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Original Article

Comparison of the standards for absorbed dose to water of the IAEA and the KRISS, Korea in accelerator photon beams

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ABSTRACT

A bilateral comparison was conducted between the International Atomic Energy Agency (IAEA) and the Korea Research Institute of Standards and Science (KRISS) to measure the absorbed dose to water in accelerator photon beams. KRISS served as a linking laboratory to compare the IAEA standard with the key comparison reference value (KCRV) of the BIPM.RI(I)–K6 program, in which KRISS participated in 2017.

Two ionization chambers from the IAEA were used as transfer instruments for the comparison. Both laboratories measured the calibration coefficients of these instruments and calculated the ratios. The ratio of the KRISS standard to the KCRV was applied to obtain the degree of equivalence of the IAEA, along with its uncertainty. The largest deviation of the IAEA measurement from the KCRV was 3.4 mGy/Gy, significantly smaller than the expanded uncertainty of 10.7 mGy/Gy ($k = 2$, 95% level of confidence).

This study demonstrates the equivalence of IAEA's measurement standard for accelerator photon beams to other primary standard dosimetry laboratories. It provides evidence for the satisfactory operation of IAEA's quality management system and enhances the international credibility of the IAEA SSDL network, particularly in high-energy accelerator photon beams from linear accelerators.

1. Introduction

Linear accelerators (linac) have traditionally been utilized by Primary Standards Laboratories in providing traceability for high energy photon and electron beams in the field of radiation therapy. Traceability is essential for ensuring that patients receive the correct dose of radiation. In 2019, with the assistance of the member states, the International Atomic Energy Agency (IAEA) Dosimetry Laboratory acquired a linac to support various activities, including calibration of dosimeters from Secondary Standards Dosimetry Laboratories (SSDL's) operating in these beam qualities.

Before the corresponding Calibration and Measurement Capability (CMC) can be published in the BIPM Key Comparison Database (KCDB) [1], the IAEA needs to demonstrate the measurement equivalence of its calibration capability for accelerator MV photon beams.

To address this requirement, an indirect comparison was conducted for the absorbed dose to water measurement in accelerator photon beams between the International Atomic Energy Agency (IAEA), Austria and the Korea Research Institute of Standards and Science (KRISS), Korea, utilizing accelerator photon beams ranging from 6 MV to 18 MV. The comparison was carried out in September 2022, using the IAEA accelerator facility in Seibersdorf (Austria) and the KRISS accelerator in Daejeon (Korea). Two transfer instruments, specifically the FC65-G and PTW 30013 models, belonged to the IAEA, were employed for the comparison. Calibration was performed separately for these transfer instruments against the absorbed dose to water standards of both the IAEA and KRISS. Subsequently, the calibration coefficients determined by both laboratories were compared. This approach enables an assessment of the equivalence of their measurement standards and the calibration capabilities.

In this study, the KRISS played as a linking laboratory facilitating the comparison of the absorbed dose to water standard of the IAEA to the key comparison reference value (KCRV) of the corresponding key comparison study, BIPM.RI(I)–K6. This enables a direct comparison of the IAEA's calibration capability to the KCRV. To achieve this, the mean ratio of the calibration coefficients of the transfer instruments determined at both laboratories was calculated. The ratio of the KRISS to the KCRV, obtained from the BIPM.RI(I)–K6 (KRISS 2017) comparison study

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Table 1
Comparison results of the KRISS standard in the BIPM.RI(I)–K6 (KRISS 2017) [2].

Nominal energy	6 MV	10 MV	18 MV
Tissue-phantom ratio 20,10 ($TPR_{20,10}$)	0.686	0.733	0.774
$R_{Dw,\mathrm{KRISS}}$	1.007 8	1.005 6	1.008 5

conducted bilaterally between the KRISS and BIPM in 2017 [2], was applied to evaluate the degree of equivalence of the IAEA. All processes and the evaluation of the related uncertainties were performed following the guidelines provided in CCRI(I)/17-09 [3].

2. Material and methods

2.1. Absorbed dose to water standards

- *The KRISS standard*

The KRISS primary standard for the absorbed dose to water of accelerator photon beams is a Domen-type [4] graphite calorimeter (C1505-4) [5].

