Comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water of the PTB, Germany and the BIPM in accelerator photon beams

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Abstract

A key comparison has been made between the absorbed dose to water standards of the Physikalisch-Technische Bundesanstalt (PTB), Germany and the BIPM in accelerator photon beams. The results show the standards to be in agreement within the standard uncertainty of the comparison of 5.7 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison has been made between the absorbed dose to water standards of the Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Bureau International des Poids et Mesures (BIPM) in the accelerator photon beam range from 6 MV to 18 MV to update the previous comparison result of 2010 (Picard *et al.* 2011) published in the BIPM key comparison database (KCDB 2022) under the reference BIPM.RI(I)-K6. The BIPM measurements took place using the accelerator facility at the DOSEO platform in Saclay (France) in September 2021. The comparison was undertaken in three radiation beams using three transfer ionization chambers belonging to the PTB; the transfer chambers were types FC65G and PTW 30013. The results of the comparison are given in terms of the mean ratio of the calibration coefficients of these transfer instruments determined at the two laboratories for each radiation quality. The final results were supplied by the PTB in November 2021.

2. Irradiation facilities

2.1 The BIPM irradiation facility and reference beam qualities

The BIPM measurements were carried out at the DOSEO platform in Saclay (France), which houses an Elekta *Versa* clinical linear accelerator, which has been characterized for use as a BIPM reference facility. This accelerator provides three high-energy photon beams at 6 MV, 10 MV and 18 MV. The radiation qualities are characterized in terms of the tissue-phantom ratio $TPR_{20,10}$, the measured values given in Table 1. Details of the BIPM measurement conditions are described by Kessler and Burns (2022).

All measurements were made with the gantry fixed for horizontal irradiation, with a source-detector distance of 1 m and at the reference depth of 10 g cm^{-2}.

The irradiation area at the DOSEO platform is temperature controlled in the range from 21 °C to 24 °C. Calibrated thermistors measure the temperature of the ambient air and the water. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. The relative humidity is controlled within the range from 40 % to 50 %. For the comparison measurements, the beam output was monitored during irradiation using a commercial parallel-plate transmission chamber fixed to a shadow tray, the same transportable arrangement used for previous comparisons in the series BIPM.RI(I)-K6.

2.2 The PTB irradiation facility and reference beam qualities

At the PTB, two Elekta Precise linear accelerators were used to calibrate the transfer chambers for the present comparison. The radiation beams, characterized in terms of the tissue-phantom ratio $TPR_{20,10}$, are included in Table 1.

Table 1. **Beam qualities**

Radiation quality	4 MV	6 MV	8 MV	10 MV	15 MV	18 MV	25 MV
BIPM $TPR_{20,10}$	---	0.686	---	0.733	---	0.774	---
PTB $TPR_{20,10}$	0.638	0.683	0.714	0.733	0.760	---	0.799

3. Details of the standards

3.1 BIPM primary standard

The BIPM primary standard is based on a graphite calorimeter described by Picard *et al.* (2009). The calorimeter consists of a graphite core placed in a cylindrical graphite jacket; the main characteristics are listed in Table 2.

Table 2. **Characteristics of the BIPM standard**

BIPM standard		Nominal values
Calorimeter core	Diameter / mm	45.0
	Thickness / mm	6.7
Calorimeter jacket	Diameter / mm	60.0
	Thickness / mm	32.0
Standard chamber	Diameter / mm	45.0
	Thickness / mm	11.0
Air cavity	Volume / cm^3	6.8
Wall	Thickness / mm	2.85
Wall material	Graphite of density / g cm^{-3}	1.85
Polarizing voltage	Applied to outer electrode / V	+80

The core is equipped with three thermistor pairs connected to three independent d.c. bridges. This core and jacket are placed in an evacuated cubic PMMA vacuum phantom with side length 300 mm. A graphite build-up plate is used to position the calorimeter centre at the reference depth of 10 g cm^{-2}. Two nominally-identical parallel-plate ionization chamber standards with graphite walls and collector, similar in design to the existing BIPM standards for air kerma and absorbed dose to water, were fabricated to serve in the determination of the absorbed dose to water from the measured absorbed dose to the graphite core. The first chamber is housed in a graphite jacket, nominally identical to the calorimeter jacket, and is positioned in the same PMMA vacuum phantom but at ambient air pressure, replacing the calorimeter core and its jacket. The second chamber is housed in a waterproof PMMA sleeve and mounted at a depth of 10 g cm^{-2} in a PMMA water phantom with the same outer dimensions and PMMA window thickness (4 mm) as the vacuum phantom.

