Metrologia 53(2016)Tech. Suppl. 06007
EURAMET.RI(I)-S13 - Final report dated 2016-02-18

First international comparison of primary absorbed dose to water standards in the medium-energy X-ray range

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Abstract

This report presents the results of the first international comparison of primary measurement standards of absorbed dose to water for the medium-energy X-ray range. Three of the participants (VSL, PTB, LNE-LNHB) used their existing water calorimeter based standards and one participant (ENEA) recently developed a new standard based on a water-graphite calorimeter. The participants calibrated three transfer chambers of the same type in terms of absorbed dose to water ($N_{D\mathrm{w}}$) and in addition in terms of air kerma (N_K) using the CCRI radiation qualities in the range 100 kV to 250 kV. The additional N_K values were intended to be used for a physical analysis of the ratios $N_{D\mathrm{w}}$ / N_K.

All participants had previously participated in the BIPM.RI(I)-K3 key comparison of air kerma standards. Ratios of pairs of NMI's N_K results of the current comparison were found to be consistent with the corresponding key comparison results within the expanded uncertainties of 0.6 % – 1 %. The $N_{D\mathrm{w}}$ results were analysed in terms of the degrees of equivalence with the comparison reference values which were calculated for each beam quality as the weighted means of all results. The participant's results were consistent with the reference value within the expanded uncertainties. However, these expanded uncertainties varied significantly and ranged between about 1-1.8 % for the water calorimeter based standards and were estimated at 3.7 % for the water-graphite calorimeter.

It was shown previously that the ratios $N_{D\mathrm{w}}$ / N_K for the type of ionization chamber used as transfer chamber in this comparison were very close (within less than 1 %) to the calculated values of $(\overline{\mu}_{\mathrm{en}}/\rho)^{\mathrm{d}}_{\mathrm{w,a}}$, the mean values of the water-to-air ratio of the mass-energy-absorption coefficients at the depth d in water. Some of the participant's results deviated significantly from the expected behavior.

1. Introduction

The objective of this investigation was to carry out the first international comparison of primary measurement standards of absorbed dose to water for the medium-energy X-ray range. The comparison was part of the JRP HLT09 “Metrology for Radiotherapy using Complex Radiation Fields (MetrExtRT)” project. It is registered as EURAMET Project 1331 and as EURAMET.RI(I)-S13 in the key comparison data base (KCDB) of the Bureau International des Poids et Mesures (BIPM). The participants and contact persons are listed in table 1. Three of the participants (VSL, PTB, LNE-LNHB) already had operating primary standards based on water calorimeters as published in references [1-3]. The VSL water calorimeter for medium energy X-rays (100 – 250 kVp) has been described by de Prez and de Pooter [1] in 2008. In the meantime a new water calorimeter was designed and built [4]. The new water calorimeter has the same measurement depth as the previous one, i.e. 3.6 g/cm^2. The same high purity cell was used[1]. ENEA recently developed a new primary standard based on a water-graphite calorimeter [5].

Three waterproof Farmer-type chambers were used as transfer chambers. Each participant calibrated the transfer chambers under reference conditions as defined below (section 4) in terms of air kerma free in air and absorbed dose to water at a depth of 2 g/cm^2. Additional charge measurements were taken by PTB, ENEA and LNE-LNHB with the transfer chambers at a depth of 5 g/cm^2 in order to obtain the ratio of charges measured at these two depths. The objective of these additional measurements was to gain preliminary practical information about a possible future quality specifier.

Table 1: Participants and contact persons

Institute	Country	Contact person	E-mail of contact person
PTB (pilot)	Germany	Ludwig Büermann	ludwig.bueermann@ptb.de
LNE-LNHB	France	Benjamin Rapp	benjamin.rapp@cea.fr
VSL	Netherlands	Leon de Prez	ldprez@vsl.nl
ENEA	Italy	Massimo Pinto	massimo.pinto@enea.it

[1] Note: Recently, at the late Draft B stage of this report, VSL discovered an error in the model for the heat transport calculations of their water calorimeter. The used values for density and heat capacity of the glass volumes were incorrect. VSL will run simulations to investigate the consequences of this error on the correction factors and publish the results as soon as they are available

2. Transfer chambers

Three ionization chambers of the same type PTW TM30013 with a nominal volume of 0.6 cm^3 were provided by PTB and used as transfer chambers. More details about the transfer chambers are listed in table 2.

Table 2: Main technical data of the transfer chambers

Manufacturer, type and sn:	PTW, TM30013, serial numbers 7463, 7484, 7485
Nominal sensitive volume:	0.6 cm^3
Chamber voltage:	± (100 - 400) V, +300 V used for the comparison [a]
Leakage current:	≤ ±4fA
Nominal response:	20 nC/Gy
Minimum air kerma rate:	0.2 mGy/s (yields about 4 pA)

[a] Potential applied to the outer electrode (i.e. collecting electrode at ground potential)

3. Radiation qualities

The CCRI radiation qualities in the range from 100 kV to 250 kV (CCEMRI 1972, ref. [6]) were used for the comparison. For simplification, in the following these four qualities are coded as F100, F135, F180 and F250. The half-value layers (HVLs) of these qualities as realized at different sites are listed in table 3. More details are given in table A1 of the appendix.

Table 3: Half-value layers (HVL) in mm Al (F100) and mm Cu at different sites

Code	F100 mm Al	F135 mm Cu	F180 mm Cu	F250 mm Cu
BIPM	4.030	0.489	0.977	2.484
PTB	4.142	0.489	1.013	2.482
LNE-LNHB	4.03	0.49	1.00	2.50
VSL	4.11	0.52	1.06	2.59
ENEA	4.02	0.494	0.996	2.498

4. Measurements and reference conditions

4.1 General measurement procedure

Measurements free in air and in the water phantom did not start before a standard wait time giving reasons to assume that the chamber had reached the ambient temperature. After the connection of the chamber and with the voltage on, at least one hour passed until the measurements began. The currents of the transfer chambers at the place of measurement were always measured with and without the radiation beam. The signal-to-background ratio of the current was always greater than 1000. The background current was subtracted from the signal current. A complete measurement consisted of at least 10 repeated single measurements and the mean value was taken as the result. The relative percentage Type A standard uncertainty of the repeated measurements did not exceed 0.1 %.

4.2 Measurement conditions at the different sites

The calibration coefficients of the transfer chambers were measured and given in terms of air kerma or absorbed dose to water per unit charge in units of Gy/C referring to standard conditions of air temperature, pressure and relative humidity of $T = 293.15$ K, $p = 101.325$ kPa and $h = 50$ %. The relative air humidity was always between 20 % and 80 %. Participants did not apply any correction for the incomplete charge collection.

The transfer chambers were calibrated under the measurement conditions listed in tables 4 and 5. Unfortunately, it was not possible to agree on exactly the same reference conditions at all participants' sites. However, it was assumed that these variations should not cause significant differences in the calibration coefficients of the transfer chambers.

Table 4 Measurement conditions for the calibration in terms of absorbed dose to water

Dimensions of the water phantom	30 cm x 30 cm x 30 cm (PTB,VSL,LNHB) 20 cm x 20 cm x 20 cm (ENEA)
Material	Water
Radiation qualities	According to table 3
Air temperature (reference condition)	20 °C
Air pressure (reference condition)	1013.25 hPa
Rel. humidity (reference condition)	around 50 %
Absorbed dose rate to water	> 0.2 mGy/s
Size of the radiation field at the point of measurement (50 % isodose)	PTB: 10 cm in diameter LNE-LNHB: 10.4 cm x 10.4 cm ENEA: 10.5 cm in diameter VSL: 8.14 cm in diameter
Measurement depth	2 g/cm^2 (PTB, ENEA, LNHB) 3.6 g/cm^2 (VSL)
Distance between source and point of measurement	100 cm (PTB, ENEA) 53 cm (LNE-LNHB) 68 cm (VSL)
Polarizing voltage	+300 V (applied to the outer electrode)

Table 5 Measurement conditions for the calibration in terms of air kerma

Radiation qualities:	According to table 3
Air temperature (reference condition)	20 °C
Air pressure (reference condition)	1013.25 hPa
Rel. humidity (reference condition)	around 50 %
Air kerma rate:	> 0.2 mGy/s
Size of the radiation field at the point of measurement (50 % isodose):	PTB: 10 cm in diameter LNE-LNHB: 7 cm in diameter ENEA: 10.5 cm in diameter VSL: 15 cm in diameter
Distance between source and point of measurement:	100 cm (PTB, ENEA) 120 cm (LNE-LNHB) 150 cm (VSL)
Polarizing voltage	+300 V (applied to the outer electrode)

4.3 Additional measurements at a depth of 5 g/cm^2

The reference depth in the water phantom for this comparison was 2 g/cm^2. It was agreed that if possible participants should perform additional charge measurements under conditions which were otherwise the same with the transfer chambers positioned at a depth of 5 g/cm^2 at all comparison radiation qualities (section 3). For this type of measurement the distance between the source and the point of measurement remained constant (i.e. the phantom was moved, not the chamber). The charge ratio obtained for the two depths was intended to be used as a possible future beam qualifier as proposed earlier by Rosser [7].

5. Course of comparison and constancy checks

The chambers were circulated between PTB and the other participants in a “star-shaped” way. After every participant’s calibration, PTB performed chamber constancy checks. For the purpose of constancy checks, the pilot laboratory repeated its determination of the calibration coefficients at all radiation qualities after every participants’ measurements. The chambers stayed at each participant’s site for no longer than 2 weeks. The results report was sent to the coordinator within 3 weeks after the calibration. The dates of calibrations at the participants’ sites and the constancy checks at PTB are listed in table 6. An additional constancy check was carried out in October 2014. The first measurements were performed by PTB in March 2014. The last participant undertook its measurements in January 2015.

