Comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water of the NRC, Canada 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 National Research Council of Canada (NRC), Canada and the BIPM in accelerator photon beams. The results show the standards to be in agreement within the standard uncertainty of the comparison of 5.8 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 National Research Council of Canada (NRC), Canada, 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 2009 (Picard *et al.* 2010) published in the BIPM key comparison database (KCDB 2021) 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 2020. The comparison was undertaken in three radiation beams using three transfer ionization chambers belonging to the NRC. The transfer chambers were types FC65G, PTW 30012 and NE 2571. 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 NRC in July 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* linear clinical 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 NRC irradiation facility and reference beam qualities

The NRC measurements were carried out using an Elekta *Precise* linear accelerator, with the three photon energies shown in Table 1, characterized in terms of the tissue-phantom ratio $TPR_{20,10}$. The irradiation area is temperature controlled at around 22 °C and the relative humidity is in the range from 30 % to 70 %. To monitor the beam output, the NRC uses both the internal accelerator monitor chamber and an external transmission chamber mounted on a shadow tray. This is the same radiation facility and monitoring system as described in detail in Picard *et al.* (2010).

Table 1. **Beam qualities**

Radiation quality	6 MV	10 MV	18 MV	25 MV
BIPM $TPR_{20,10}$	0.686	0.733	0.774	---
NRC $TPR_{20,10}$	0.681	0.731	---	0.800

3. Details of the standards

3.1 BIPM primary standard

The BIPM primary standard is 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 NRC primary standard

The Canadian primary standard for absorbed dose to water in both ^{60}Co and high-energy photon beams operated at the NRC is a sealed water calorimeter. The calorimeter has been described in detail by Ross *et al*. (2000). The radiation-induced temperature rise is measured by thermistors mounted in a glass vessel, filled with high purity water. For high-energy photon beams, a cylindrical geometry vessel is used, with the radiation beam entering through the curved wall. An ensemble of vessels of the same nominal geometry but different water preparations (to confirm good control of radiochemistry) are used to realize the absorbed dose to water.

The NRC water calorimeter has been in use in MV photon beams for over two decades and the determination of absorbed-dose calibration coefficients for Farmer-type ionization chambers is summarized by McEwen (2010).

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, $D_{\mathrm{w,BIPM}}$, is evaluated as:

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

where

D_{c}	measured absorbed dose to the graphite core;
$Q_{\mathrm{c,st}}$	ionization charge measured by the standard chamber positioned in the graphite jacket, replacing the core;
$Q_{\mathrm{w,st}}$	ionization charge measured by the standard chamber positioned in water;
$(D_{\mathrm{w}}/D_{\mathrm{c}})^{\mathrm{MC}}$	calculated ratio of absorbed dose to water and to the graphite core using Monte Carlo simulations;
$(D_{\mathrm{cav,c}}/D_{\mathrm{cav,w}})^{\mathrm{MC}}$	calculated ratio of cavity doses in graphite and in water using Monte Carlo simulations;

k_{rn} measured correction for radial non-uniformity 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} 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

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

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 $C_{w,c}$ 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.