3.2 PTB primary standard

The PTB primary standard in high-energy photon beams is a water calorimeter operated at a water temperature of 4 °C. The details of the calorimetric method for the determination of the absorbed dose to water (D_w) in photon beams have been described by Krauss and Kapsch (2014). Since then, the design of the PTB water calorimeter was changed by replacing the original large outer housing by a more compact design, without changing the principal method of the absorbed dose determination. The new design of the water calorimeter is described in Krauss *et al.* (2012). Nevertheless, the uncertainty budget for the determination of the absorbed dose to water was re-evaluated in advance of the current comparison which results in a relative standard uncertainty of 2.9 parts in 10^3 for the D_w determination (Table 12) and of 3.2 parts in 10^3 for the determination of the calibration coefficient for a transfer ionization chamber. A component of 2 parts in 10^3 is added to the comparison results (Table 13) for interpolation arising from the different $TPR_{20,10}$ values at the two laboratories, as described in section 4.3.

4. Determination of the absorbed dose to water

4.1 Absorbed dose to water at the BIPM: formalism and method

The BIPM determination of absorbed dose to water is based on calorimetric and ionometric measurements combined with Monte Carlo calculations. The method is described in a number of previous comparison reports, for example Kessler *et al.* (2019) and details of the standard are given in Kessler and Burns (2022). The absorbed dose to water at the reference depth, $D_{w,BIPM}$, is evaluated as:

$$D_{\mathrm{w,BIPM}} = D_{\mathrm{c}} \frac{Q_{\mathrm{w,st}}}{Q_{\mathrm{c,st}}} \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{c}}}\right)^{\mathrm{MC}} \left(\frac{D_{\mathrm{cav,c}}}{D_{\mathrm{cav,w}}}\right)^{\mathrm{MC}} k_{\mathrm{rn,st}} \quad (1)$$

where

D_c	measured absorbed dose to the graphite core;
$Q_{c,st}$	ionization charge measured by the standard chamber positioned in the graphite jacket, replacing the core;
$Q_{w,st}$	ionization charge measured by the standard chamber positioned in water;
$(D_w/D_c)^{MC}$	calculated ratio of absorbed dose to water and to the graphite core using Monte Carlo simulations;
$(D_{cav,c}/D_{cav,w})^{MC}$	calculated ratio of cavity doses in graphite and in water using Monte Carlo simulations;
$k_{rn,st}$	measured correction for radial non-uniformity for the standard chamber in water.

The ionization charges $Q_{w,st}$ and $Q_{c,st}$ are normalized to 293.15 K and 101.325 kPa and corrected for ion recombination. In practice, two nominally-identical standard chambers are used; the air cavity volume for each is known and a correction $k_{vol,st}$ is made for the small difference in volume with a relative standard uncertainty of 3 parts in 10^4.

Equation 1 can also be expressed as

$$\begin{aligned} D_{\mathrm{w,BIPM}} &= Q_{\mathrm{w,st}} \frac{D_{\mathrm{c}}}{Q_{\mathrm{c,st}}} C_{\mathrm{w,c}} k_{\mathrm{rn,st}} \\ &= Q_{\mathrm{w,st}} N_{D,\mathrm{c,st}} C_{\mathrm{w,c}} k_{\mathrm{rn,st}} \end{aligned} \quad (2)$$

where

$C_{w,c}$ represents the total Monte Carlo conversion factor;

$N_{D,c,st}$ is the measured calibration coefficient for the standard chamber in graphite.

The conversion factor $C_{w,c}$ and the calibration coefficients $N_{D,c,st}$ for the standard chamber in graphite for given $TPR_{20,10}$ values are taken to be those derived from quadratic fits, as explained in Kessler *et al.* (2019). Figure 1 shows the conversion factors plotted as a function of the calculated $TPR_{20,10}$, calculated for the beams of seven National Metrology Institutes (NMIs) that participated in the BIPM.RI(I)-K6 key comparison.