Table 6: Month of calibration and constancy check

Participant	Calibration	Constancy (PTB)
PTB	March 2014	June 2014
LNE-LNHB	July 2014	July 2014
ENEA	Nov. 2014	Dec. 2014
VSL	Jan. 2015	Jan. 2015

The pilot laboratory (PTB) participated in the comparison completing its measurements and submitting its results report prior to the other participants. The report on these measurements was sent to the EURAMET TC-IR Chair Lena Johansson before the next participant had finished its measurements (i.e. before July 2014 according to table 6). This procedure was a sign of confidence in PTB.

6. Results and discussion

6.1 Constancy of the transfer chambers

In total, six repeated air kerma and absorbed dose calibrations were conducted at PTB each time the chambers were back from the star-shaped comparison. It is noted that PTB routinely uses reference transfer chambers for the absorbed dose calibrations (see ref. [2] for the description of the reference transfer chamber calibration) whereas air kerma calibrations are always done directly against the primary standard. The mean values and the relative standard deviations σ of the six calibration factors obtained from the repeated measurements are listed in table 7. From the results it is concluded that the chambers the chambers showed a stable response within about 0.1 % when used free in air as well as in the water phantom. This value was used for the relative uncertainty of the transfer chamber’s long-term stability.

Table 7: Mean values of the air kerma (table on top) and absorbed dose (2 g/cm^2, table on bottom) calibration coefficients of the transfer chambers in units of 10^7 Gy/C obtained from the six repeated measurements at the PTB and the relative standard deviations, σ.

	SN 7484		SN 7485		SN 7463	
N_K	Mean	σ %	Mean	σ %	Mean	σ %
F100	4.834	0.08	4.809	0.13	4.775	0.09
F135	4.827	0.03	4.800	0.07	4.771	0.09
F180	4.825	0.07	4.801	0.08	4.776	0.06
F250	4.824	0.12	4.805	0.08	4.782	0.07

	SN 7484		SN 7485		SN 7463	
$N_{D\mathrm{w}}$	Mean	σ %	Mean	σ %	Mean	σ %
F100	4.978	0.12	4.962	0.11	4.925	0.14
F135	5.086	0.08	5.068	0.07	5.034	0.09
F180	5.169	0.06	5.150	0.06	5.119	0.07
F250	5.274	0.06	5.253	0.05	5.226	0.06

6.2 Air kerma calibration coefficients

6.2.1 Reported results

The air kerma calibration coefficients and the corresponding relative standard uncertainties as reported by the participants are summarized in table 8.

Table 8: Air kerma calibration coefficients in units of 10^7 Gy/C and the relative standard uncertainties u_{rel} for each transfer chamber as reported by the participants.

S/N	Qual	PTB	LNHB	ENEA	VSL
	u_{rel}	0.25 %	0.34 %	0.37 %	0.45 %
7484	F100	4.832	4.818	4.879	4.833
	F135	4.824	4.809	4.835	4.816
	F180	4.822	4.807	4.873	4.812
	F250	4.823	4.812	4.842	4.803
7485	F100	4.816	4.796	4.852	4.803
	F135	4.805	4.786	4.801	4.786
	F180	4.804	4.789	4.845	4.787
	F250	4.807	4.786	4.824	4.785
7463	F100	4.781	4.765	4.814	4.767
	F135	4.778	4.758	4.772	4.757
	F180	4.780	4.765	4.825	4.759
	F250	4.784	4.762	4.805	4.760

To check the consistency of the three transfer chamber calibration factors at a participant's site the following ratios of pairs of transfer chamber calibration factors were calculated: SN

7485/ SN 7484, SN 7463 / SN7484 and SN 7463 / SN 7485. These ratios are expected to be independent of the beam quality and thus four values are obtained for each pair. The mean and standard deviation of these four values for each participant are listed in table 9. Further, the mean and standard deviation of the ratios of the four participants were calculated and are also shown in table 9.

Table 9: Ratios of pairs of transfer chamber calibration factors calculated for SN 7485/ SN 7484, SN 7463 / SN7484 and SN 7463 / SN 7485 and the mean values and standard deviations σ of those for the ratios obtained from the data of the four participants.

Ratio of S/N		PTB	LNHB	ENEA	VSL	Mean	σ
7485	Mean	0.9964	0.9954	0.9945	0.9947	0.9952	0.0009
/7484	σ	0.0003	0.0007	0.0014	0.0012		
7463	Mean	0.9908	0.9898	0.9890	0.9885	0.9895	0.0010
/7484	σ	0.0010	0.0010	0.0027	0.0020		
7463	Mean	0.9943	0.9944	0.9945	0.9938	0.9943	0.0003
/7485	σ	0.0010	0.0007	0.0018	0.0010		

An inspection of table 9 shows that the relative standard deviations of the ratios never exceeded 0.2 % except for one value at ENEA which was 0.27 %. The relative standard deviations of the same pair of ratios among the four participants did not exceed 0.1 %. From these results it is concluded that all participants got consistent results from the three transfer chambers, most of them to within 0.15 % and all within 0.3 %.

6.2.2 Consistency check with the BIPM.RI(I)-K3 key comparison

All participants had previously participated in the key comparison BIPM.RI(I)-K3 of the air-kerma standards of the National Metrology Institutes (NMIs) and the BIPM in medium-energy X-rays [8-11]. These results are summarized in table 10.

Table 10: Results of the key comparisons K3 [8-11] updated as at the KCDB of the BIPM [12]. The numbers relate to $R_{K,\mathrm{NMI}} = N_{K,\mathrm{NMI}} / N_{K,\mathrm{BIPM}}$ which is the ratio of the air kerma calibration coefficients and u_{rel} is the relative standard uncertainty of $R_{K,\mathrm{NMI}}$.

NMI	PTB	LNE-LNHB	ENEA[1)]	VSL
u_{rel}	0.25 %	0.39 %	0.31 %	0.40 %
F100	1.0027	1.0004	1.0058	1.0045
F135	1.0045	1.0012	1.0057	1.0036
F180	1.0049	0.9999	1.0088	1.0033
F250	1.0055	0.9980	1.0063	1.0012

[1)] $R_{K,\mathrm{ENEA}}$ results relate to the ENEA transfer chamber T4 [11]. These values were taken for the consistency check because due to time restrictions ENEA did not use its primary standard but the T4 transfer chamber to calibrate the transfer chambers of this comparison.

In order to check the consistency of the results of the current comparison listed in table 8 with those of the K3 key comparison listed in table 10, ratios of pairs of NMI results as obtained in the current comparison (designated as direct results) are compared with those obtained from the K3 results at the BIPM (designated as indirect results). The direct results are obtained from the current comparison according to

$$R_{\mathrm{dir}} = N_{K,\mathrm{NMI\text{-}1}} / N_{K,\mathrm{NMI\text{-}2}} \tag{1}$$

where $N_{K,\mathrm{NMI\text{-}1}}$ and $N_{K,\mathrm{NMI\text{-}2}}$ are the air kerma calibration coefficients of NMI-1 and NMI-2 taken from table 8. The indirect results are obtained by

$$R_{\mathrm{indir}} = R_{K,\mathrm{NMI\text{-}1}} / R_{K,\mathrm{NMI\text{-}2}} \tag{2}$$

where $R_{K,\mathrm{NMI\text{-}1}}$ and $R_{K,\mathrm{NMI\text{-}2}}$ are the ratios of the air kerma determinations of NMI-1 and NMI-2 with respect to that of the BIPM standard taken from table 10. Consistency can be checked by the ratio R_{cons} defined by

$$R_{\mathrm{cons}} = R_{\mathrm{indir}} / R_{\mathrm{dir}} \tag{3}$$

The uncertainty of R_{cons} can easily be estimated because most of the uncertainty components are 100 % correlated and are cancelled out as can be seen by the following equations:

$$\begin{aligned} R_{\mathrm{cons}} &= R_{\mathrm{indir}} / R_{\mathrm{dir}} = (R_{K,\mathrm{NMI\text{-}1}} / R_{K,\mathrm{NMI\text{-}2}}) / N_{K,\mathrm{NMI\text{-}1}} / N_{K,\mathrm{NMI\text{-}2}} \\ &= [(N_{K,\mathrm{NMI\text{-}1}} / N_{K,\mathrm{BIPM}}) * (N_{K,\mathrm{BIPM}} / N_{K,\mathrm{NMI\text{-}2}})]_{\text{at BIPM}} * (N_{K,\mathrm{NMI\text{-}2}} / N_{K,\mathrm{NMI\text{-}1}})_{\text{this comp.}} \end{aligned}$$

Except for Type A uncertainties due to the measurement process, all other (Type B) uncertainties of the BIPM, NMI-1 and NMI-2 are cancelled out because they relate to the same primary air kerma standards. Hence, the relative uncertainty $u(R_{\mathrm{cons}})$ is obtained by combining the Type A uncertainties of the six independent transfer chamber calibrations which enter into R_{cons}, i.e. two times each at BIPM, NMI-1 and NMI-2. The relative Type A uncertainties were taken from the K3 reports of the participating NMIs and are listed in table 11. The resulting values of $u(R_{\mathrm{cons}})$ are listed in table 12 together with the values of R_{cons}.

Table 11: Relative Type A uncertainties assigned to transfer chamber calibration at different sites

NMI	BIPM	PTB	LNE-LNHB	ENEA	VSL
$u_{\mathrm{rel}\,/\,\%}$	0.05	0.13	0.22	0.17 (0.33[1)])	0.14

[1)]Type A uncertainty for the transfer chamber calibration against the T4 chamber of ENEA

Table 12: Ratios R_{cons} according to equation (3) and the corresponding relative standard uncertainties $u(R_{\mathrm{cons}})$

	LNHB / PTB	ENEA /PTB	VSL / PTB	ENEA / LNHB	VSL / LNHB	ENEA / VSL
$u(R_{\mathrm{cons}})$ / %	0.37	0.42	0.28	0.49	0.38	0.43
F100	1.001	0.995	1.004	0.994	1.002	0.992
F135	1.001	1.001	1.003	1.001	1.002	0.999
F180	0.998	0.994	1.002	0.996	1.004	0.993
F250	0.996	0.997	1.000	1.001	1.004	0.997

The consistency of the indirect and direct results is evaluated from the criterion $c < 1$ as defined in the following equation:

$$c \equiv \left|1 - R_{\mathrm{cons}}\right| / (2u(R_{\mathrm{cons}})) \leq 1 \tag{4}$$

This criterion simply means that the absolute value of the difference R_{indir} - R_{dir} is less than the expanded uncertainty of that difference.

