medium range
Connector type	TNC triaxial	BNC/banana (M)
Other remarks	waterproof	waterproof
Suggested voltages for recombination measurements	+300 V / +75 V	+200 V / +60 V

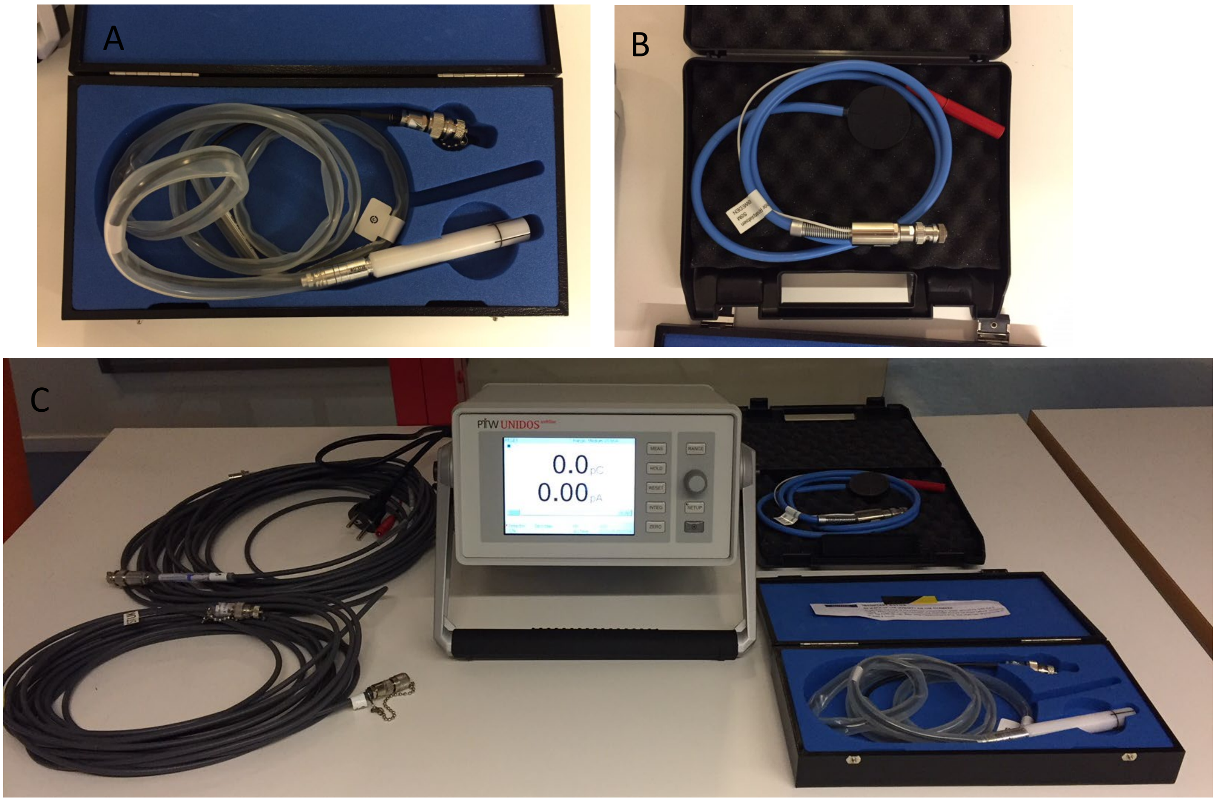

Figure 1. Transfer instruments. A) Cylindrical ionization chamber IBA FC65G-3738, B) Plane-parallel ionization chamber PTW Roos TB34001-0706, C) All transfer instruments including ionization chambers, electrometer and connection cables.