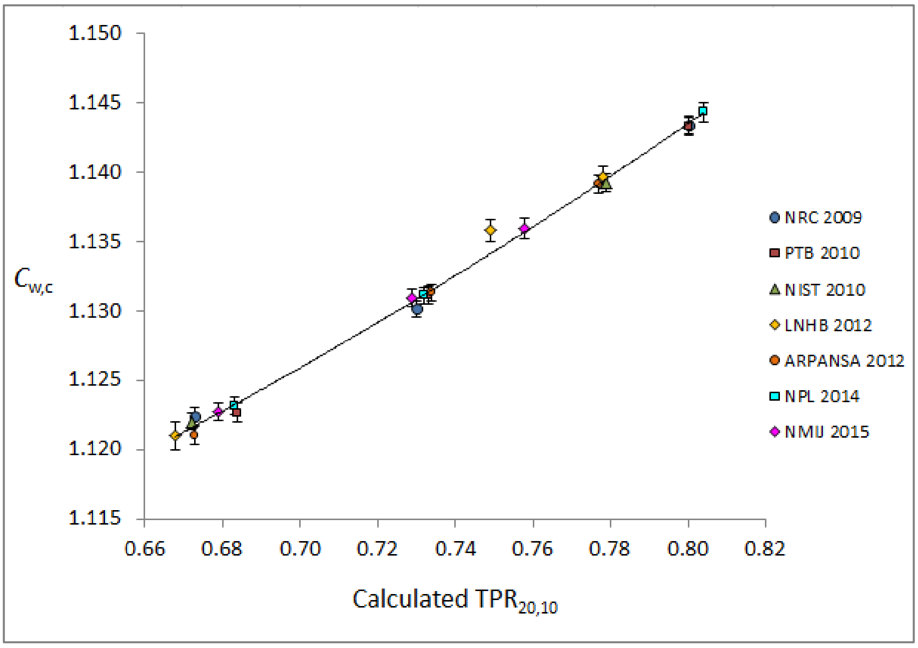

Figure 1. The dose conversion factor $C_{w,c}$ for the BIPM standard, calculated using the phase-space files supplied by participating NMIs. The line is a weighted quadratic fit to the data; the deviations about this line are consistent with the typical statistical standard uncertainty of 5 parts in 10^4.

Figure 2 shows the normalized $N_{D,c,st}$ determinations and a quadratic fit to the data; the plot shows the coefficients determined at all the NMIs that participated in the BIPM.RI(I)-K6 key comparison and at the DOSEO facility in Saclay (France). These latter data are included in the fit.

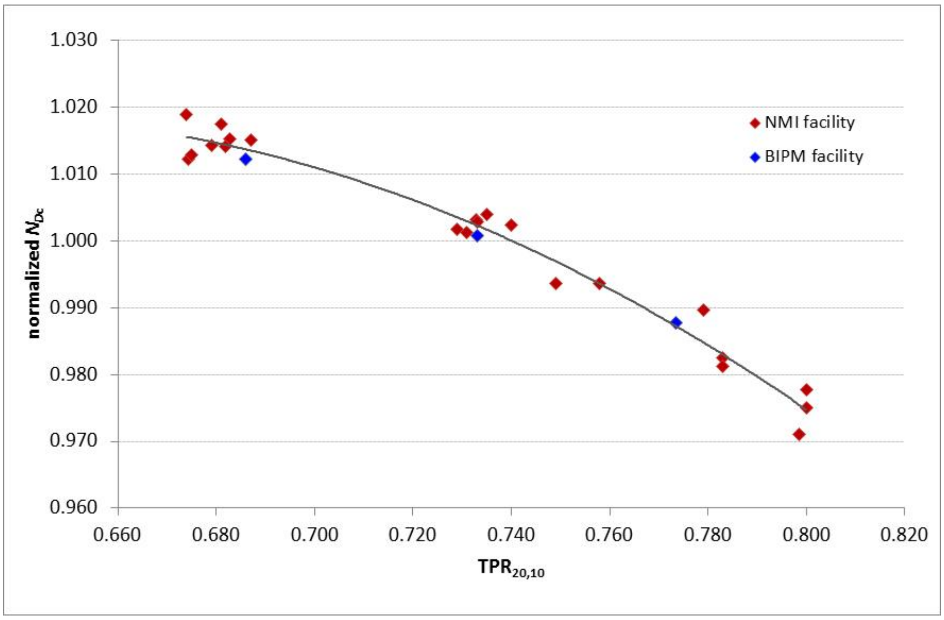

Figure 2. The calibration coefficients $N_{D,c,st}$ determined by the BIPM at various NMI facilities (red) and at the BIPM facility (blue), normalized to the mean, as a function of the measured $TPR_{20,10}$. The solid line is a quadratic fit to the combined data set.

4.2 Absorbed dose to water at the BIPM: practical determination

For the present comparison, instead of using the standard chamber in water, a NE 2571 chamber was used as the BIPM reference. Since 2017, this chamber has been calibrated periodically against the primary standard and has been fully characterized to be considered as a reference chamber. The relative standard uncertainty corresponding to the long-term stability of its calibration coefficient $N_{D,\mathrm{w,ref\,ch}}$ is 6 parts in 10^4, included in Table 10.