Table 13: Values of c according to equation (4).

	LNHB / PTB	ENEA /PTB	VSL / PTB	ENEA / LNHB	VSL / LNHB	ENEA / VSL
F100	0.2	0.6	0.6	0.6	0.3	1.0
F135	0.1	0.1	0.4	0.1	0.3	0.2
F180	0.3	0.7	0.3	0.4	0.5	0.9
F250	0.5	0.4	0.0	0.1	0.5	0.4

Results listed in table 13 indicate that the results of the direct (this comparison) and indirect comparison (BIPM.RI(I)-K3) are consistent within the expanded uncertainties of the differences.

6.3 Absorbed dose to water calibration coefficients

6.3.1 Reported results

The absorbed dose calibration coefficients and the corresponding relative standard uncertainties as reported by the participants are summarized in table 14. Appendix 2 summarizes the corresponding uncertainty budgets.

Table 14: Absorbed dose calibration coefficients in units of 10^7Gy/C of the transfer chambers and the corresponding relative standard uncertainties given in percent (%) as reported by the participants.

Qual	PTB		LNHB		ENEA		VSL	
S/N 7484	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u
F100	4.979	0.91	4.920	1.02			4.995	0.83
F135	5.088	0.82	5.153	0.66			5.201	0.76
F180	5.170	0.67	5.151	0.85	5.190	1.9	5.218	0.72
F250	5.274	0.67	5.362	0.64	5.360	1.9	5.315	0.75
S/N 7485	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u
F100	4.962	0.91	4.881	1.02			4.965	0.83
F135	5.068	0.82	5.122	0.66			5.174	0.76
F180	5.153	0.67	5.117	0.85	5.160	1.9	5.192	0.72
F250	5.257	0.67	5.331	0.64	5.330	1.9	5.295	0.75
S/N 7463	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u	$N_{D\mathrm{w}}$	u
F100	4.928	0.91	4.850	1.02			4.929	0.83
F135	5.037	0.82	5.089	0.66			5.140	0.76
F180	5.122	0.67	5.090	0.85	5.120	1.9	5.160	0.72
F250	5.229	0.67	5.305	0.64	5.290	1.9	5.265	0.75

It is noted that the standard uncertainties given by PTB, LNE-LNHB and VSL are similar, whereas those of ENEA are significantly greater by more than a factor of 2. This is largely due to the fact that the ENEA standard had been designed and constructed recently during the research project “MetrExtRT” and its earliest conservative determination of the absorbed dose to water was carried out for this supplementary comparison [5].

6.3.2 Evaluation of the degree of equivalence

The degree of equivalence (DoE) of a national measurement standard is expressed quantitatively by two terms: its deviation, *D*, from the comparison reference value (CRV) and the uncertainty, *U*, of this deviation (at a 95 % level of confidence). If x_i denotes the comparison result of participant i and x_r the CRV, the relative deviations can be expressed as $D_\mathrm{i} = (x_\mathrm{i}-x_\mathrm{r})/x_\mathrm{r}$.

The comparison results x_i and the uncertainties u_i associated with the data obtained from the calibration coefficients and their uncertainties of the transfer chambers shown in table 14 were evaluated following the procedures described by Cox in reference [13]. The comparison reference values x_r were calculated from the data x_i and u_i of all participants as the weighted mean (procedure A in [13]). Before the weighted mean can be accepted as the CRV, it must pass the chi-square test for independence (consistency check). The weighted mean values of the calibration coefficients, x_r, the corresponding relative uncertainties u_r, the observed chi-squared values χ^2_obs and the calculated *p*-values defined as probability $\Pr\{\chi^2(\nu) > \chi^2_\mathrm{obs}\}$ used for the consistency check are listed in table 15. $\nu = N-1$ is the degree of freedom if *N* is the number of values x_i. Consistency can be assumed because the *p*-values were always greater than 0.05. Consequently, the weighted mean values can be accepted as the CRV.

Table 15: Weighted mean values of the calibration coefficients in units of 10^7Gy/C, the corresponding relative uncertainties u_r given in percent (%), χ^2_obs and $p = \Pr\{\chi^2(\nu) > \chi^2_\mathrm{obs}\}$ for consistency check (see text).

S/N 7484	x_r	u_r	χ^2_obs	*p*-value
F100	4.969	0.53	1.39	0.50
F135	5.150	0.43	3.87	0.14
F180	5.182	0.41	1.54	0.67
F250	5.320	0.39	3.34	0.34
S/N 7485	x_r	u_r	χ^2_obs	*p*-value
F100	4.941	0.53	2.01	0.37
F135	5.123	0.43	3.41	0.18
F180	5.157	0.41	1.74	0.63
F250	5.296	0.39	2.42	0.49
S/N 7463	x_r	u_r	χ^2_obs	*p*-value
F100	4.907	0.53	1.84	0.40
F135	5.090	0.43	3.31	0.19
F180	5.126	0.41	1.55	0.67
F250	5.268	0.39	2.49	0.48

The deviations D_i and the expanded uncertainties of these, U_i, were evaluated as described in [13]. The results expressed in parts of 10^3 (mGy/Gy) are summarized in table 16. Results are given for each single transfer chamber and in addition as a mean value of those. All participants obtained consistent results from the measurements with the three transfer chambers. The mean values are regarded as the final results of the DoE evaluation and are also shown in figure 1.

Table 16: Degree of equivalence D_i and the corresponding expanded uncertainty U expressed in parts of 10^3 (mGy/Gy) for each transfer chamber (a – c) and the mean value of the three transfer chambers (d)

a) Transfer chamber S/N 7484

Qual	PTB		LNHB		ENEA		VSL	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
F100	1.9	14.9	-9.9	17.5			5.2	16.6
F135	-12.0	14.0	0.6	10.1			9.9	15.2
F180	-2.3	10.5	-6.0	14.8	1.5	37.1	6.9	14.4
F250	-8.6	11.0	7.9	10.2	7.5	37.2	-0.9	15.0

b) Transfer chamber S/N 7485

Qual	PTB		LNHB		ENEA		VSL	
7485	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
F100	4.2	14.9	-12.2	17.5			4.8	16.6
F135	-10.7	14.0	-0.2	10.1			9.9	15.2
F180	-0.9	10.5	-7.8	14.8	0.5	37.1	6.7	14.4
F250	-7.5	11.0	6.5	10.2	6.3	37.2	-0.3	15.0

c) Transfer chamber S/N 7463

Qual	PTB		LNHB		ENEA		VSL	
7463	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
F100	4.3	14.9	-11.7	17.5			4.4	16.6
F135	-10.5	14.0	-0.3	10.1			9.8	15.2
F180	-0.9	10.5	-7.1	14.8	-1.3	37.1	6.5	14.4
F250	-7.5	11.0	7.0	10.2	4.1	37.2	-0.6	15.0

d) Mean values of the results of the three transfer chambers

Qual	PTB		LNHB		ENEA		VSL	
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
F100	3.5	14.9	-11.3	17.5			4.8	16.6
F135	-11.1	14.0	0.0	10.1			9.9	15.2
F180	-1.4	10.5	-7.0	14.8	0.3	37.1	6.7	14.4
F250	-7.8	11.0	7.1	10.2	6.0	37.2	-0.6	15.0

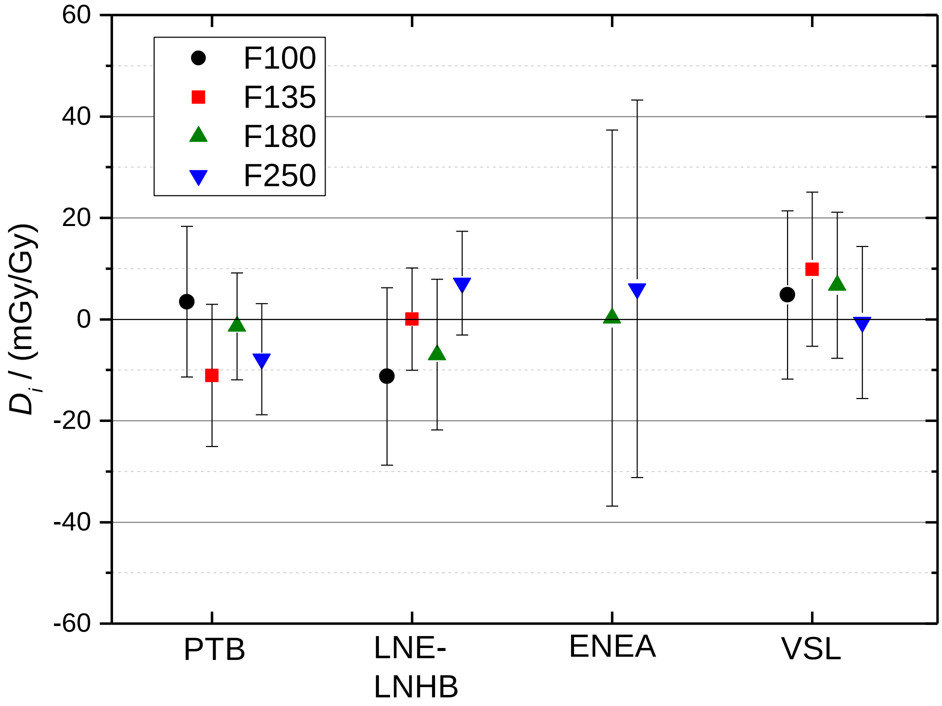

Figure 1: Degree of equivalence D_i and the corresponding expanded uncertainty U_i

From figure 1 it is concluded that all the participant’s results are consistent with the comparison reference value that was estimated as the weighted mean. Reasons for the larger uncertainties of ENEA were already mentioned above. It is noted that the results obtained by ENEA with the newly developed water-graphite calorimeter compare well with those of the more established water calorimeters of the other three participants.