The absorbed dose rate to water at KRISS is determined through calorimetric measurement using the graphite calorimeter, and it is calculated as,

$$\dot{D}_{\mathrm{w,KRISS}} = \left(\frac{C_{\mathrm{C,eff}}}{m_{\mathrm{eff}}}\right) \bullet \Delta\dot{T}_{\mathrm{irr}} \bullet\ k_{\mathrm{G}\rightarrow\mathrm{W}} \bullet k_{\mathrm{W,rn}} \bullet k_{\mathrm{BS}}^{-1} \tag{1}$$

where $C_{\mathrm{C,eff}}$ represents the effective heat capacity, m_{eff} is the effective mass of the core, $\Delta\dot{T}_{\mathrm{irr}}$ is the rate of temperature rise of the core, $k_{\mathrm{G}\rightarrow\mathrm{W}}$ is the conversion factor of absorbed dose to graphite to water, $k_{\mathrm{W,rn}}$ is the radial non-uniformity correction factor, and k_{BS} is the correction factor for the difference in backscattering between graphite and water phantoms to an external monitor chamber.

The calibration coefficients of the KRISS secondary standard chambers were determined for the available photon beams at the KRISS as,

$$N_{Dw,\mathrm{KRISS}} = \frac{\dot{D}_{\mathrm{w,KRISS}}}{\dot{Q}_{\mathrm{KRISS}} \bullet k_{\mathrm{TP}} \bullet k_{\mathrm{s}} \bullet k_{\mathrm{rn}}} \tag{2}$$

where $\dot{Q}_{\mathrm{KRISS}}$ represents the ionization charge rate, k_{TP} is the temperature and atmospheric pressure correction factor, k_{s} is the recombination correction factor, and k_{rn} is the radial non-uniformity correction factor for the secondary standard chambers. In equations (1) and (2), the absorbed dose rate ($\dot{D}_{\mathrm{w,KRISS}}$) and ionization charge rate ($\dot{Q}_{\mathrm{KRISS}}$) are presented as a ratio to the reading from the external monitor chamber rather than as a ratio to time. This external monitor chamber is a transmission type chamber (7862, PTW, Germany). When we perform the measurement, we check the stability of this chamber with a NE2471 placed at a repeatable place, before, in the middle and at the end of the series of measurement. Thus, we rate the related uncertainty of using this chamber as an external monitor chamber to be 0.1 %.

The equivalence of KRISS standard to other primary standard dosimetry laboratories was verified in 2017 through participating in the BIPM.RI(I)–K6 (KRISS 2017) comparison program [2]. The BIPM.RI(I)–K6 (KRISS 2017) comparison study was conducted indirectly using two transfer instruments, following a similar approach to that employed in this study. The comparison results were represented by a parameter $R_{Dw,\mathrm{KRISS}}$, which is the mean ratio of the calibration coefficients of the transfer instruments determined at the KRISS to the KCRV. Table 1 provides the values of $R_{Dw,\mathrm{KRISS}}$, the associated relative standard uncertainty was 0.6 %.

- *The IAEA standard*

The IAEA standard for absorbed dose to water of accelerator photon beams consists of the ionization chamber FC65-G (sn. 1551) and accompanying auxiliary instruments such as an electrometer, thermometer, barometer, hygrometer. This standard chamber was calibrated by the BIPM to establish traceability for photon beam qualities in the range from 6 MV ($TPR_{20,10} = 0.665$) to 18 MV ($TPR_{20,10} = 0.774$), using ^{60}Co gamma beams and three accelerator photon beams (6 MV, 10 MV and 18 MV). The auxiliary instruments employed in the measurements are traceable to the Austrian National standards (BEV) and are subject to stability checks prescribed by the Quality Management System (QMS) of the IAEA Dosimetry Laboratory.