The absorbed dose to water was thus determined as

$$D_{\mathrm{w,BIPM}} = Q_{\mathrm{w,ref\,ch}} N_{D,\mathrm{w,ref\,ch}} k_{\mathrm{rn,ref\,ch}} k_{\mathrm{s,ref\,ch}} \quad (3)$$

where

$Q_{\mathrm{w,ref\,ch}}$	ionization charge measured by the reference chamber positioned in water (normalized to the monitor chamber);
$N_{D,\mathrm{w,ref\,ch}}$	calibration coefficient of the reference chamber;
$k_{\mathrm{rn,ref\,ch}}$	radial non-uniformity correction factor for the reference chamber;
$k_{\mathrm{s,ref\,ch}}$	ion recombination correction factor for the reference chamber.

The ionization charge $Q_{\mathrm{w,ref\,ch}}$ is normalized to 293.15 K and 101.325 kPa; no correction for humidity is applied.

The correction factor $k_{\mathrm{s,ref\,ch}}$ for losses due to ion recombination for the reference chamber was determined using the method of Niatel as described by Boutillon (1998) for continuous radiation and implemented for pulsed radiation by Picard *et al.* (2011). The ion recombination correction factor for pulsed radiation, k_{s}, can be expressed as:

$$k_{\mathrm{s}} = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} Q_{\mathrm{p}} \quad (4)$$

where Q_{p} is the charge per pulse expressed in pC, k_{init} is the initial recombination and diffusion and k_{vol} is the volume recombination coefficient. Table 3 gives the values for k_{init} and k_{vol} for the reference chamber, for the operating voltage of 250 V. For a typical charge per pulse of up to 10 pC, $k_{\mathrm{s,ref\,ch}}$ is of the order of 1 part in 10^2 and the standard uncertainty for $k_{\mathrm{s,ref\,ch}}$ is estimated to be 3 parts in 10^4, as shown in Table 10. The correction factors for the three radiation qualities are presented in Table 4.

Table 3. Ion recombination for the BIPM reference chamber NE 2571

Coefficient	Value
initial recombination and diffusion, k_{init}	12.9×10^{-4}
volume recombination coefficient, k_{vol} / pC^{-1}	7.1×10^{-4}

The factors that correct for the non-uniformity of the beams were calculated from the beam profiles in water measured by the BIPM. For thimble chamber types of similar dimensions to the NE 2571, the correction factors for the three different beams are presented in Table 4 with an estimated relative standard uncertainty of 3 parts in 10^4, as shown in Table 10. Note that this correction will largely cancel when the reference chamber is used to calibrate a transfer chamber of similar dimensions.

Table 4. Correction factors for the BIPM reference chamber NE 2571

Radiation quality	6 MV	10 MV	18 MV
ion recombination $k_{\mathrm{s,ref\ ch}}$	1.0040	1.0063	1.0083
radial non-uniformity $k_{\mathrm{rn,ref\ ch}}$	1.0000	0.9980	1.0000

4.3 Absorbed dose to water at the PTB: determination of $N_{D,\mathrm{w,lab}}$

As explained in section 3.2, the PTB determination of absorbed dose to water is based on calorimetric measurements.

At the reference depth in the water phantom, the absorbed dose to water D_{w} is evaluated as:

$$D_{\mathrm{w}} = \Delta T \, c_p \prod k_i \qquad (5)$$

where ΔT is the radiation induced temperature increase measured using two temperature sensors located inside the calorimetric detector, c_{p} is the specific heat capacity of water at 4°C and the k_i are the correction factors for the heat defect, for heat conduction effects, for perturbation effects and for the lateral (radial) inhomogeneity of the irradiation field.

After the calorimetric determination of D_{w}, calibration coefficients $N_{D,\mathrm{w},Q}$ of ionization chambers can be directly determined inside the water phantom of the calorimeter by replacing the calorimetric detector with the ionization chamber under test at the same measurement position.

Because the $\mathrm{TPR}_{20,10}$ values of the beams available at the PTB differ from the beam qualities used for this comparison (see Table 1) the procedure explained below was applied to obtain calibration coefficients for the beam qualities available at the BIPM irradiation facility.

From the calibration coefficients obtained in all high-energy photon beams available at the PTB and in the ^{60}Co reference beam individual beam quality correction factors k_Q were determined for the three transfer chambers used in this comparison. Two separate measurement campaigns were performed, the corresponding mean value for each transfer chamber then taken as the final values of the k_{Q} factor. The corresponding k_Q values for the beam qualities used in this comparison were obtained by interpolation of the PTB results using a fit function as given in equation (6) in Andreo *et al.* (2020). Finally, the calibration coefficients $N_{D,\mathrm{w,PTB}}$ of the transfer chambers for the beam qualities used in this comparison were obtained from the corresponding beam quality correction factors k_Q and the calibration coefficient at the reference beam quality ^{60}Co.