6.3.3 Evaluation with respect to the ratio N_{Dw} / N_K

If one compares the $N_{D\mathrm{w}}$ values at the different qualities normalized to the value $N_{D\mathrm{w}}$ at F250 (table 17), it is found that there are significant deviations of up to about 3 % between the participants’ results. Using physical arguments gained from an analysis of the measured ratios $N_{D\mathrm{w}}$ / N_K, this section examines which of the data shown in table 17 reflect the most probable variance of the chamber’s response with the radiation quality.

Table 17: $N_{D\mathrm{w}}$(Quality) normalized to $N_{D\mathrm{w}}$(F250)

Quality	PTB	LNE-LNHB	ENEA	VSL
F100	0.943	0.916		0.938
F135	0.964	0.960		0.977
F180	0.980	0.960	0.968	0.981
F250	1.000	1.000	1.000	1.000

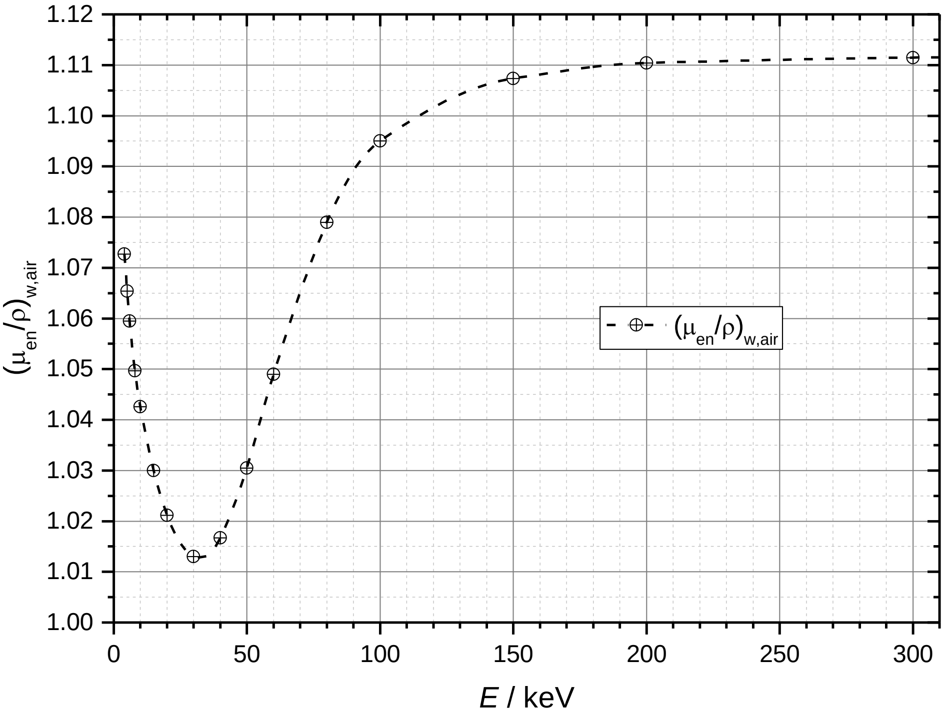

Figure 2: Ratio of water-to-air mass energy-absorption coefficients as a function of photon energy. Mass energy-absorption coefficients of air and water were taken from [14].

Medium-energy X-ray dosimetry protocols used today provide procedures to determine the calibration coefficient N_{Dw} of suitable ionization chambers from the air kerma calibration coefficient N_K according to the following equation:

$$N_{D_{\mathrm{w}}} = N_K * \left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)^{\mathrm{d}}_{\mathrm{w,a}} * k_{\mathrm{ch}} * k_{\mathrm{sheath}}, \tag{5}$$

where $(\overline{\mu}_{\mathrm{en}}/\rho)^{\mathrm{d}}_{\mathrm{w,a}}$ is the mean value of the water-to-air ratio of the mass-energy-absorption coefficients at the depth d in water, k_{ch} is the overall chamber correction factor that accounts for the change in the chamber response due to the displacement of water by the ionization chamber (air cavity plus wall) and the presence of the chamber stem, the change in the energy, and the angular distribution of the photon beam in the phantom compared to that used for the calibration in air, and k_{sheath} is a correction factor for the effects of a waterproofing sheath. The transfer chamber of the type TM30013 is waterproof, thus k_{sheath} must not be applied. The correction factor k_{ch} for this chamber type was shown [2] to vary by less than about 0.5 % for qualities generated with tube voltages between 70 and 280 kV (quality codes TH 70 to TH 280 in ref. [2]).

$(\overline{\mu}_{\mathrm{en}}/\rho)^{\mathrm{d}}_{\mathrm{w,a}}$ is obtained with relative uncertainties of about 0.3 %. Mean values for the radiation qualities of table 18 were calculated based on the mono-energetic ratios shown in figure 2 and averaged with photon fluence spectra measured at PTB. Photon fluence spectra at 2 cm and 5 cm depths of a water phantom were obtained by the EGSnrc [15] user code

FLURZnrc [16] using a parallel beam of photons of a circular diameter of 10 cm and the measured free-in-air spectra incident on a cylindrical water phantom of a diameter of 30 cm. Results for the qualities TH 70 – TH 280 and the F qualities are shown in table 18 together with the chamber correction factor k_{ch} as published in [2]. Similar values can be expected for the transfer ionization chambers of the same type as used in the current comparison.

Table 18: Ratio for water-to-air of the mean mass energy-absorption coefficients averaged over the incident photon spectrum free in air and at 2 cm and 5 cm depths (d) in a reference water phantom, the chamber correction factor k_{ch} and the radiation quality correction factor k_{Q} with respect to the air kerma calibration coefficient at TH280 of the chamber TM30013-425 as published in [2]. The values for the F qualities were obtained from additional calculations and measurements according to the methods described in [2].

Radiation quality	Tube voltage kV	Mean energy[1] keV	$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{air}}$	$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=2\,cm}}$	$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=5\,cm}}$	k_{ch}	k_{Q}
TH 70	70	37.4	1.020	1.020	1.021	1.004	1.000
F 100	100	44.4	1.030	1.029	1.031	1.005	0.999
TH 100	100	46.8	1.033	1.031	1.032	1.005	0.999
TH 120	120	55.6	1.043	1.038	1.040	1.007	0.997
F 135	135	66.4	1.055	1.047	1.047	1.007	0.998
TH 140	140	66.2	1.055	1.047	1.048	1.007	0.998
TH 150	150	81.2	1.071	1.060	1.059	1.006	0.999
F 180	180	91.6	1.076	1.065	1.064	1.006	0.999
TH 200	200	110.2	1.089	1.078	1.076	1.005	0.998
TH 250	250	140.3	1.099	1.090	1.089	1.003	0.999
F 250	250	139.7	1.098	1.089	1.087	1.003	0.999
TH 280	280	165.5	1.105	1.098	1.097	1.002	1.000

[1] Air kerma weighted

From table 18 it is obvious that values of $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=2\,cm}}$ and $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=5\,cm}}$ differ by no more than about 0.2 % so that calibrations at different depths will not result in significantly different calibration coefficients. The quality correction factor k_{Q} with respect to the air kerma calibration coefficient normalized at TH 280 of the chamber TM30013 was shown to be almost equal to one for TH 70 to TH 280 [2]. Thus, it can be expected that this chamber type will correctly indicate the air kerma at the different depths of a water phantom because the air kerma response is almost independent of the photon fluence spectrum in this energy range. In summary, according to the results described above it is expected that the ratios $N_{D\mathrm{w}}$ / N_K of the transfer chambers are close to $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d}}$ within less than 1 %. Therefore, this chamber type was well suited for this type of comparison and the conclusions which can be made. It has already been mentioned that all the participants obtained consistent results from the three transfer chamber measurements free in air and in the reference phantom. Therefore, mean values of the ratios $R_{D,K} = N_{D\mathrm{w}} / N_K$ and the corresponding standard uncertainties were calculated from the three single results of the transfer chambers and are listed in table 19. Results of $R_{D,K}$ are also shown in figure 3 together with the corresponding calculated values of $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=2\,cm}}$ and the corresponding results obtained at PTB for the qualities TH70 to TH280 which are consistent with those already published in [2] for a different chamber but of the same type.