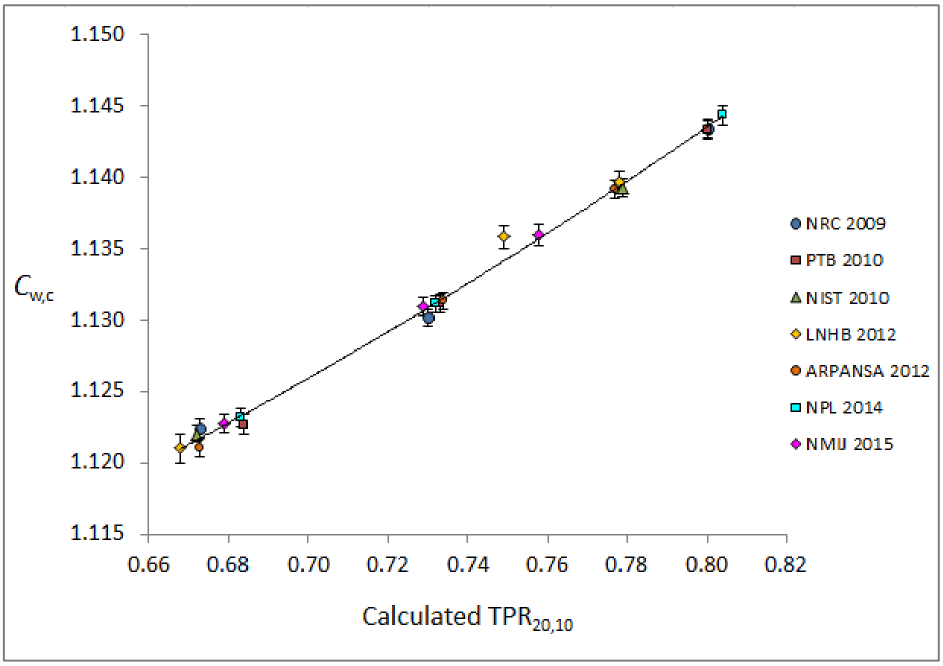

Figure 1. The dose conversion factor $C_{w,c}$ for the BIPM standard, calculated using the phase-space files supplied by participating NMIs. The line is a weighted quadratic fit to the data; the deviations about this line are consistent with the typical statistical standard uncertainty of 5 parts in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

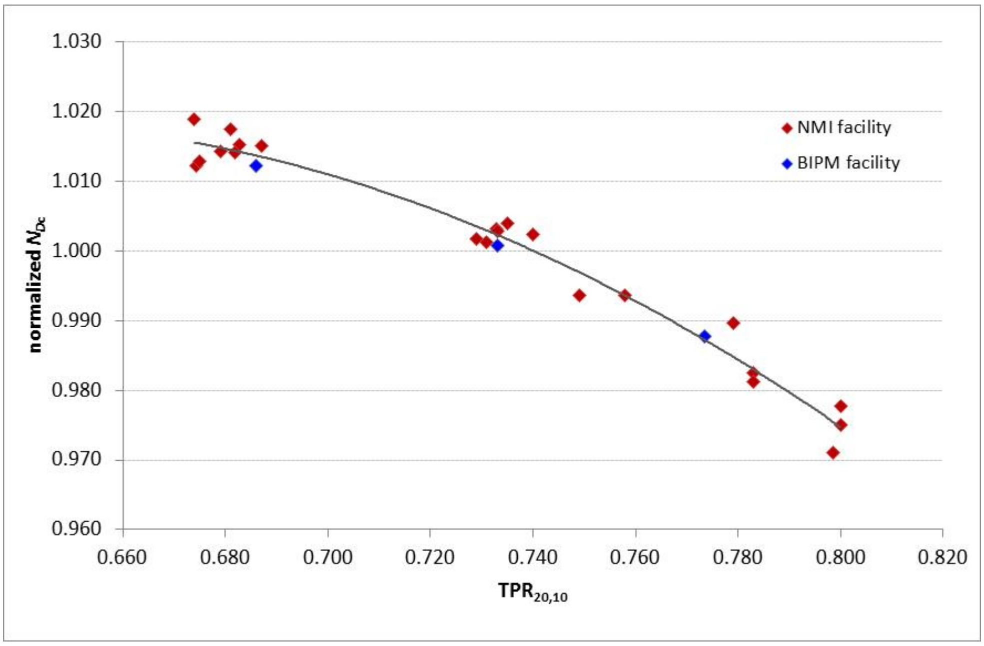

Figure 2. The calibration coefficients $N_{D,c,st}$ determined by the BIPM at various NMI facilities (red) and at the BIPM facility (blue), normalized to the mean, as a function of the measured $TPR_{20,10}$. The solid line is a quadratic fit to the combined data set.