The absorbed dose rate to water at the IAEA is determined through ionometric measurement using the IAEA standard chamber, and it is calculated as,

$$\dot{D}_{\mathrm{w,IAEA}} = N_{Dw,\mathrm{IAEA}}\left(TPR_{20,10}\right) \bullet I_{\mathrm{IAEA}} \bullet k_{\mathrm{TP}} \bullet k_{\mathrm{s}} \bullet k_{\mathrm{rn}} \tag{3}$$

where $N_{Dw,\mathrm{IAEA}}(TPR_{20,10})$ represents the absorbed dose to water calibration coefficient for the specific beam quality $TPR_{20,10}$, I_{IAEA} is the ionization current, k_{TP} is the temperature and atmospheric pressure correction factor, k_{s} is the recombination correction factor, and k_{rn} is the radial non-uniformity correction factor. I_{IAEA} measured at the IAEA is determined by the integration of the charge in the feedback capacitor of the electrometer. The integrated charge is read with a defined frequency (1 Hz) for a defined period of time. At the end of the measurement, the gradient of the integrated charge along time is determined by the linear interpolation. All readings are normalized to the reading of a transmission monitor chamber attached to the gantry. The stability of this transmission monitor chamber at the IAEA is tested by recording and comparing ratio of readings of the reference standard and the transmission monitor in a very reproducible set-up.

Since accelerator photon beams qualities at the BIPM do not directly match those at the IAEA, the calibration coefficients of the IAEA standard for the available photon beams at the IAEA were derived using a non-linear fit of $N_{D,w}$ *vs.* $TPR_{20,10}$ as

$$N_{Dw,\mathrm{IAEA}}\left(TPR_{20,10}\right) = c_{\mathrm{IAEA}} \frac{1+\exp\left(\frac{a_{\mathrm{IAEA}}-0.57}{b_{\mathrm{IAEA}}}\right)}{1+\exp\left(\frac{a_{\mathrm{IAEA}}-\mathrm{TPR}_{20,10}}{b_{\mathrm{IAEA}}}\right)} \tag{4}$$

where a_{IAEA}, b_{IAEA} and c_{IAEA} are the chamber specific coefficients of the non-linear fit function.

2.2. Comparison formula

In the comparison between the KRISS and IAEA, two transfer instruments were used. The calibration coefficients of these transfer instruments to the standards were determined separately by both laboratories. Subsequently, the calibration coefficients determined by the laboratories were compared. To ensure the stability of the transfer instruments throughout the study, the IAEA conducted calibration both before and after sending them to KRISS. These stability check results were considered when estimating the uncertainty associated with the transfer instrument.

The calibration coefficients of the transfer instruments were determined at each laboratory as,

$$N_{Dw,\mathrm{lab}} = \dot{D}_{\mathrm{w},lab} \Big/ \left(I_{lab}\prod_i k_i\right) \tag{5}$$

where $\dot{D}_{\mathrm{w},lab}$ represents the absorbed dose rate to water at the KRISS or the IAEA, and I_{lab} is the corresponding ionization current for a transfer instrument measured at each laboratory, k_{i} is the *i*th correction factor.

The calibration coefficients determined by both laboratories is compared as a ratio $R_{Dw,i}$, .

$$R_{Dw,i} = \frac{N_{Dw,\mathrm{IAEA},i}(\mathrm{KRISS})}{N_{Dw,\mathrm{KRISS},i}} \tag{6}$$

where $N_{Dw,\mathrm{IAEA},i}(\mathrm{KRISS})$ represents the calibration coefficient of the ith transfer instrument determined by the IAEA for the specific photon beam quality available at the KRISS, and $N_{Dw,\mathrm{KRISS},i}$ is the calibration coefficient determined directly by the KRISS at the corresponding photon beam quality. $N_{Dw,\mathrm{IAEA},i}(\mathrm{KRISS})$ is obtained by employing the non-linear fitting function, as described in equation (4), to match the beam quality, since photon beams qualities at the KRISS do not directly match those at the IAEA.

Following the guidelines provided in CCRI(I)/17-09 [3], the parameter $R_{Dw,\mathrm{IAEA}}$, which is defined as the ratio of absorbed dose to water standard of accelerator photon beams of the IAEA to that of the BIPM, is calculated as,

$$R_{Dw,\mathrm{IAEA}} = \frac{\sum_{i=1}^{p} R_{Dw,\mathrm{IAEA},i}}{p} \tag{7}$$

$$R_{Dw,\mathrm{IAEA},i} = R_{Dw,i} \bullet R_{Dw,\mathrm{KRISS}} \tag{8}$$

where p represents the number of the transfer instruments ($p = 2$), $R_{Dw,\mathrm{KRISS}}$ is the comparison result of the KRISS obtained in the BIPM.RI(I)–K6 (KRISS 2017) comparison study [2].