Table 19: Calculated ratios $R_{D,K} = N_{D\mathrm{w}} / N_K$ for all participants

Qual	PTB		LNHB		ENEA		VSL	
	$R_{D,K}$	u	$R_{D,K}$	u	$R_{D,K}$	u	$R_{D,K}$	u
F100	1.030	0.010	1.019	0.011			1.034	0.010
F135	1.055	0.009	1.070	0.008			1.081	0.010
F180	1.072	0.008	1.069	0.010	1.064	0.021	1.084	0.009
F250	1.093	0.008	1.114	0.008	1.104	0.021	1.106	0.010

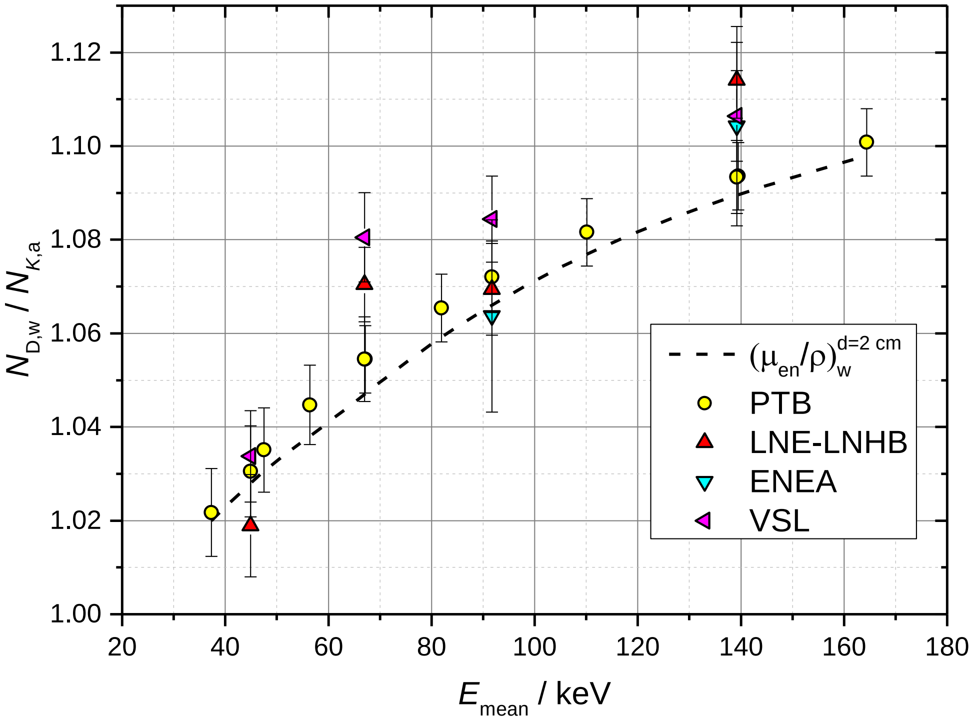

Figure 3: Ratios $R_{D,K} = N_{D\mathrm{w}} / N_K$ and calculated values of $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=2\,cm}}$ taken from table 18 as a function of the air kerma weighted mean energy of the radiation qualities.

Finally, the ratios $R_{D,K}$ were divided by the corresponding ratios $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,a}}^{\mathrm{d=2\,cm}}$ taken from table 18 in order to obtain the overall chamber correction factor k_{ch} from the participants' results according to equation (5). Values of k_{ch} are listed in table 20 and also shown in figure 4.

Table 20: Calculated values of the overall chamber correction factor k_{ch}

Qual	PTB		LNHB		ENEA		VSL	
	k_{ch}	u	k_{ch}	u	k_{ch}	u	k_{ch}	u
F100	1.001	0.010	0.990	0.011			1.005	0.010
F135	1.007	0.009	1.022	0.008			1.032	0.010
F180	1.007	0.008	1.004	0.010	0.999	0.021	1.018	0.009
F250	1.004	0.008	1.023	0.008	1.014	0.021	1.016	0.010

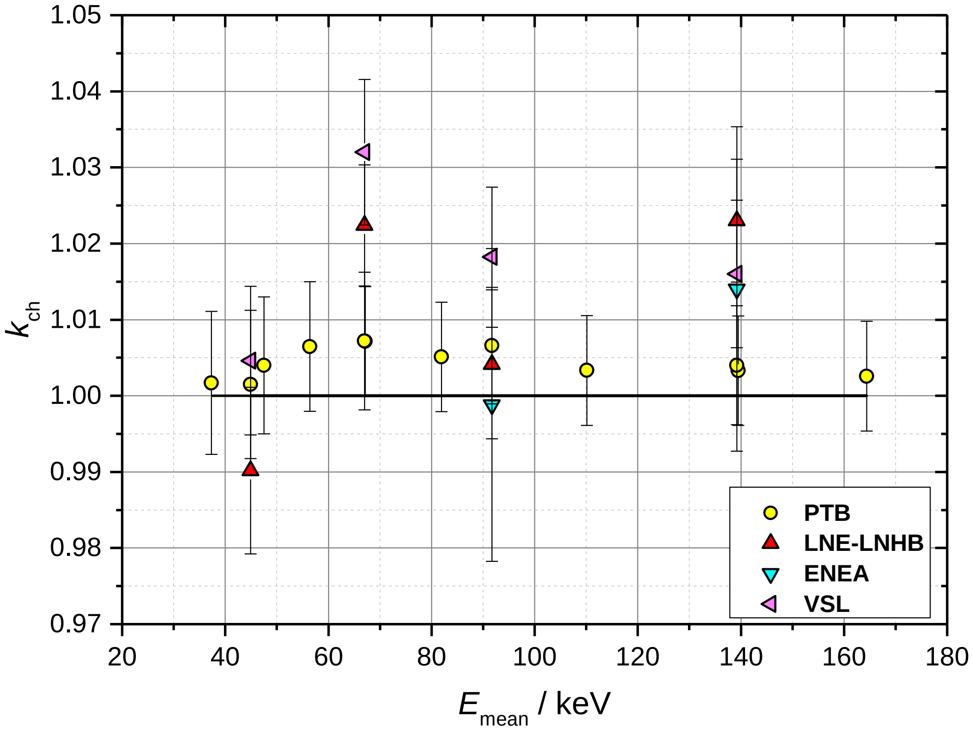

Figure 4: Overall chamber correction factor k_{ch} as a function of the air kerma weighted mean energy of the radiation qualities as obtained from the participants' results.

From table 20 and figure 4 it becomes obvious that except for the PTB data, the majority of the participants' results reflect a variation of k_{ch} at the different beam qualities, which seems unlikely. LNE-LNHB obtained consistent N_K results but it is very improbable that k_{ch} changes its sign and varies by more than 3 % when moving from the quality F100 to F135, or changes by about 2 % when moving from F180 to F250. In addition, at VSL the N_K results reflected consistency, but k_{ch} increases by about 2 % when moving from F100 to F135, and decreases again by 1.5 % when moving to F250. In conclusion, it is very helpful to analyse results with respect to k_{ch} in order to find arguments for the consistency of the results with physical models and to find possible problems with the standards or measurements. Clearly, the uncertainties of ENEA's newly developed standard currently appear to be too large to benefit from such an analysis. For the primary absorbed dose standards of LNE-LNHB and VSL however it gives hints for possible improvements.

6.4 Ratios of measured charges at 2 and 5 g/cm^2

PTB, ENEA and LNE-LNHB performed the additional charge measurements at a depth of 5 g/cm^2. PTB and ENEA carried out these measurements for all three transfer chambers, LNE-LNHB just for one of them. It turned out that the ratios of the measured charges at 2 and 5 g/cm^2 designated thereafter as $R_{2/5,}$ were almost the same for all transfer chambers at PTB and ENEA. Therefore, mean values from the three chambers were calculated for the results of each of these participants and these are listed in table 21 together with their relative standard uncertainties. The results obtained at LNE-LNHB from just one of the transfer chambers are also shown in table 21; the LNE-LNHB standard uncertainties u are due to the uncertainties of two charge measurements, and due to twice the uncertainties in the positioning of the chambers

Table 21: Ratios $R_{2/5}$ as obtained by the participants

Qual	PTB		LNE-LNHB		ENEA	
	$R_{2/5}$	u	$R_{2/5}$	u	$R_{2/5}$	u
F100	1.632	0.004	1.572	0.005	1.629	0.004
F135	1.401	0.003	1.357	0.004	1.381	0.001
F180	1.327	0.002	1.295	0.004	1.315	0.001
F250	1.278	0.002	1.250	0.004	1.267	0.001

The ratios of the values $R_{2/5}$ obtained by pairs of participants were calculated and are listed in table 22. Results indicate that the ratios PTB / ENEA are close to unity, showing that differences in their $R_{2/5}$ values were around 1%. The same could not be ascertained for ratios involving LNE-LNHB, showing differences up to about 4%. Possibly, the reason is that PTB and ENEA took measurements at a distance of 100 cm, whereas LNE-LNHB measured at 50 cm.

Table 22: Comparison of the ratios R of $R_{2/5}$ (NMI-1) to $R_{2/5}$ (NMI-2) obtained by the participants

Qual	ENEA/PTB		LNE-LNHB/PTB		LNE-LNHB/ENEA	
	R	u	R	u	R	u
F100	0.999	0.006	0.963	0.006	0.965	0.006
F135	0.986	0.003	0.969	0.005	0.982	0.004
F180	0.990	0.002	0.976	0.004	0.985	0.004
F250	0.992	0.002	0.978	0.004	0.986	0.004

These measurements were intended to give the first experimental results of a possible future quality specifier which could be used instead of the aluminium half-value layer or mean energy. Based on the results obtained here, a standardization of the measurement conditions should be followed to enrich the current data set, before a conclusion on the suitability of $R_{2/5}$ as a beam qualifier can be made. The further discussion of this topic is beyond the scope of this comparison report and will be dealt with later.

7. Summary and conclusion

This report presents the results of the first international comparison of primary measurement standards of absorbed dose to water for the medium-energy X-ray range. Three of the participants (VSL$^{1)}$, PTB, LNE-LNHB) used their well established water calorimeter based standards and one participant (ENEA) has recently developed a new standard based on a water-graphite calorimeter. The participants calibrated three transfer chambers of the same type in terms of absorbed dose to water ($N_{D\mathrm{w}}$) and air kerma (N_K) using the CCRI radiation qualities in the range 100 kV to 250 kV. The additional N_K values were intended to be used for a physical analysis of the ratios $N_{D\mathrm{w}}$ / N_K.

All participants had previously participated in the BIPM.RI(I)-K3 key comparison of air kerma standards. Ratios of pairs of NMI's N_K results of the current comparison were found to be consistent with the corresponding key comparison results within the expanded uncertainties of 0.6 – 1 %.

The $N_{D\mathrm{w}}$ results were first analysed in terms of the degree of equivalence with the comparison reference value which was calculated as the weighted mean of all results. All results were consistent with the reference value within the expanded uncertainties of the deviations. However, these expanded uncertainties varied significantly and ranged between about 1-1.8 % for the water calorimeter based standards and were estimated at 3.7 % for the water-graphite calorimeter. This is largely due to the fact that the ENEA standard has been designed and constructed during the recent research project MetrExtRT and its earliest determination of the absorbed dose to water was carried out for this supplementary comparison.