4.2 Absorbed dose to water at the BIPM: practical determination

For the present comparison, instead of using the primary standard, an NE 2571 chamber (serial number 3299) was used as the BIPM reference. Since 2017, this chamber and several others have been calibrated periodically against the primary standard and have been fully characterized to be considered as reference chambers. The relative standard uncertainty corresponding to the long-term stability of the calibration coefficient $N_{D,\mathrm{w,ref\,ch}}$ for each of these reference chambers is 6 parts in 10^4, included in Table 10.

The absorbed dose to water was thus determined as

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

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_{rn}	radial non-uniformity correction factor for the reference chamber;
k_{s}	ion recombination correction factor.

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_{s} 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 recombination correction k_{s} for pulsed radiation can be expressed as:

$$k_{\mathrm{s}} = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} Q_{\mathrm{p}} \tag{4}$$

where Q_{p} is the charge per pulse, 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 operating voltage of 250 V. For a typical charge per pulse of up to 10 pC, k_s is of the order of 1 part in 10^2 and the standard uncertainty for k_s 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 also given in Table 4 with an estimated relative standard uncertainty of 3 parts in 10^4, as shown in Table 10.

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

Radiation quality	6 MV	10 MV	18 MV
ion recombination k_s	1.0042	1.0064	1.0083
radial non-uniformity k_{rn}	1.0000	0.9980	1.0000

4.3 Absorbed dose to water at the NRC

As explained in section 3.2, the NRC determination of absorbed dose to water is based on calorimetric measurements using a water calorimeter. The glass vessel is positioned at the reference depth in a cubic water phantom of side length 300 mm and the water is controlled at 4 °C to minimize convective effects.

The dose to water, D_w is then given by:

$$D_{w,NRC} = \Delta T_w \, c_w \, k_t \, k_c \, k_v \, k_p \, k_{dd} \, k_\rho k_{HD} \tag{5}$$

where

- ΔT_w radiation-induced temperature rise;
- c_w specific heat capacity of water;
- k_t transient effects on the thermistor response, due to dose deposition in the thermistor itself;
- k_c conductive heat transfer. The 3-D heat transport equation is solved using finite element methods to determine the effect due to excess heat in the glass components and temperature gradients (radial and axial);
- k_v convective heat transfer. This correction is assumed to be unity since the calorimeter is operated at 4 ºC;
- k_p perturbation of the radiation field by the vessel and probes;
- k_{dd} non-uniformity of the dose profile;
- k_ρ correction for the change in density (equivalent to a change in depth) when comparing the dose measured by the water calorimeter at 4 ºC and ion chambers at room temperature;
- k_{HD} heat defect. This correction accounts for the difference between the energy absorbed and the energy appearing as heat, which is due primarily to radiation-induced chemical reactions.

The complexity of operation of the water calorimeter means that the absorbed dose is transferred to a set of Farmer-type reference chambers. Multiple types, including those used in this comparison, are employed to avoid any bias due to a single manufacturing design. All chambers are compared to the primary standard water calorimeter in a thin PMMA sleeve (1 mm thick), irrespective of whether they are waterproof. This provides consistent positioning. The effect of the PMMA sleeve has been evaluated through measurements and Monte Carlo simulations and is summarized in Muir *et al.* (2011). For this comparison, the same sleeve was used for all chambers at the NRC and at the BIPM and no correction for the effect of the sleeve was applied.

The calibration coefficient of the reference chamber is given by:

$$N_{D,w,NRC} = \frac{D_w/R_{mon}}{M_{ch}/R_{mon}} \tag{6}$$

where

D_w absorbed dose to water, obtained in Equation (5), determined at 4 °C;

M_{ch} fully-corrected chamber reading, determined at ~ 22 °C;

R_{mon} reading of monitor chamber mounted on the shadow tray of the linear accelerator, used to transfer between chamber and calorimeter as measurements are made at different times, often days apart. This is described in detail by Picard *et al.* (2010).

5. Comparison procedure

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

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}}/I_{\mathrm{lab}} \tag{7}$$

where $\dot{D}_{\mathrm{w,\,lab}}$ is the water absorbed dose rate determined by a given laboratory, the NRC 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 chambers FC65G, serial number 1233, NE 2571, serial number 3694 and PTW 30012 serial number 447, belonging to the NRC, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 5.