Finally, the degree of equivalence of the IAEA is expressed with a pair of terms D and U [6]. D represents the relative difference given as

$$D = R_{Dw,\mathrm{IAEA}} - 1 \tag{9}$$

with its expanded uncertainty (at a 95 % level of confidence) $U = k\, u_{R,\mathrm{IAEA}}$, where k is the coverage factor and $u_{R,\mathrm{IAEA}}$ is the standard uncertainty of $R_{Dw,\mathrm{IAEA}}$. In this study, a coverage factor of $k = 2$ is assumed since each measurement result is obtained with sufficient number of degrees of freedom [6].

The standard uncertainty of $R_{Dw,\mathrm{IAEA}}$ is evaluated as follows [3],

$$u^2_{R,\mathrm{IAEA}} = \left[u^2_{\mathrm{IAEA}} + u^2_{\mathrm{BIPM}} - \sum_j f_j^2\left(u^2_{\mathrm{IAEA},j} + u^2_{\mathrm{BIPM},j}\right)\right] + u^2_{\mathrm{tr}} + u^2_{\mathrm{LINK}} \tag{10}$$

where u_{IAEA} is the relative standard uncertainty of the IAEA; u_{BIPM} is the relative standard uncertainty of the BIPM standard ($D_{\mathrm{w,BIPM}}$); u_{tr} and u_{LINK} are the uncertainties arising from the transfer instruments and the linking mechanism, respectively. The summation term in equation (10) takes into account the correlation of the jth uncertainty component between the IAEA and the BIPM using the correlation factor f_j $(0 \le f_j \le 1)$.

In this study, the comparison between the KRISS and IAEA is conducted indirectly through the exchange of multiple transfer instruments, with the stability of these instruments assessed by the IAEA. Therefore, the uncertainties u_{tr} and u_{LINK} are calculated following the guideline of CCRI(I)/17-09 [3], as expressed in equations (11) and (12), respectively.

For the uncertainty arising from the transfer instruments (u_{tr}):

$$u^2_{\mathrm{tr}} = \frac{\sum_{i=1}^{p}\left(R_{Dw,\mathrm{IAEA},i} - R_{Dw,\mathrm{IAEA}}\right)^2}{p(p-1.4)} \tag{11}$$

where p represents the number of the transfer instruments ($p = 2$), and $R_{Dw,\mathrm{IAEA}}$ and $R_{Dw,\mathrm{IAEA},i}$ are defined in equations (7) and (8), respectively.

For the uncertainty arising from the linking mechanism (u_{LINK}):

$$u^2_{\mathrm{LINK}} = 2u^2_{D,\mathrm{KRISS,statistical}} + 2u^2_{I,\mathrm{KRISS,statistical}} + u^2_{I,\mathrm{BIPM}} \tag{12}$$

where $u_{\mathrm{D,KRISS,\ statistical}}$ and $u_{I,\mathrm{KRISS,\ statistical}}$ respectively represent the relative combined standard uncertainty of the type A components and the others related to the repeatability of D_{w} and I measurements performed by the KRISS, $u_{I,\mathrm{BIPM}}$ is the relative combined standard uncertainty of I measurement performed by the BIPM. In this study, only the type A standard uncertainty of D_{w} for the KRISS is taken account into $u_{\mathrm{D,KRISS,\ statistical}}$, since the measurement using the primary standard was not conducted again after the BIPM.RI(I)–K6 (KRISS 2017) was performed in 2017.

Table 2
The ion recombination correction factors for the transfer instruments determined by the IAEA.

	FC65-G (sn. 1552)		PTW 30013 (sn. 11748)	
	pC/pulse	k_s	pC/pulse	k_s
6 MV	4.4	1.003 2	3.9	1.002 5
10 MV	4.9	1.003 6	4.4	1.002 7
18 MV	10.6	1.007 6	9.5	1.005 4

Table 3
The ion recombination correction factors for the transfer instruments determined by the KRISS.