Because the transfer chambers reflect an almost energy-independent air kerma response it was expected that the ratios $N_{D\mathrm{w}}$ / N_K follow approximately the mean values of the water-to-air ratios of the mass-energy-absorption coefficients. It was found that this expectation was almost confirmed by the results of one participant (PTB) whereas most of the other results deviated significantly from the expected behaviour in a way that appears unlikely. These results may give hints for future improvements of these standards.

The BIPM has plans to introduce and establish a key comparison of standards of absorbed dose to water for the medium-energy X-ray range. For this purpose the BIPM develops its own primary standard. As soon as the BIPM is ready it is planned to link the results of this comparison to the new key comparison reference values by a bilateral comparison of the standards of the BIPM and the PTB acting as link laboratory.

$^{1)}$Note: Recently, at Draft B stage of this report, VSL discovered an error in the model for the heat transport calculations of their water calorimeter. The used values for density and heat capacity of the glass volumes were incorrect. VSL will run simulations to investigate the consequences of this error on the correction factors and publish the results as soon as they are available

Acknowledgment

This work was supported by the EMRP joint research project EMRP-HLT09 Metrology for radiotherapy using complex radiation fields (MetrExtRT) which has received funding from the European Union on the basis of Decision No 912/2009/EC. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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Appendix 1 Details of radiation qualities

Table A1: Details of the CCRI medium-energy radiation qualities as realized at the participants' sites. Reference conditions for the absorbed dose to water and air kerma rates are indicated for each participant in tables 4 and 5, respectively.

PTB	Radiation quality	F100	F135	F180	F250
Additional Al filtration / mm		3.506	2.302	2.302	2.302
Additional Cu filtration / mm		-	0.222	0.512	1.590
HVL / mm Cu		4.04 (Al)	0.489	1.013	2.482
$(\mu/\rho)_{\mathrm{air}}$ / cm^2 g^{-1}		0.287	0.196	0.168	0.143
$\dot{K}_{\mathrm{PTB}}$ / mGy s^{-1}		0.82	0.68	0.92	0.91
$\dot{D}_W$ / mGy s^{-1}		1.2	1.1	1.4	1.3

ENEA	Radiation quality	F100	F135	F180	F250
Additional Al filtration / mm		3.66	4.08	4.06	4.02
Additional Cu filtration / mm		-	0.20	0.49	1.70
HVL / mm Cu		4.02 (Al)	0.494	0.996	2.498
$(\mu/\rho)_{\mathrm{air}}$ / cm^2 g^{-1}		0.259	0.183	0.162	0.140
$\dot{K}_{\mathrm{air}}$ / mGy s^{-1}		2.0	1.6	1.9	2.1
$\dot{D}_{\mathrm{W}}$ / mGy s^{-1}				2.8	2.8

VSL	Radiation quality	F100	F135	F180	F250
Additional Al filtration / mm		3.662	1.001	1.001	1.001
Additional Cu filtration / mm		-	0.305	0.598	1.748
HVL / mm Cu		4.11(Al)	0.52	1.06	2.59
$(\mu/\rho)_{\mathrm{air}}$ / cm^2 g^{-1}		0.281	0.184	0.157	0.133
$\dot{K}_{\mathrm{air}}$ / mGy s^{-1}		0.79	0.76	0.81	0.70
$\dot{D}_W$ / mGy s^{-1}		3.8	4.5	5.5	5.1

LNHB	Radiation quality	F100	F135	F180	F250
Additional Al filtration / mm		3.22	2.50	2.97	2.97
Additional Cu filtration / mm		-		0.51	1.72
HVL / mm Cu		4.03 (Al)	0.49	1.00	2.50
$(\mu/\rho)_{\mathrm{air}}$ / cm^2 g^{-1}		0.222	0.181	0.163	0.144
$\dot{K}_{\mathrm{air}}$ / mGy s^{-1}		1.31	1.24	0.87	1.07
$\dot{D}_W$ / mGy s^{-1}		7.73	9.37	6.66	8.06

Appendix 2 Uncertainty budgets of D_w and N_{Dw}

A.2.1 ENEA

The following Tables 3 and 10 were copied from the ENEA comparison report of results. Please see reference [5] for details and explanations.

Table 3. Uncertainty budget of the absorbed dose to water determination with ENEA's primary standard.

Relative standard uncertainty	u_{iA}	u_{iB}
fc, fractional change of thermistor resistance during irradiation / $(\Delta\Omega/\Omega)\ C^{-1}$)	0.015	0.0014
k_{qa}, quasi adiabatic calibration factor / (J/($\Delta\Omega/\Omega$))	0.0016	0.0021
k_r, radial non-uniformity of the beam across the core surface	0.0014	0.0010
$C_{w,g}$, graphite to water absorbed dose conversion factor	0.0010	0.0093
m_c, effective core mass	0.0010	0.0046
monitor chamber normalization	0.0005	0.0021
calorimeter positioning		0.0025
quadratic sum	0.0152	0.0112
combined standard uncertainty	**0.019**	

Table 10. Uncertainty budget of the calibration coefficients in terms of absorbed dose to water, N_{Dw}

Relative standard uncertainty	u_{iA}	u_{iB}
D_W, standard	0.015	0.011
monitor chamber normalization	0.0005	0.0016
chamber signal, I_{transf}	0.0005	0.0013
chamber positioning		0.0025
quadratic sum	0.0152	0.0117
combined relative standard uncertainty	**0.019**	

A.2.2 LNHB

The following Tables 3 and 6 were copied from the LNHB comparison report of results. Please see reference [3] for details and explanations.

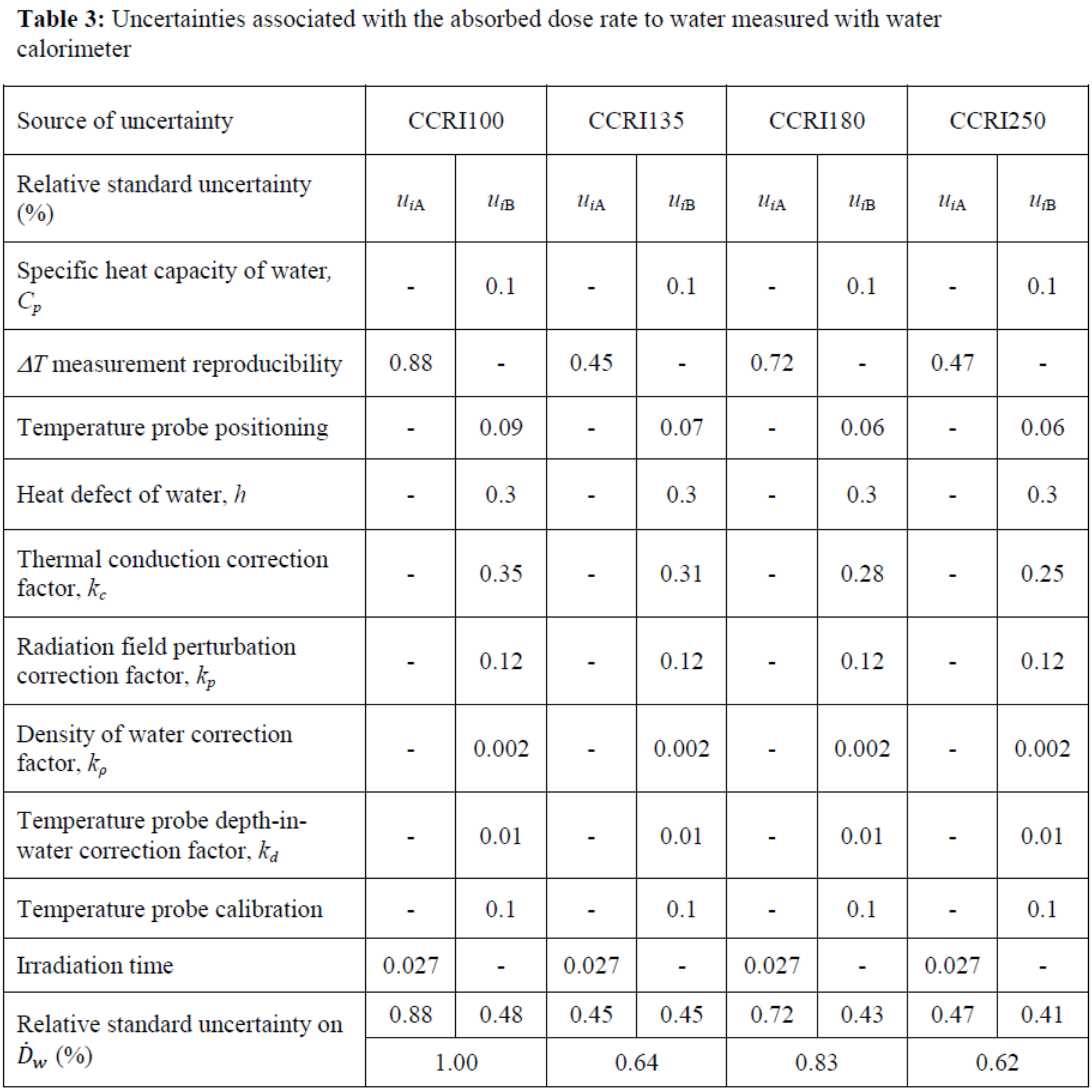
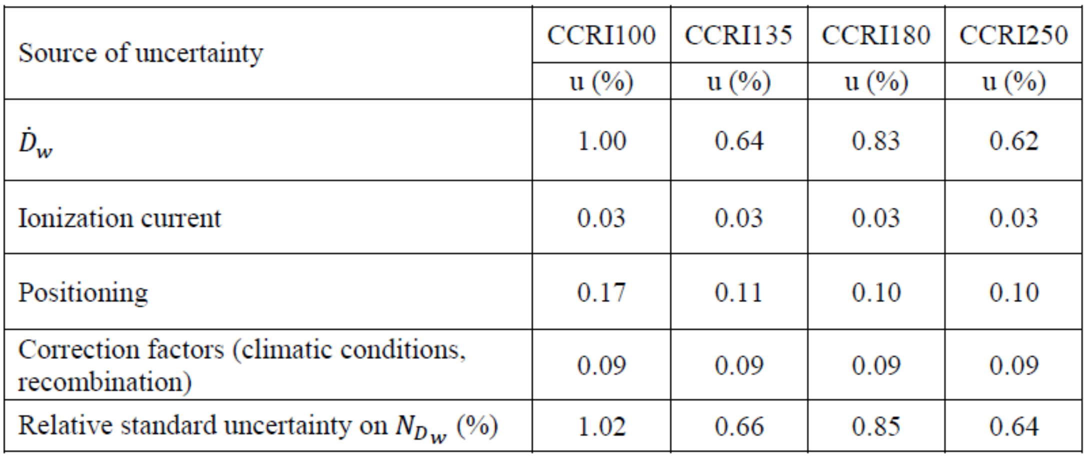