Each laboratory established a reference rate for absorbed dose to water at their facilities in accordance with their own procedure typically following an equation such as:

$$\dot{D}_{\mathrm{w}} = N_{\mathrm{D,w,PSDL}} I_{\mathrm{SSDL}} \tag{1}$$

where $N_{\mathrm{D,w,PSDL}}$ is the calibration coefficient used by the given SSDL in order to reach traceability to a primary standards laboratory for absorbed-dose-to-water measurements in Co-60 beams, and where I_{SSDL} is the ionization current measured by the SSDL with an electrometer system with traceability to electrical standards. Each SSDL would position a transfer chamber at the reference dose rate such that the calibration coefficient for the transfer chamber could be computed as:

$$N_{\mathrm{D,w}} = \frac{\dot{D}_{\mathrm{w}}}{I_{\mathrm{M}}} \tag{2}$$

where $\dot{D}_{\mathrm{w}}$ is the reference absorbed dose to water rate from above, and where I_{M} is signal from the transfer chamber measured by the SSDL at the specific reference polarities stated in table 3 using (i) either their own electrometer systems with traceability to electrical standards or (ii) the transfer electrometer. In accordance with TRS-398, I_{M} is corrected to standard conditions of air temperature, pressure and relative humidity chosen for the comparison. No further correction (for example, for polarity or recombination) should be applied to I_{M}.

The reference value for the comparison was obtained as an average of calibrations coefficients from all participating laboratories and the results for both chambers are presented separately. R_{SSDL} values for each laboratory are calculated by relation:

$$R_{\mathrm{SSDL}} = \frac{N_{\mathrm{D,w,SSDL}}}{N_{\mathrm{D,w,average}}} \tag{3}$$

where $N_{\mathrm{D,w,SSDL}}$ is the calibration coefficient of the each laboratory and $N_{\mathrm{D,w,average}}$ is the average of all results for the specific chamber.

Uncertainties U_{c} for each laboratory were evaluated using a common uncertainty budget.

Uncertainty for $N_{\mathrm{D,w,average}}$ was calculated based on the each laboratory's uncertainty budget. The contribution of the PSDL was subtracted from the original uncertainty budgets to obtain uncertainty budget only for the laboratory. Uncertainty for $N_{\mathrm{D,w,average}}$ was calculated as a square root of the square sum of each laboratory's uncertainty and uncertainty of PSDL's was added once i.e.

$$U_{N_{\mathrm{D,w,average}}} = \sqrt{U^2_{\mathrm{C,SSM}} + U^2_{\mathrm{C,SIS}} + U^2_{\mathrm{C,DTU}} + U^2_{\mathrm{C,STUK}} + U^2_{\mathrm{C,DSA}} + U^2_{\mathrm{C,BIPM}} + U^2_{\mathrm{C,PTB}}} \tag{4}$$

and thus, the uncertainty for R for each laboratory was obtained as a square root of a square sum of each laboratory's own uncertainty and the uncertainty for $N_{\mathrm{D,w,average}}$. Uncertainties for R are calculated only for the laboratory electrometers.

Degrees of equivalence were calculated using the mean of R values with laboratory electrometer results for each laboratory as the comparison reference value (CRV). To obtain uncertainty for degrees of equivalence all uncertainties from the primary laboratories (BIPM or PTB) were subtracted from the original uncertainty budgets and if the uncertainty budgets deviated for two chambers, the budget for the cylindrical chamber was used. The deviation is equal to R-1.

The correction factors for polarity k_{pol} and recombination k_{rec} were determined either by laboratory's own methods or calculated according to IAEA TRS 398 by the following relations:

$$k_{\mathrm{pol}} = \frac{\left(|M_+| + |M_-|\right)}{2M} \tag{5}$$

in which M_+ and M_- are measured values (electrometer readings) obtained at positive and negative polarity, respectively, and M is a measured value (electrometer reading) with routinely used polarizing voltage of the chamber (in here, +300 V or +200 V, depending on the chamber).