5. Comparison procedure

The comparison of the PTB and BIPM standards was carried out indirectly using the calibration coefficients $N_{D,\mathrm{w,lab}}$ for three transfer chambers given by

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}} / I_{\mathrm{lab}} \qquad (6)$$

where $\dot{D}_{\mathrm{w,\,lab}}$ is the water absorbed dose rate determined by a given laboratory, the PTB or the BIPM, and I_{lab} is the corresponding ionization current for a transfer chamber measured by each laboratory, using its own measurement system.

The ionization chamber FC65G, serial number 771, and the two PTW 30013 chambers, serial numbers 6762 and 11027, belonging to the PTB, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 5.

Table 5. Characteristics of the PTB transfer chambers

Parameter	FC65G	PTW 30013	
Cavity diameter / mm	6.2	6.2	
Nominal volume / cm^3	0.65	0.60	
Wall material	graphite	graphite	PMMA
Wall thickness / mm	0.40	0.09	0.335
Polarizing voltage [a] / V	-250	+250	

[a] Potential applied to the outer electrode

The essential details for the determination of the calibration coefficients $N_{D,\mathrm{w}}$ for the transfer chambers are described below.

Positioning

The chambers were positioned by each laboratory with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source.

Applied voltage and polarity

A collecting voltage of 250 V (negative polarity for the FC65G and positive polarity for the PTW 30013) was applied to the outer electrode of the chambers at least 30 min before any measurements were made. No corrections were applied by either laboratory for polarity.

Charge measurements

The charge was measured by the BIPM using a Keithley electrometer, model 6517, and a set of calibrated external capacitors. The capacitors are in a sealed box with a desiccant to minimize the moisture content. At PTB the ionization current is measured using a Keithley 616 electrometer as a buffer amplifier whose output voltage (which is proportional to the input current) is digitized using an analog-digital converter. The entire measurement chain is calibrated using a calibrated Keithley 6430 SourceMeter.
The chambers were pre-irradiated for at least 10 min (≈ 20 Gy) by the BIPM and the PTB before any measurements were made.

Ambient conditions

For the BIPM and PTB arrangements, the water temperature is measured for each current measurement and it was stable to better than 0.1 °C.

The ionization current is normalized to 293.15 K and 101.325 kPa for both laboratories. Relative humidity is in the range from 40 % to 60 % at the PTB facility. No correction for humidity is applied to the ionization current measured by either laboratory.

Ion recombination

Ion recombination was measured by the BIPM for each chamber using the Niatel method as described previously using equation 4. Table 6 gives the values for k_{init} and k_{vol}, for each chamber, for the operating voltage of 250 V. Ion recombination was also determined using the two-voltage method, as described in the TRS 398 protocol (IAEA 2000). The results obtained using both methods are presented in Table 7, showing a general agreement of 2 parts in 10^4. For the PTB, the correction for ion recombination was determined from the vertical intercept of the Jaffé-plot (interpolation line of $1/M$ vs $1/U$ where M is the ionization current obtained for a chamber voltage U).

Table 6. Ion recombination for the PTB transfer chambers determined at the BIPM

Coefficient	FC65G	PTW 30013	
	771	6762	11027
initial recombination and diffusion, k_{init}	5.7×10^{-4}	16.0×10^{-4}	14.1×10^{-4}
volume recombination coefficient, k_{vol} / pC^{-1}	7.6×10^{-4}	6.6×10^{-4}	7.1×10^{-4}

Radial non-uniformity correction

The correction factors for the radial non-uniformity of the beam over the section of the transfer chambers were calculated by the BIPM from the measured beam profiles in water; they are the same as those for the BIPM reference chamber NE 2571 given in Table 4, with an uncertainty of 3 parts in 10^4. The correction factors applied by the BIPM are summarized in Table 7 (for ion recombination, the factors evaluated using the Niatel method were used).

Table 7. BIPM correction factors for the PTB transfer chambers

Radiation quality			6 MV	10 MV	18 MV
ion recombination $k_{s,tr\ ch}$	FC65G	Niatel	1.0034	1.0059	1.0078
		TRS 398	1.0034	1.0058	1.0077
	PTW sn 6762	Niatel	1.0038	1.0056	1.0072
		TRS 398	1.0038	1.0055	1.0071
	PTW sn 11027	Niatel	1.0037	1.0056	1.0073
		TRS 398	1.0038	1.0055	1.0073
radial non-uniformity $k_{rn,tr\ ch}$	BIPM		1.0000	0.9980	1.0000

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and the thickness of the PMMA front window of the water phantom (4 mm for the BIPM and 3 mm for the PTB) is included as a water-equivalent thickness in g cm^{-2} when positioning the chamber.