Table 3: Uncertainties associated with the absorbed dose rate to water measured with water calorimeter

Source of uncertainty	CCRI100		CCRI135		CCRI180		CCRI250	
Relative standard uncertainty (%)	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$	$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Specific heat capacity of water, C_p	-	0.1	-	0.1	-	0.1	-	0.1
ΔT measurement reproducibility	0.88	-	0.45	-	0.72	-	0.47	-
Temperature probe positioning	-	0.09	-	0.07	-	0.06	-	0.06
Heat defect of water, h	-	0.3	-	0.3	-	0.3	-	0.3
Thermal conduction correction factor, k_c	-	0.35	-	0.31	-	0.28	-	0.25
Radiation field perturbation correction factor, k_p	-	0.12	-	0.12	-	0.12	-	0.12
Density of water correction factor, k_ρ	-	0.002	-	0.002	-	0.002	-	0.002
Temperature probe depth-in-water correction factor, k_d	-	0.01	-	0.01	-	0.01	-	0.01
Temperature probe calibration	-	0.1	-	0.1	-	0.1	-	0.1
Irradiation time	0.027	-	0.027	-	0.027	-	0.027	-
Relative standard uncertainty on $\dot{D}_w$ (%)	0.88	0.48	0.45	0.45	0.72	0.43	0.47	0.41
	1.00		0.64		0.83		0.62	

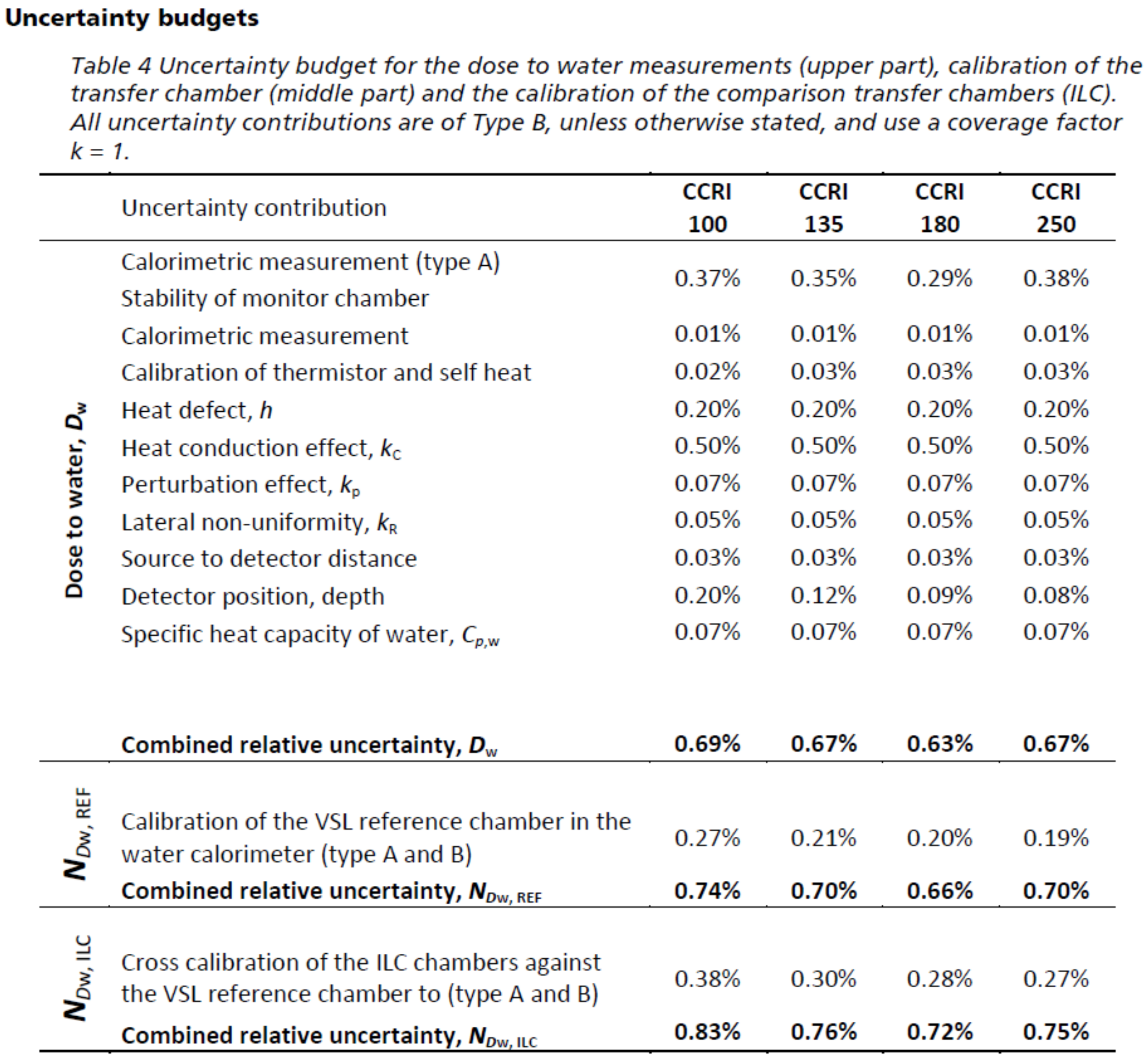
Table 6: Uncertainties associated with the calibration of the transfer chambers in terms of absorbed dose to water



Source of uncertainty	CCRI100	CCRI135	CCRI180	CCRI250
	u (%)	u (%)	u (%)	u (%)
$\dot{D}_w$	1.00	0.64	0.83	0.62
Ionization current	0.03	0.03	0.03	0.03
Positioning	0.17	0.11	0.10	0.10
Correction factors (climatic conditions, recombination)	0.09	0.09	0.09	0.09
Relative standard uncertainty on N_{D_w} (%)	1.02	0.66	0.85	0.64

A.2.3 VSL

The following Table 4 was copied from the VSL comparison report of results. Please see reference [1] for details and explanations.



Uncertainty budgets

Table 4 Uncertainty budget for the dose to water measurements (upper part), calibration of the transfer chamber (middle part) and the calibration of the comparison transfer chambers (ILC). All uncertainty contributions are of Type B, unless otherwise stated, and use a coverage factor k = 1.

	Uncertainty contribution	**CCRI 100**	**CCRI 135**	**CCRI 180**	**CCRI 250**
Dose to water, D_w	Calorimetric measurement (type A) Stability of monitor chamber	0.37%	0.35%	0.29%	0.38%
	Calorimetric measurement	0.01%	0.01%	0.01%	0.01%
	Calibration of thermistor and self heat	0.02%	0.03%	0.03%	0.03%
	Heat defect, h	0.20%	0.20%	0.20%	0.20%
	Heat conduction effect, k_c	0.50%	0.50%	0.50%	0.50%
	Perturbation effect, k_p	0.07%	0.07%	0.07%	0.07%
	Lateral non-uniformity, k_R	0.05%	0.05%	0.05%	0.05%
	Source to detector distance	0.03%	0.03%	0.03%	0.03%
	Detector position, depth	0.20%	0.12%	0.09%	0.08%
	Specific heat capacity of water, $C_{p,w}$	0.07%	0.07%	0.07%	0.07%
	Combined relative uncertainty, D_w	**0.69%**	**0.67%**	**0.63%**	**0.67%**
$N_{Dw, REF}$	Calibration of the VSL reference chamber in the water calorimeter (type A and B)	0.27%	0.21%	0.20%	0.19%
	Combined relative uncertainty, $N_{Dw, REF}$	**0.74%**	**0.70%**	**0.66%**	**0.70%**
$N_{Dw, ILC}$	Cross calibration of the ILC chambers against the VSL reference chamber to (type A and B)	0.38%	0.30%	0.28%	0.27%
	Combined relative uncertainty, $N_{Dw, ILC}$	**0.83%**	**0.76%**	**0.72%**	**0.75%**

A.2.4 PTB

The following Table 4 was copied from reference [2] and shows the uncertainty budget of the D_w determination with the PTB water calorimeter. Details are explained in reference [2].