$$k_{\mathrm{rec}} = \frac{\left(V_1/V_2\right)^2 - 1}{\left(V_1/V_2\right)^2 - \left(M_1/M_2\right)} \tag{6}$$

in which V_1 is the routinely used polarizing voltage (in here, +300 V or +200 V, depending on the chamber), V_2 is an another polarizing voltage used in a measurement to which applies that $V_1/V_2 \geq 3$ (in here , +75 V or +60 V) and M_1 and M_2 are measured values using the respective polarizing voltages. One laboratory (DTU) measured both initial and volume recombination using the Niatel method (Andreo et al., 2017). The measurement of volume recombination provides a direct estimate of changes in recombination associated with difference in dose rate during calibration.

The electrometer sensitivity correction factor k_{elec} in medium range was determined according to the protocol of each laboratory.

3 Results

3.1 Cylindrical ionization chamber IBA FC65G-3738

For the cylindrical ionization chamber IBA FC65G-3738 the results with both electrometers and some key parameters are presented in figures 2–3 and table 4.

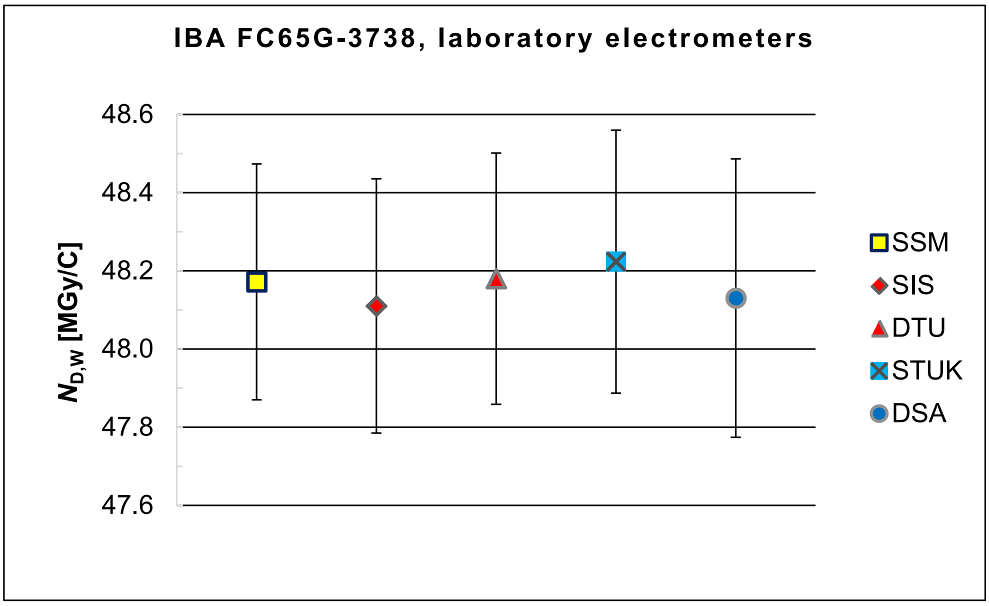

Figure 2. The results for the cylindrical chamber using laboratory electrometers.