Table 5. Characteristics of the NRC transfer chambers

Parameter	FC65G	NE 2571	PTW 30012
Cavity diameter / mm	6.2	6.3	6.1
Nominal volume / cm^3	0.65	0.69	0.60
Wall material	graphite	graphite	graphite
Wall thickness / mm	0.40	0.36	0.425
Polarizing voltage [(a)] / V	+300	+300	+300

[(a)] Potential applied to the outer electrode at the BIPM, see text below for the NRC configuration.

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

At the BIPM a collecting voltage of 300 V (positive polarity) was applied to the outer electrode of the chambers at least 30 min before any measurements were made. At the NRC the outer electrode is maintained at ground potential and a polarizing voltage is applied to the collecting (central) electrode with the same magnitude and opposite polarity as at the BIPM. 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 sealed boxes filled with dried air. At the NRC, the same type of electrometer is used but the internal capacitors are used for charge measurement. The chambers were pre-irradiated for at least 10 min (≈ 20 Gy) by the BIPM and to at least 10 Gy by the NRC before any measurements were made.

Ambient conditions

For the BIPM and NRC arrangements, the water temperature is measured for each current measurement and it was stable to better than 0.1 °C. The ionization current was normalized to 293.15 K and 101.325 kPa for both laboratories. Relative humidity is in the range from 30 % to 70 % at the NRC 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 300 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 NRC, the correction for ion recombination was determined by obtaining Jaffé plots (1/polarizing voltage versus 1/chamber reading) at a range of dose-per-pulse values, as described in McEwen (2010). The results are also included in the table. The difference in k_{s} between the BIPM and NRC is expected due to different dose-per-pulse values at the two linear accelerators.

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

Coefficient	FC65G	NE 2571	PTW 30012
initial recombination and diffusion, k_{init}	17.6×10^{-4}	7.12×10^{-4}	15.3×10^{-4}
volume recombination coefficient, k_{vol} / pC^{-1}	6.2×10^{-4}	6.7×10^{-4}	5.3×10^{-4}

Radial non-uniformity correction

The correction factors calculated by the BIPM for the radial non-uniformity of the beam over the section of the transfer chambers were calculated 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 same approach is taken at the NRC to calculate the radiation non-uniformity correction and applies to both the reference and transfer chambers. The correction factors applied by the BIPM and the NRC are summarized in Table 7.

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and a water phantom with a PMMA front window (4 mm for the BIPM and 1.8 mm for the NRC). At the BIPM, the window thickness is included as a water-equivalent thickness in g cm^{-2} when positioning the chamber. At the NRC, the window thickness is not taken into account, leading to a reference depth slightly greater than the nominal 10 g cm^{-2}.

All the chambers were inserted in the sleeve provided by the NRC and no sleeve corrections are applied.

Table 7. Correction factors for the NRC transfer chambers

Radiation quality			6 MV	10 MV	18 MV	25 MV
ion recombination k_s	FC65G	BIPM (Niatel)	1.0042	1.0059	1.0075	---
		BIPM (TRS 398)	1.0042	1.0055	1.0075	---
		NRC	1.0025	1.0040	---	1.0039
	NE 2571	BIPM (Niatel)	1.0034	1.0055	1.0074	---
		BIPM (TRS 398)	1.0033	1.0054	1.0073	---
		NRC	1.0029	1.0048	---	1.0047
	PTW 30012	BIPM (Niatel)	1.0034	1.0048	1.0060	---
		BIPM (TRS 398)	1.0033	1.0046	1.0058	---
		NRC	1.0023	1.0036	---	1.0036
radial non-uniformity k_{rn}	BIPM		1.0000	0.9980	1.0000	---
	NRC		0.9991	0.9960	---	0.9968

6. Results of the comparison

6.1 Measurement results

Each transfer chamber was set-up and measured by the BIPM on two separate occasions. The results were reproducible to better than 5 parts in 10^4. For the NRC measurements, the chambers were calibrated before and after the measurements at the BIPM, and compared to historical calibration data for each chamber. The reproducibility at the NRC is estimated to be better than 8 parts in 10^4.