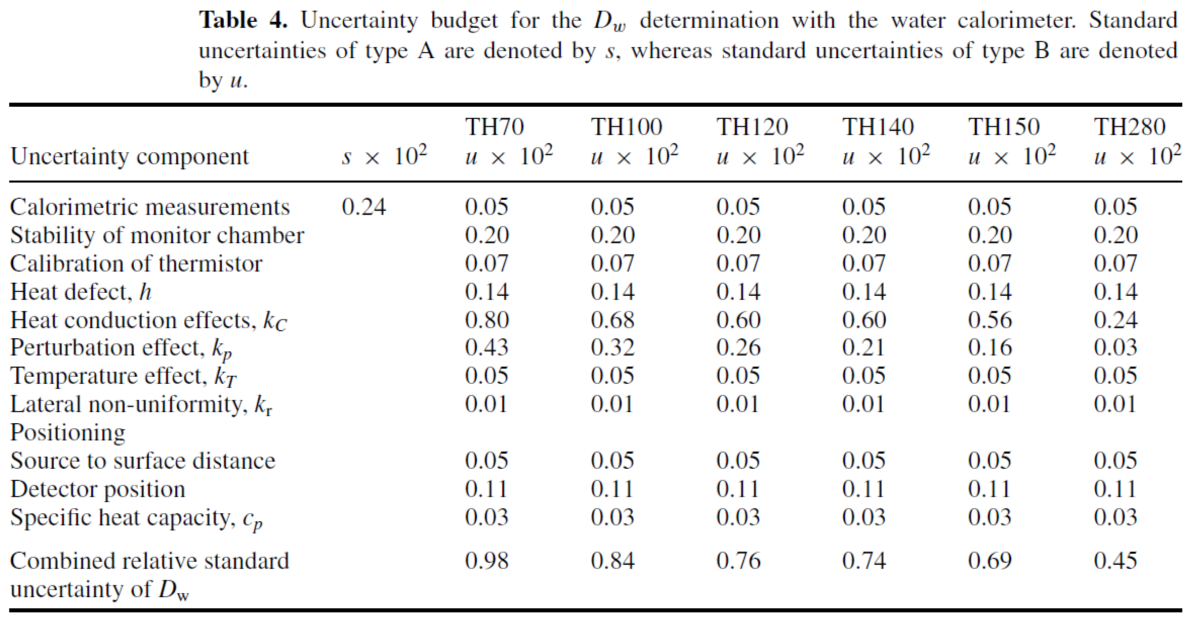


Table 4. Uncertainty budget for the D_w determination with the water calorimeter. Standard uncertainties of type A are denoted by s, whereas standard uncertainties of type B are denoted by u.

Uncertainty component	$s \times 10^2$	TH70 $u \times 10^2$	TH100 $u \times 10^2$	TH120 $u \times 10^2$	TH140 $u \times 10^2$	TH150 $u \times 10^2$	TH280 $u \times 10^2$
Calorimetric measurements	0.24	0.05	0.05	0.05	0.05	0.05	0.05
Stability of monitor chamber		0.20	0.20	0.20	0.20	0.20	0.20
Calibration of thermistor		0.07	0.07	0.07	0.07	0.07	0.07
Heat defect, h		0.14	0.14	0.14	0.14	0.14	0.14
Heat conduction effects, k_C		0.80	0.68	0.60	0.60	0.56	0.24
Perturbation effect, k_p		0.43	0.32	0.26	0.21	0.16	0.03
Temperature effect, k_T		0.05	0.05	0.05	0.05	0.05	0.05
Lateral non-uniformity, k_r		0.01	0.01	0.01	0.01	0.01	0.01
Positioning							
Source to surface distance		0.05	0.05	0.05	0.05	0.05	0.05
Detector position		0.11	0.11	0.11	0.11	0.11	0.11
Specific heat capacity, c_p		0.03	0.03	0.03	0.03	0.03	0.03
Combined relative standard uncertainty of D_w		0.98	0.84	0.76	0.74	0.69	0.45

Two commercial ionization chambers of type NE2561-240 and TM30013-425 were calibrated in terms of absorbed dose to water directly in the phantom of the calorimeter at the same depths of water (5g/cm^2) as the calorimetric detector. This procedure and the associated uncertainties are described in detail in reference [2]. These two chambers are since then in use as PTB’s absorbed dose to water transfer standards for the calibration of client’s chambers under reference conditions and were also used for the current comparison. The following Table 10 was copied from reference [2] and shows the uncertainties of the D_w determination with the PTB reference transfer chambers. Details are explained in reference [2].

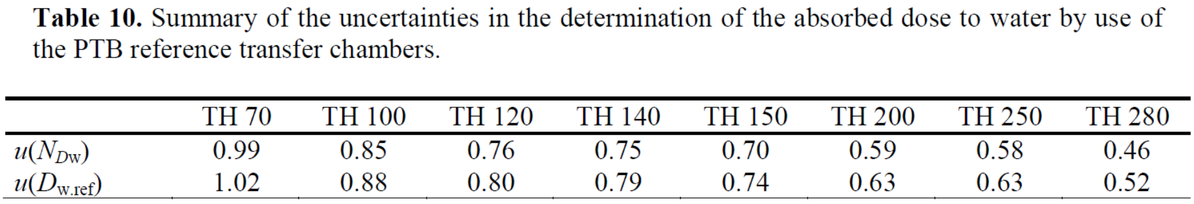


Table 10. Summary of the uncertainties in the determination of the absorbed dose to water by use of the PTB reference transfer chambers.

	TH 70	TH 100	TH 120	TH 140	TH 150	TH 200	TH 250	TH 280
$u(N_{Dw})$	0.99	0.85	0.76	0.75	0.70	0.59	0.58	0.46
$u(D_{w,\mathrm{ref}})$	1.02	0.88	0.80	0.79	0.74	0.63	0.63	0.52

PTB routinely uses the reference qualities denoted as TH-series as listed in Table 1 of reference [2]. For the measurements of this comparison there are two differences to the PTB standard procedure:

1. Different reference depth in water (2 g/cm^2 instead of 5 g/cm^2).
2. Different radiation qualities are used (CCRI qualities instead of TH-series).

Supported by additional measurements and calculations it was assumed that the calibration coefficients of the reference transfer chambers originally measured at 5 g/cm^2 in the water phantom of the calorimeter can also be used in the depth 2 g/cm^2. The calibration coefficients of the reference transfer chamber type TM30013-425 for the CCRI medium-energy qualities were obtained by interpolation of the known calibration coefficients for the PTB TH-series

[2]. Note that TH 100, TH 140 and TH 250 are very similar to CCRI 100, CCRI 135 and CCRI 250 (see Table 18 in the main text of this report). Interpolated values are shown in Figure 1 which was adopted from the PTB report of results.

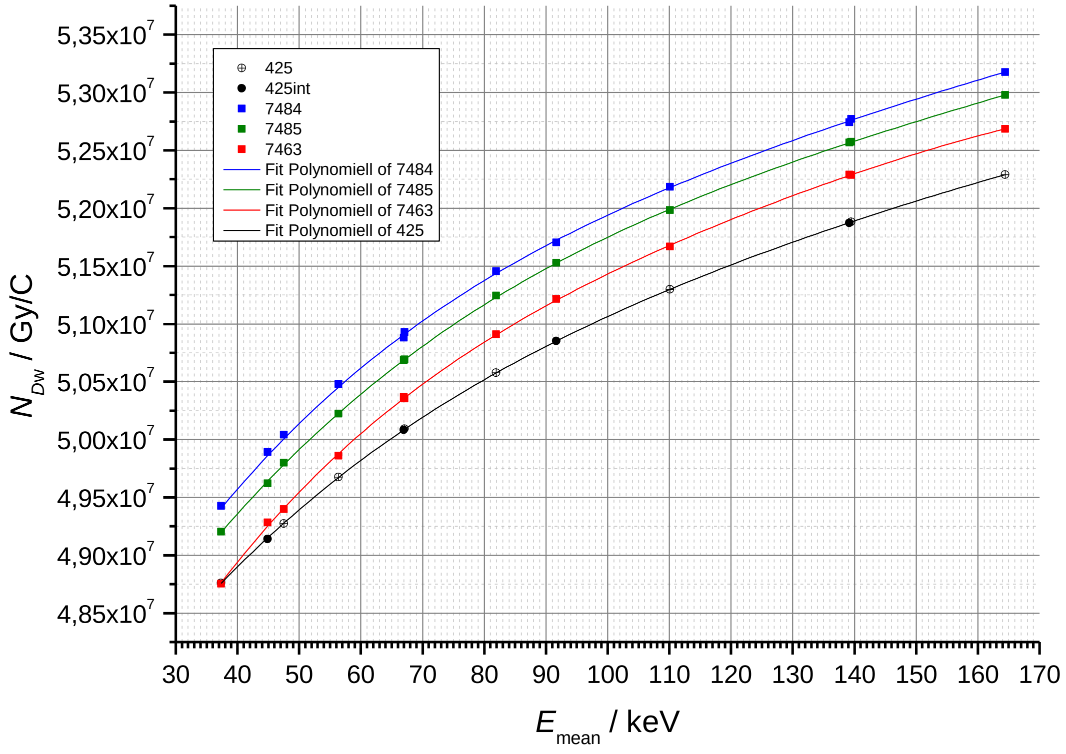


Figure 1: Interpolated calibration coefficients (black circles) of the PTB reference transfer chamber TM30013-425 and those of the same chamber measured directly in the water phantom of the calorimeter [2] (open circles with crosses). The mean energy is the air kerma weighted mean energy evaluated on the basis of measured photon fluence spectra. The coloured points are the calibration coefficients obtained for the transfer chambers of this comparison. The lines are polynomiell fits to the measured points.

The uncertainties of the calibration coefficients of the transfer chambers, $u(N_{Dw,trans})$, of this comparison were calculated by using $u(D_{W,ref})$ of Table 10 (in [2]) for the similar CCRI qualities and additional uncertainties due to the long term stability of the PTB transfer standard $u(k_{stab})$, positioning of the transfer chamber $u(pos)$ and the corrected charge measurement $u(Q_{corr})$. Results are shown in Table 11 taken from the PTB results report.

Table 11: Relative percentage standard uncertainties used for the estimation of the total uncertainties of the calibration coefficients of the transfer chambers of this comparison.

Quality code	$u(D_{W,ref})$	$u(k_{stab})$	$u(pos)$	$u(Q_{corr})$	$u(N_{Dw,trans})$
100 kV	0.88	0.2	0.04	0.1	0.91
135 kV	0.79	0.2	0.04	0.1	0.82
180 kV	0.63	0.2	0.04	0.1	0.67
250 kV	0.63	0.2	0.04	0.1	0.67