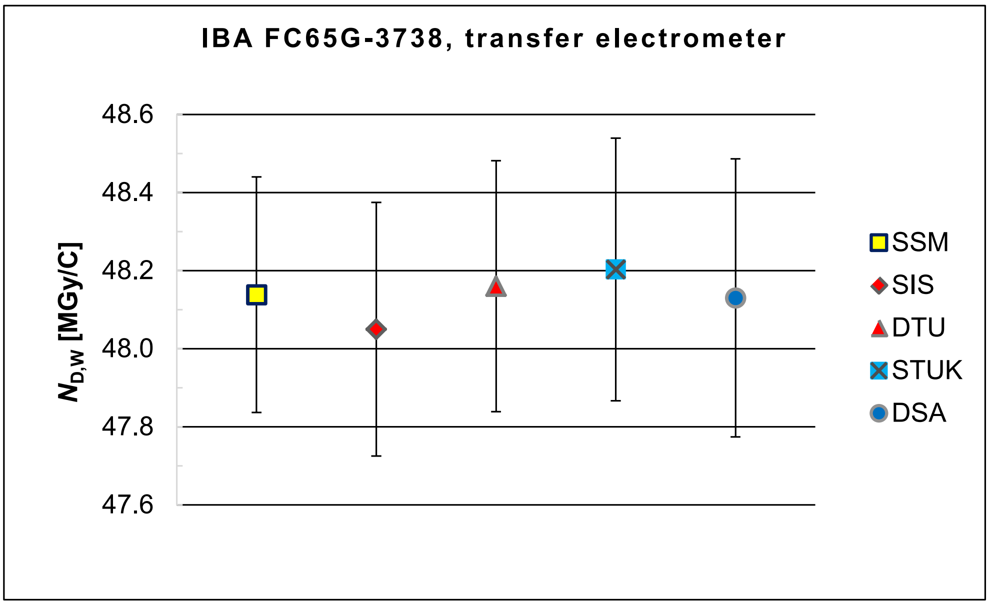

Figure 3. The results for the cylindrical chamber using the transfer electrometer.

Table 4. The results for the cylindrical chamber FC65G-3738.

SSDL	**$N_{D,w}$ (lab)[1] [MGy/C]**	**$N_{D,w}$ (transfer) [2] [MGy/C]**	**U_c[3] [%]**	**R_{lab} [1,3]**	**$R_{transfer}$[2]**	**k_{pol}[1]**	**k_{rec}[1]**	**$\dot{D}_w$ [mGy/s]**
SSM	48.17	48.14	0.63	1.0002 (U_c = 1.2)	1.0000	1.00083	1.00018	14.3
SIS	48.11	48.05	0.68	0.9989 (U_c = 1.3)	0.9982	1.0011	1.0010	7.63
DTU	48.18	48.16	0.67	1.0004 (U_c = 1.3)	1.0005	1.0008	1.0007	16
STUK	48.22	48.20	0.70	1.0013 (U_c = 1.2)	1.0014	1.00074	1.00017	10.9
DSA	48.13	48.05	0.74	0.9993 (U_c = 1.3)	0.9999	1.0010	1.0002	8.4
SSM	48.17	48.14						13.6
Average[3]	48.163 (U_c = 1.2)	48.120				1.0009	1.0005	
Max-Min / ave [%][4]	0.24	0.32						
Relative st.dev. [%][5]	0.08	0.13				0.01	0.03	

[1] Results obtained with laboratory electrometer

[2] Results obtained with transfer electrometer

[3] Relative expanded uncertainty U_c given with coverage factor k = 2.

[4] (Maximum $N_{D,w}$ – Minimum $N_{D,w}$) / Average $N_{D,w}$ [%]

[5] Standard deviation of the entire population of $N_{D,w}$ / Average $N_{D,w}$ [%]

As observed from the figures and table above all $N_{D,w}$ are in close agreement and well inside the uncertainty estimates. This suggests that the quality of the investigated calibration capabilities are equivalent for the participating laboratories. The results show a minor variance, however, this variance cannot be explained by traceability and difference between primary laboratories (BIPM vs. PTB) (BIPM.RI[I]-K4 key comparison).

3.2 Plane-parallel ionization chamber PTW TB34001-0706

For the plane-parallel chamber PTW TB34001-0706 the results with both electrometers and some key parameters are presented in figures 4–5 and table 5.