All the chambers were inserted in water without sleeve.

6. Results of the comparison

6.1 Measurement results

The PTW transfer chambers were set-up and measured by the BIPM on two separate occasions and the FC65G was set-up and measured on three separate occasions. The results were reproducible to better than 4 parts in 10^4. At the PTB, the chambers were calibrated on 3 separate occasions before the measurements at the BIPM and once on the return of the chambers. The reproducibility at the PTB is estimated to be better than 6 parts in 10^4.

The result of the comparison, $R_{D,\mathrm{w}}$, is expressed in the form

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,PTB}} / N_{D,\mathrm{w,BIPM}} \qquad (7)$$

in which the value interpolated in terms of $TPR_{20,10}$ from the measurements made at the PTB is compared with the mean of the measurements made at the BIPM for this $TPR_{20,10}$ (see end of section 4.3).

The results for each chamber are presented in Table 8.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	6 MV	10 MV	18 MV
FC65G-771			
$N_{D,\mathrm{w,PTB}}$ / Gy µC^{-1}	47.13	46.71	46.15
$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	47.06	46.77	46.18
PTW 30013-6762			
$N_{D,\mathrm{w,PTB}}$ / Gy µC^{-1}	53.09	52.52	51.85
$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	52.92	52.55	51.87
PTW 30013-11027			
$N_{D,\mathrm{w,PTB}}$ / Gy µC^{-1}	53.20	52.64	51.97
$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	53.03	52.65	51.96

The final results $R_{D,\mathrm{w,PTB}}$ in Table 9 are evaluated as the mean for the three transfer chambers. For each quality, the corresponding uncertainty s_{tr} is the standard uncertainty of this mean, derived from the spread of the three results. The mean value of s_{tr} for the three qualities, $s_{\mathrm{tr,comp}} = 0.0004$, is a global representation of the comparison uncertainty arising from the transfer chambers and is included in Table 14.

To check the stability of the transfer instruments, the chambers were measured in the PTB ^{60}Co beam before and after the measurements at the BIPM. This gives rise to a relative standard deviation for each chamber, taken as a representation of the stability of the transfer instruments. The stability is estimated to be 4 parts in 10^4 (Table 14).

Table 9. Comparison results

Radiation quality	6 MV	10 MV	18 MV
$N_{D,\mathrm{w,PTB}}/N_{D,\mathrm{w,BIPM}}$ using FC65G	1.0015	0.9989	0.9993
$N_{D,\mathrm{w,PTB}}/N_{D,\mathrm{w,BIPM}}$ using PTW 6762	1.0031	0.9995	0.9995
$N_{D,\mathrm{w,PTB}}/N_{D,\mathrm{w,BIPM}}$ using PTW 11027	1.0031	0.9999	1.0003
s_{tr}	0.0005	0.0003	0.0003
$R_{D,\mathrm{w,PTB}}$	1.0026	0.9994	0.9997

The results shown in Table 9 demonstrate the agreement between the two standards for absorbed dose to water within the relative standard uncertainty of the comparison of 5.7 parts in 10^3 evaluated below.

6.2 Uncertainties

The uncertainties associated with the BIPM primary standard and the calibration of the BIPM reference chamber are listed in Table 10. Table 11 summarizes the uncertainties associated with the calibration of the PTB transfer chambers used for the comparison.

For the PTB, the uncertainties are listed in Table 12 and Table 13 for the standard and the calibration of the chambers used for the comparison, respectively. The combined standard uncertainty u_c for the comparison results $R_{D,\mathrm{w,PTB}}$ is presented in Table 14.

Table 10. Uncertainties associated with the BIPM standard and the calibration of the BIPM reference chamber

Relative standard uncertainty [1]	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{D,\mathrm{c,st}}$	0.23	0.14
$C_{\mathrm{w,c}}$	0.05	0.25
$Q_{\mathrm{w,st}}/Q_{\mathrm{w,ref\ ch}}$	0.05	0.05
$k_{\mathrm{rn,st}}$	–	0.10
$k_{\mathrm{s,st}}$	–	0.05
$k_{\mathrm{vol,st}}$	–	0.03
depth standard	–	0.05
$k_{\mathrm{rn,ref\ ch}}$ [2]	–	0.03
$k_{\mathrm{s,ref\ ch}}$ [2]	–	0.03
depth BIPM reference chamber	–	0.05
stability $Q_{\mathrm{w,st}}/Q_{\mathrm{w,ref\ ch}}$	0.06	–
$N_{D,\mathrm{w,ref\ ch}}$	0.25	0.32

(1) expressed as one standard deviation.
u_{iA} represents the relative uncertainty estimated by statistical methods, type A
u_{iB} represents the relative uncertainty estimated by other methods, type B.