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

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,NRC}} / N_{D,\mathrm{w,BIPM}} \tag{8}$$

in which the average value of measurements made at the NRC before and after those made at the BIPM is compared with the mean of the measurements made at the BIPM.
The NRC calibration coefficients for the BIPM beams were calculated by interpolation, using a quadratic fit to the results provided by the NRC as a function of the $\mathrm{TPR}_{20,10}$ of the NRC beams. The results for each chamber are presented in Table 8. To evaluate the uncertainty related to the interpolation procedure, an alternative fit to the NRC results was made, based on the equation for k_Q given in Andreo *et al*. (2020). A relative uncertainty of 5 parts in 10^4, evaluated from the differences in the interpolated values for the two fits, is included in Table 14.

Table 8. Calibration coefficients for the transfer chambers

Radiation quality	6 MV	10 MV	18 MV
FC65G-1233			
$N_{D,\mathrm{w,NRC}}$ / Gy μC^{-1}	47.81	47.52	47.01
$N_{D,\mathrm{w,BIPM}}$ / Gy μC^{-1}	47.63	47.34	46.78
NE 2571-3694			
$N_{D,\mathrm{w,NRC}}$ / Gy μC^{-1}	44.77	44.44	43.95
$N_{D,\mathrm{w,BIPM}}$ / Gy μC^{-1}	44.58	44.30	43.79
PTW 30012-447			
$N_{D,\mathrm{w,NRC}}$ / Gy μC^{-1}	52.56	52.13	51.57
$N_{D,\mathrm{w,BIPM}}$ / Gy μC^{-1}	52.35	52.03	51.41

The final results $R_{D,\mathrm{w,NRC}}$ in Table 9 are evaluated as the mean for the three transfer chambers

Table 9. Comparison results

Radiation quality	6 MV	10 MV	18 MV
$N_{D,\mathrm{w,NRC}}/N_{D,\mathrm{w,BIPM}}$ using FC65G	1.0037	1.0039	1.0049
$N_{D,\mathrm{w,NRC}}/N_{D,\mathrm{w,BIPM}}$ using NE 2571	1.0044	1.0031	1.0036
$N_{D,\mathrm{w,NRC}}/N_{D,\mathrm{w,BIPM}}$ using PTW 30012	1.0040	1.0020	1.0031
s_{tr}	0.0002	0.0006	0.0005
$R_{D,\mathrm{w,NRC}}$	1.0040	1.0030	1.0039

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.

The values $N_{D,\mathrm{w,NRC}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose rms value is taken as a representation of the stability of the transfer instruments.

The results shown in Table 9 demonstrate the agreement between the two standards for absorbed dose to water at the level of 4 parts in 10^3 which is within the combined standard uncertainty u_c of the comparison of 5.8 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 NRC transfer chambers used for the comparison.

For the NRC, 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 $R_{D,\mathrm{w,NRC}}$ 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

(0) 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).

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

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	0.05	–
$N_{D,\mathrm{w,tr\ ch}}$	0.26	0.33

Table 12. **Uncertainties associated with the NRC standard**

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Determination of linac output		
reproducibility ΔT/MU	0.16	
$c_{\mathrm{w,p}}$ specific heat capacity		(< 0.005)
thermistor sensitivity (calibration)		0.08
positioning calorimeter		0.13
k_{c} heat loss		0.10
k_{p} vessel perturbation		0.05
k_{rho} density of water		0.02
k_{dd} profile non-uniformity		0.05
k_{HD} heat defect, three systems		0.15
Calibration of reference ionization chamber		
long term reproducibility of monitor chambers (3)	0.10	0.10
reproducibility M_{raw}/MU	0.02	
positioning of chamber		0.05
P_{dd} profile non-uniformity		0.04
P_{ion} ion recombination		0.08
P_{pol} polarity		0.03
P_{elec} calibration of electrometer		0.01
P_{TP} correction for air density		0.05
humidity		0.06
$N_{D,\mathrm{w,ref\ ch}}$	0.19	0.30

(3) Component for transfer between water calorimeter and reference chamber, see Eq. (6).