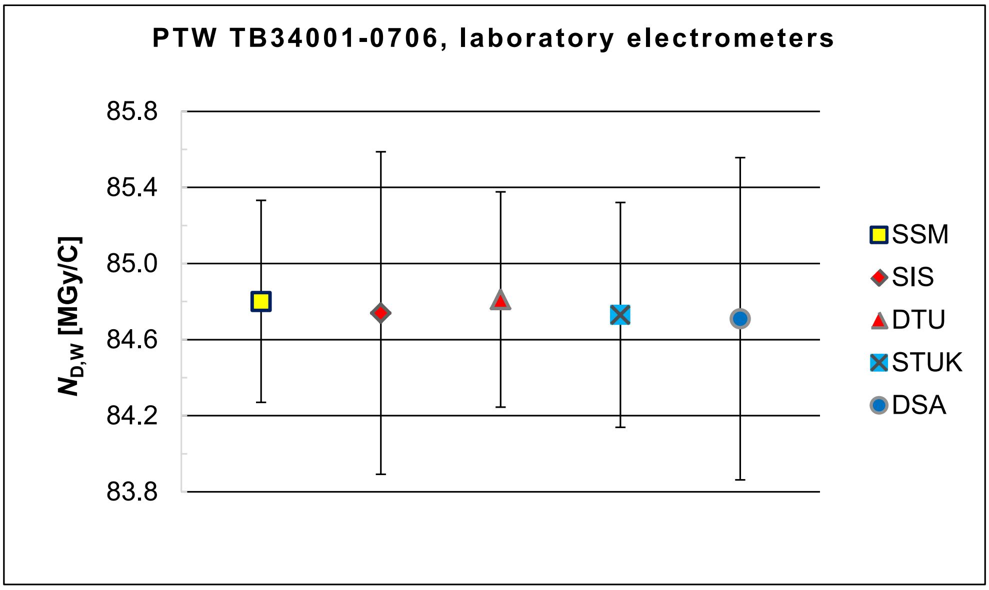

Figure 4. The results for the plane-parallel chamber using laboratory electrometers.

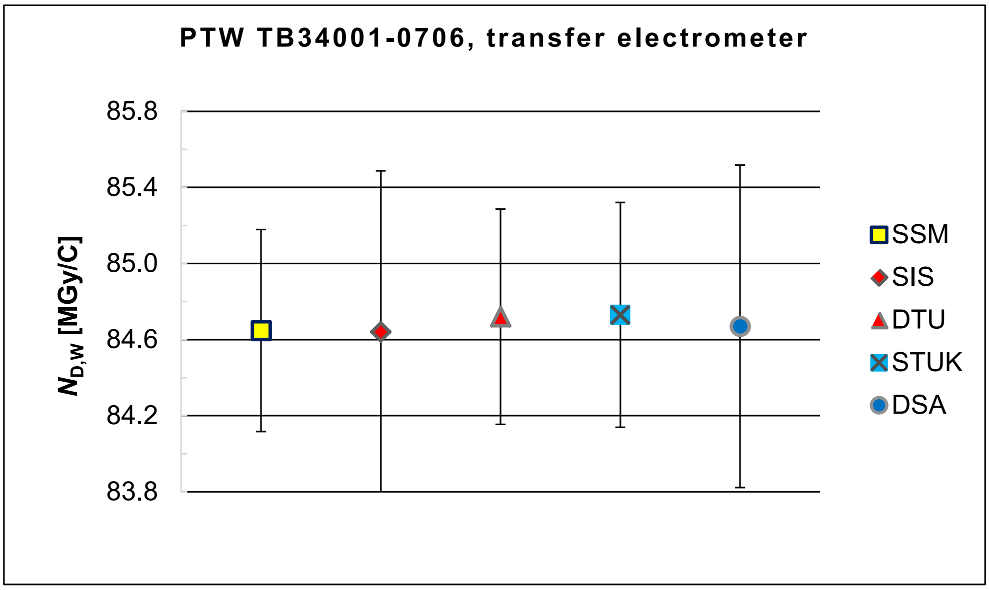

Figure 5. The results for the plane-parallel chamber using the transfer electrometer.

Table 5. The results for the plane-parallel chamber PTW TB34001-0706. Dose rates are the same as for the cylindrical chamber.