(2) uncertainty removed from the analysis when the reference chamber is used to calibrate the transfer chamber.

Table 11. Uncertainties associated with the calibration of the PTB transfer chambers by the BIPM

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{D,\mathrm{w,ref\ ch}}$	0.25	0.32
$Q_{\mathrm{w,ref\ ch}}/Q_{\mathrm{w,tr\ ch}}$	0.05	0.05
depth BIPM reference chamber	–	0.05
depth transfer chamber	–	0.05
$k_{\mathrm{s,tr\ ch}}$	–	0.03
short-term reproducibility	0.04	–
$N_{D,\mathrm{w,BIPM}}$	0.26	0.33

Table 12. Uncertainties associated with the PTB standard

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
mean radiation induced temperature change per monitor signal	0.04	0.16
correction for heat defect	–	0.14
correction for heat conduction	–	0.08
correction for field perturbation	–	0.15
correction for radial non-uniformity	–	0.03
deviation from reference conditions, positioning	–	0.08
absorbed dose per monitor signal	0.04	0.29

Table 13. Uncertainties associated with the calibration of the transfer chambers at the PTB

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
absorbed dose per monitor signal	0.04	0.29
stability of monitor calibration coefficient	–	0.05
charge reading per monitor signal	0.04	0.01
correction for environment conditions	–	0.05
correction for ion recombination	–	0.05
correction for radial non-uniformity	–	0.10
deviation from reference conditions, positioning	–	0.04
calibration coefficient $N_{D,\mathrm{w},Q}$ in the PTB beams	0.06	0.32
interpolation for beam quality	–	0.2
calibration coefficient $N_{D,\mathrm{w,PTB}}$ for BIPM beam qualities	0.06	0.38

Table 14. Uncertainties associated with the comparison result

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
$N_{D,\mathrm{w,PTB}}/N_{D,\mathrm{w,BIPM}}$	0.26	0.50
$k_{\mathrm{rn,tr\ ch}}$	–	0.03
transfer chambers $s_{\mathrm{tr,comp}}$	0.04	–
stability of transfer chambers	0.04	–
combined standard uncertainty $R_{D,\mathrm{w,PTB}}$	0.57	

7. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here $D_{w,BIPM}$, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each NMI i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (D_{wi} – D_{w,BIPMi})/ D_{w,BIPMi} = x_i – 1$ and its expanded uncertainty $U_i = 2\ u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 15 gives the values for D_i and U_i for each NMI, i, taken from the BIPM key comparison database (KCDB 2021) and this report. These data are presented graphically in Figure 3.

Table 15. Degrees of equivalence

Beam quality corresponding to measured $TPR_{20,10}$ between 0.63 (included) and 0.71 (excluded)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
NIST	3.5	11.4
ARPANSA	-3.5	11.0
NPL	-2.7	12.4
VSL	-4.1	10.8
NMIJ	-3.4	9.4
NIM	-8.3	12.0
KRISS	7.8	12.0
METAS	-1.7	13.2
LNE-LNHB	-2.3	11.8
NRC	4.0	11.6
PTB	2.6	11.4

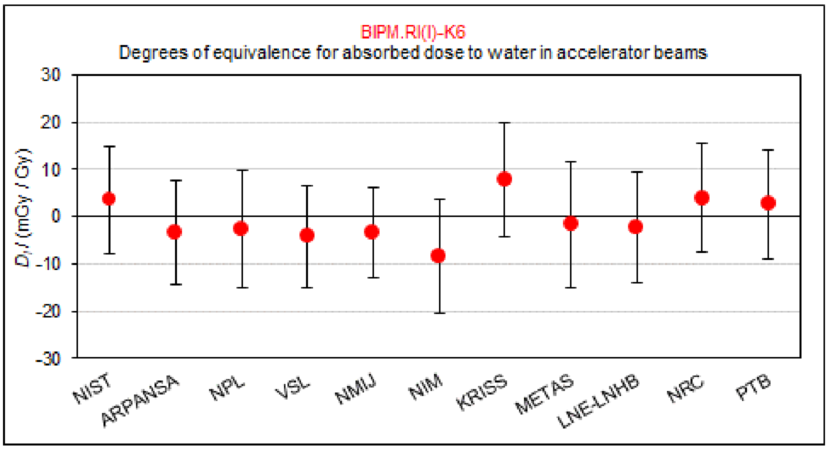

Figure 3a. Graph of the degrees of equivalence with the KCRV

Beam quality corresponding to measured $TPR_{20,10}$ between 0.71 (included) and 0.77 (excluded)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
ARPANSA	-7.6	12.0
NPL	-0.5	13.2
VSL	-4.2	12.8
NMIJ	-4.1	11.0
NIM	-5.9	11.8
KRISS	5.6	12.0
METAS	-3.2	13.2
LNE-LNHB	-3.8	11.8
NRC	3.0	11.6
PTB	-0.6	11.4