Table 13. Uncertainties associated with the NRC calibration of the transfer chambers

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{D,\mathrm{w,ref\ ch}}$	0.19	0.30
long term stability of reference chambers	0.07	
short term reproducibility M_{raw}/MU	0.02	
positioning chamber		0.05
P_{dd} profile non-uniformity (4)		---
P_{ion} ion recombination		0.08
$\mathrm{P_{TP}}$		0.05
humidity		0.06
$N_{D,\mathrm{w,tr\ ch}}$	0.21	0.32

(4) No correction as the reference chamber and transfer chamber are the same dimensions.

Table 14. Uncertainties associated with the comparison result

Relative standard uncertainty	$100\ u_{i\mathrm{A}}$	$100\ u_{i\mathrm{B}}$
$N_{D,\mathrm{w,NRC}}/N_{D,\mathrm{w,BIPM}}$	0.33	0.46
$k_{\mathrm{rn,tr\ ch}}$	–	0.03
transfer chambers $s_{\mathrm{tr,comp}}$	0.04	–
interpolation procedure	–	0.05
stability of transfer chambers	0.06	–
Combined standard uncertainty u_{c} for $R_{D,\mathrm{w,NRC}}$	0.0058	

7. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here $D_{\mathrm{w,BIPM}}$, is taken as the key comparison reference value (KCRV) (Allisy-Roberts *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 $D_i = (D_{\mathrm{w}i} - D_{\mathrm{w,BIPM}i})/\ D_{\mathrm{w,BIPM}i} = x_i - 1$ 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 Figures 3a, 3b and 3c.

Table 15. Degrees of equivalence

Beam quality corresponding to measured $\mathrm{TPR}_{20,10}$ between 0.63 (included) and 0.71 (excluded)

Lab i	D_i / (mGy/Gy)	U_i / (mGy/Gy)
PTB	1.3	10.4
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

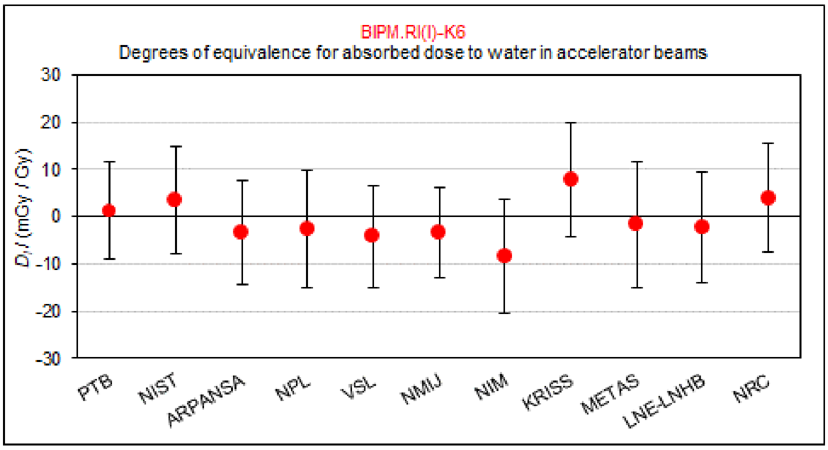

Figure 3a. Graph of the degrees of equivalence with the KCRV

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

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
PTB	3.4	11.4
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