SSDL	**$N_{\mathrm{D,w}}$ (lab)[1] [MGy/C]**	**$N_{\mathrm{D,w}}$ (transfer)[2] [MGy/C]**	**U_c[3] [%]**	**R_lab[1]**	**R_transfer[2]**	**k_pol[1]**	**k_rec[1]**
SSM	84.72	84.65	0.63	1.0005 (U_c = 1.6)	0.9996	1.0014	1.0002
SIS	84.74	84.64	1.00	0.9998 (U_c = 1.8)	0.9995	1.0009	1.0010
DTU	84.73	84.72	0.67	1.0006 (U_c = 1.6)	1.0005	1.0009	1.0012
STUK	84.81	84.73	0.70	0.9997 (U_c = 1.6)	1.0006	1.0009	1.0002
DSA	84.71	84.67	1.0	0.9994 (U_c = 1.7)	0.9999	1.0005	1.0003
SSM	84.88						
Average	84.742 (U_c = 1.5)	84.682				1.0009	1.0006
Max-Min / Ave [%][4]	0.12	0.11					
Relative st.dev. [%][5]	0.04	0.04				0.03	0.04

[1] Results with laboratory electrometer
[2] Results with transfer electrometer
[3] Relative expanded uncertainty U_c given with coverage factor k = 2.
[4] (Maximum $N_{\mathrm{D,w}}$ – Minimum $N_{\mathrm{D,w}}$) / Average $N_{\mathrm{D,w}}$ [%]
[5] Standard deviation of the entire population of $N_{\mathrm{D,w}}$ / Average $N_{\mathrm{D,w}}$ [%]

As observed from the figures and table above, all $N_{\mathrm{D,w}}$ are in close agreement and well inside the uncertainty estimates both for the cylindrical and the plane-parallel chamber. The data therefore suggests that the quality of the measurement are equivalent for the participating laboratories. Unfortunately, the plane-parallel chamber used as a transfer chamber broke (water leakage) and the second round measurements by SSM might not be fully adequate.

The initial hypothesis was that the results for plane-parallel chamber would vary more than for the cylindrical chamber. However, this was not the case – rather, the results vary even less for the plane-parallel chamber. Similarly as for the cylindrical chamber the minor variation observed in the results cannot be explained by differences between primary laboratories (BIPM vs. PTB) (BIPM.RI[I]-K4 Key comparison).

3.3 Degrees of equivalence for comparison

The degrees of equivalence for the comparison were calculated based on *R* values for the each laboratory and from uncertainties the primary laboratory contribution was subtracted. The result for the degrees of equivalence are presented in table 6 and figure 6 below.

Table 6. Degrees of equivalence for the comparison.

SSDL	**Mean *R***	**Deviation: *R* - 1 [ppm]**	**U_c w/o PSDL U_c k = 1**	**U_c for comparison k = 2**
SSM	1.00035	0.35	0.10	0.21
SIS	0.99935	-0.65	0.23	0.46
DTU	1.0005	0.50	0.22	0.45
STUK	1.0005	0.50	0.19	0.37
DSA	0.99935	-0.65	0.22	0.44