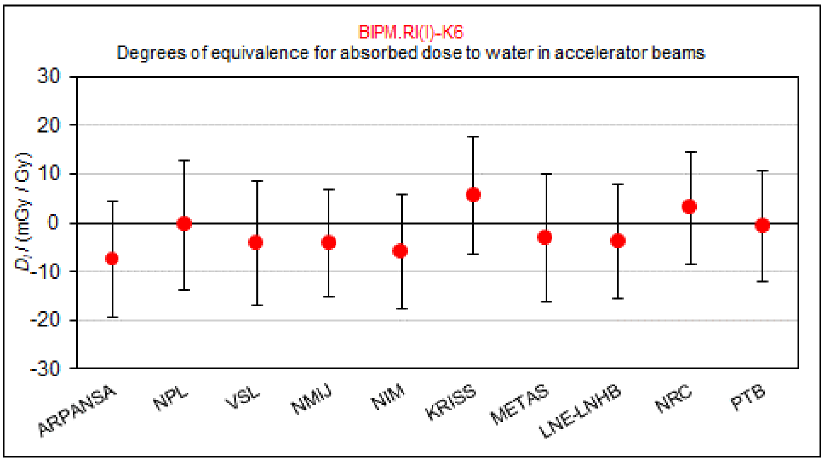

Figure 3b. Graph of the degrees of equivalence with the KCRV

Beam quality corresponding to measured $TPR_{20,10}$ between 0.77 (included) and 0.81(included)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
NIST	-4.2	11.8
ARPANSA	-6.8	11.8
NPL	-4.3	16.2
VSL	1	14.8
KRISS	8.5	12.0
METAS	-1.2	13.2
LNE-LNHB	-4.4	11.8
NRC	3.9	11.6
PTB	-0.3	11.4

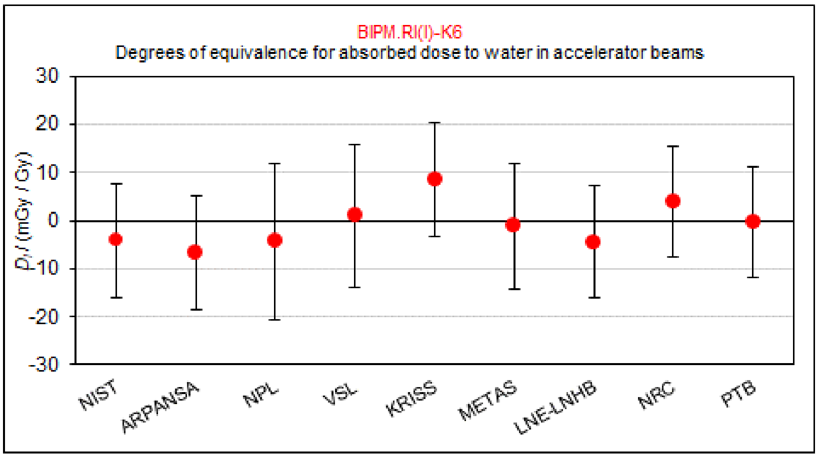

Figure 3c. Graph of the degrees of equivalence with the KCRV

8. Conclusions

A new key comparison has been carried out between the PTB and the BIPM standards for absorbed dose to water in accelerator photon beams, using three ionization chambers as transfer instruments. The comparison result is evaluated as the ratio of the calibration coefficients measured by the PTB and the BIPM. The results show the standards to be in agreement within the standard uncertainty of the comparison of 5.7 parts in 10^3. The present results are in agreement within the uncertainties with the results of the previous comparison (1.0013 at 6 MV, 1.0034 at 10 MV; 1.0018 at 25 MV, with a combined standard uncertainty of 6 parts in 10^3) carried out in the Elekta accelerator beams at the PTB in 2010.

When compared with the results for the other laboratories that have carried out comparisons in terms of absorbed dose to water, the PTB standard for absorbed dose to water is in good agreement with the ensemble of results.

Note that the data presented in the tables, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database (KCDB 2022).

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