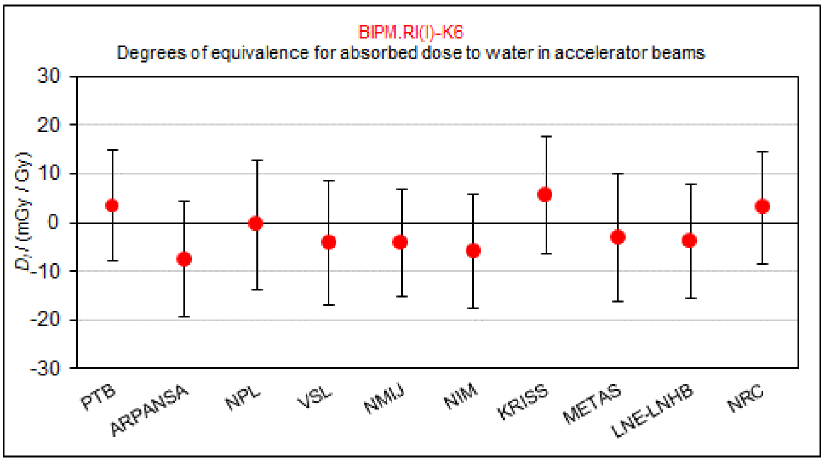

Figure 3b. Graph of the degrees of equivalence with the KCRV

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

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
PTB	1.8	12.8
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

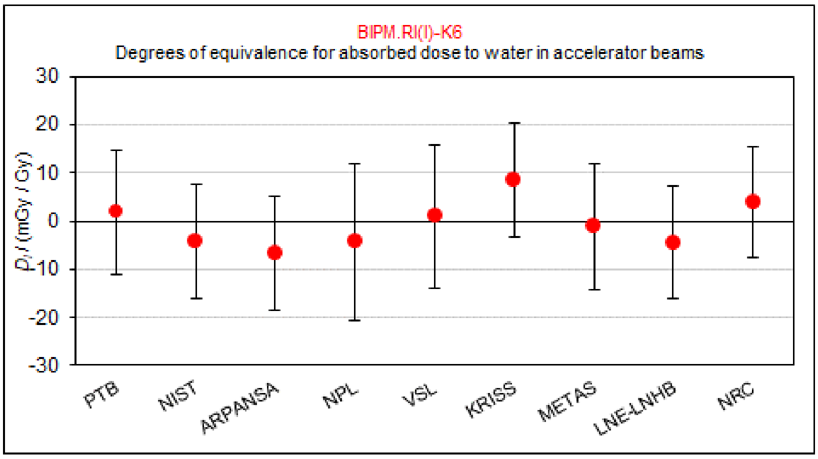

Figure 3c. Graph of the degrees of equivalence with the KCRV

8. Conclusions

A new key comparison has been carried out between the NRC 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 NRC and the BIPM. The results show the standards to be in agreement within the standard uncertainty of the comparison of 5.8 parts in 10^3.

The present results are in reasonable agreement within the uncertainties with the results of the comparison carried out in 2009 (0.997 at 6 MV, 1.001 at 10 MV; 0.994 at 25 MV, with a combined standard uncertainty of 5.5 parts in 10^3). Nevertheless, the new results show less scatter and are higher, on average, by 0.6 %. It is of note that the 2009 comparison was the first in the BIPM.RI(I)-K6 series, for which the newly-developed BIPM standard was transported to the NRC. Beam instabilities allowed less time for calorimetric measurements than anticipated and, as the BIPM monitoring system was not fully developed at that time, it suffered from variations much larger than the present system. The use of the fit for $N_{D,\mathrm{c,st}}$ shown in Figure 1 and, to a lesser extent, the fit for $C_{\mathrm{w,c}}$ of Figure 2 remove much of this scatter. Furthermore, as noted in the report of the second comparison in 2010 (Picard *et al.* 2011), the first comparison used a thicker and less well-machined polyethylene sleeve for the

BIPM standard in water, which was replaced for all subsequent comparisons by a thin PMMA sleeve. Recent investigations have shown that, while the old and new sleeves were in close agreement in the BIPM Co-60 beam, in accelerator beams they show a difference of up to 0.4 % at 20 MV.

When compared with the results for the other laboratories that have carried out comparisons in terms of absorbed dose to water, the NRC 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 2021).

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