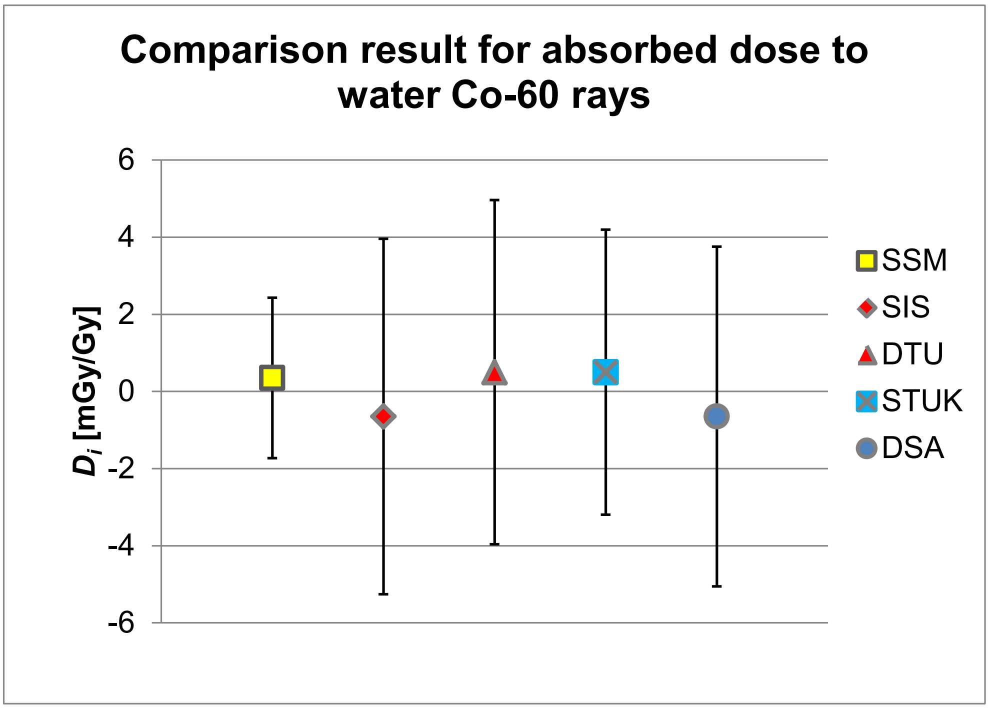

Figure 6. Degrees of equivalence for the comparison.

As observed from Table 6 and figure 6 the comparison results are well within the uncertainties given by the participants. The results presented show an agreement between the SSDLs and CRV at the level of the standard uncertainty of the comparison of 2.1, 4.6, 4.5, 3.7 and 4.4 parts in 10^3 for SSM, SIS, DTU, STUK and DSA, respectively.

3.4 Other measurements

The results for k_{pol} and k_{rec} are presented in tables 4 and 5 together with calibration coefficients for the chambers. The correction factors are measured with each laboratory's own electrometers. All laboratories identified that correction factors for polarity and recombination are small. However, the numbers in the table are presented with more significant numbers than the two voltage method would allow (uncertainty approximately 0,1 % for $k_{\mathrm{rec}} < 1.03$) according to IAEA TRS398. Additionally, a dose rate is known to have an effect on k_{rec}. Thus, it cannot be concluded without uncertainty estimates whether the slight numerical differences between the measurement results are significant or not, but it seems that the accuracy of two voltage method used by the most of the laboratories does not allow distinguishing such a small differences as observed here.

The electrometer sensitivity correction factor k_{elec} for the medium range of the transfer electrometer are presented below in table 6 for those laboratories with capabilities to measure the value. Some of the laboratories give this factor with more significant numbers than others. Based on the uncertainty estimates given, it can be concluded that there's a good agreement in the quality of electrometer calibration for the participating laboratories.

Table 7. Results for the electrometer sensitivity correction k_{elec} for the transfer electrometer.

SSDL	**k_{elec} (Medium range)**	**U_c (k = 2)**
SSM	0.9991	0.0012
DTU	0.9992	0.0010
STUK	0.999	0.001
DSA	0.9990	0.0012

4 Conclusions

The study demonstrated good agreement for calibration results among the participating laboratories. All results were well inside the stated uncertainties. The results showed no significant difference between calibration results for the plane-parallel chamber and calibration results for the cylindrical chamber. The data did not indicate any systematic differences related to what primary standards laboratory that provided traceability to the gray (either PTB or BIPM).

In the first place this comparison was aimed as “a working comparison” and it demonstrated that all laboratories are well capable of calibration of both chamber types. Furthermore, the comparison demonstrated an easy and simple method to do regional comparisons showing the powerful Nordic cooperation in the field of radiation dosimetry and simultaneously highlighting the importance of a good measurement protocol. One lesson learned from this study was the importance to include detailed information of the connections/connectors (whether the polarizing voltages are in the wall or in the central electrode) and if possible, also to use a transfer electrometer in the comparisons like this. In the future, the comparison should be repeated in a fully blinded manner to be able to use it to truly support Calibration and Measurement Capabilities (CMCs) of the laboratories.

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APPENDIX

Uncertainty budget for cylindrical ionization chamber with laboratory electrometer

Co-60 beam, cylindrical chamber										
Participant	SSM		SIS		DTU		STUK		DSA	
Uncertainty budget for SSDL										
Absorbed dose	s_i	u_i	s_i	u_i	s_i	u_i	s_i	u_i	s_i	u_i
	Uncertainty (%)		*Uncertainty (%)*		*Uncertainty (%)*		*Uncertainty (%)*		*Uncertainty (%)*	
1 Reference standard, set-up and radiation field										
Calibration coefficient reported by PSDL	0.20	0.22		0.25		0.25	0.20	0.22	0.20	0.22
Long term stability of reference standard	0.05		0.08			0.03		0.04	0.07	
Spectral difference of SSDL and PSDL		0.06				0.05		0.06		0.04
Difference in radial non-uniformity of the beam and field size		0.004				0.05		0.12		0.10
Combined uncertainties of reference standard and setup	**0.21**	**0.23**	**0.08**	**0.25**	**0.00**	**0.26**	**0.20**	**0.26**	**0.21**	**0.24**
2 Use of reference standard										
Chamber and phantom positioning (distance, orientation, field size, water density, positioning of source)		0.018	0.01	* 0.15	0.03	0.11		0.03		0.09
Current/charge measurement including leakage	0.020	0.017	0.01	0.08			0.03	0.03	0.06	
Air temperature correction	0.006	0.018		0.07				0.02	0.06	
Air pressure correction	0.0007	0.007		0.01				0.004	0.02	
Humidity		0.020						0.06	0.02	
Deacay of Co-60		0.005								
Combined uncertainties in measuring with reference standard	**0.02**	**0.04**	**0.01**	**0.18**	**0.03**	**0.11**	**0.03**	**0.08**	**0.09**	**0.09**
Combined uncertainties in absorbed dose determination, K_{std} (1+2)	**0.21**	**0.23**	**0.08**	**0.31**	**0.03**	**0.28**	**0.20**	**0.27**	**0.23**	**0.26**
3 Use of transfer chamber										
Chamber and phantom positioning (distance, orientation, field size, water density, positioning of source)		0.018	0.01		0.03	0.17		0.03		0.09
Current/charge measurement including leakage	0.02	0.017	0.01	0.08			0.03	0.03	0.06	
Air temperature correction	0.006	0.018		0.07				0.02	0.06	
Air pressure correction	0.0007	0.01		0.01				0.004	0.02	
Humidity		0.020						0.06		
Deacay of Co-60		0.015						0.01		
Combined uncertainty in measuring with tranfer chamber	**0.02**	**0.04**	**0.01**	**0.11**	**0.03**	**0.17**	**0.03**	**0.08**	**0.09**	**0.09**
Relative combined standard uncertainties (1+2+3)	**0.21**	**0.23**	**0.08**	**0.33**	**0.04**	**0.33**	**0.20**	**0.28**	**0.25**	**0.28**
Total uncertainties for the absorbed dose calibration coefficient, 1σ	**0.31**		**0.34**		**0.33**		**0.35**		**0.37**	
Expanded uncertainties, k=2	**0.63**		**0.68**		**0.67**		**0.70**		**0.74**	

s_i represents the relative uncertainty estimated by statistical methods (Type A)

u_i represents the relative uncertainty estimated by other methods (Type B)

* includes uncertainty due to the use of working standard