	FC65-G (sn. 1552)		PTW 30013 (sn. 11748)	
	pC/pulse	k_s	pC/pulse	k_s
6 MV	4.1	1.002 9	3.6	1.002 6
10 MV	5.4	1.003 7	4.9	1.003 1
18 MV	5.1	1.003 5	4.5	1.003 0

2.3. Measurements

In the comparison between the KRISS and IAEA, two transfer instruments, specifically the FC65-G (sn. 1552) and PTW 30013 (sn. 11748) owned by the IAEA, were used. The linear accelerator used at the KRISS was ELEKTA Synergy®, whereas VARIAN TrueBeam® was used for calibrations performed at the IAEA. The measurements were conducted with the gantries fixed for horizontal irradiation, at the source to surface distance (SSD) of 100 cm, and at the reference depth of 10 g/cm^2. Two PMMA walled water phantoms were employed. Thickness of the entrance window of the water phantoms used at the IAEA and KRISS were 0.3717 g/cm^2 and 0.4492 g/cm^2, respectively. A PMMA waterproof sleeve with a wall thickness of 1 mm was provided by the IAEA and used for measurements at both laboratories.

At the IAEA, the calibration of the transfer instruments included additional points, such as ^{60}Co gamma-ray and two other energies (8, 15 MV) of the accelerator photons. This was done to obtain the chamber specific coefficients in equation (4). These coefficients are essential to facilitate the comparison of the calibration coefficients determined separately by the IAEA and KRISS using equation (6).

During irradiation, a parallel-plate transmission chamber was used to monitor the beam output at each laboratory. The calibration of the transfer instruments at the IAEA and KRISS was performed against their respective secondary standard chambers: the IAEA secondary standard chamber FC65-G (sn. 1551) and the KRISS secondary standard chamber PTW 30013 (sn. 9304).

The transfer instruments were positioned with their stems perpendicular to the beam direction, and with the appropriate marking on the stem faced the source. A collecting voltage of 300 V and 400 V (positive polarity) was applied to the collector electrode of the chambers FC65-G (sn. 1552) and PTW 30013 (sn. 11748), respectively. The polarity effect

Table 4
The radial non-uniformity correction factor k_{rn} for transfer instruments determined at the IAEA and KRISS.

Nominal energy	6 MV	10 MV	18 MV
$k_{\mathrm{rn,IAEA}}$	1.000 02	0.999 71	0.999 99
$k_{\mathrm{rn,KRISS}}$	0.999 50	0.998 00	0.997 50

Table 5
Calibration coefficients determined for the FC65-G (sn.1552).

	IAEA				KRISS	
	$TPR_{20,10,}$	$N_{D,w}$			$TPR_{20,10,}$	$N_{D,w}$
		Pre-KRISS	Post-KRISS	Weighted mean		
6 MV	0.6651	47.693 *10*[a)]	47.745 *1*	47.698	0.684	47.815
10 MV	0.7374	47.126 *10*	47.158 *1*	47.129	0.734	47.454
18 MV	0.7802	46.600 *10*	46.635 *1*	46.603	0.778	47.064

[a)] Numbers in italic represent the number of repetitions of the measurements.

Table 6
Calibration coefficients determined for the PTW-30013 (sn.11748).

	IAEA				KRISS	
	$TPR_{20,10,}$	$N_{D,w}$			$TPR_{20,10,}$	$N_{D,w}$
		Pre-KRISS	Post-KRISS	Weighted mean		
6 MV	0.6651	53.239 *6*[a)]	53.279 *2*	53.249	0.684	53.324
10 MV	0.7374	52.550 *6*	52.533 *2*	52.546	0.734	52.889
18 MV	0.7802	51.929 *6*	51.943 *2*	51.933	0.778	52.440

[a)] Numbers in italic represent the number of repetitions of the measurements.

was not corrected at either laboratory.

The recombination correction was determined using the two-voltage method [7] at the IAEA and using the method by Burns and McEwen [8] at the KRISS. The recombination correction factors of the transfer instruments determined at the IAEA and KRISS are reported in Tables 2 and 3. The charge per pulse determined at the IAEA is based on the charge integrated per 1 s divided by the pulse frequency of the linear accelerator at a given setting. At 18 MV, which was set at 100 MU/min, both pC/pulse and k_s were higher than the other energies. The pulse frequency at this setting at 18 MV was 30 Hz, while for the other beam energies was 60 Hz. At IAEA, calibration of the chambers was done at 6 energies of the beams including ^{60}Co gamma-ray and two other energies (8, 15 MV) of the accelerator photons. However, on Table 2, the pC/pulse and k_s only at 6, 10, 18 MV are displayed.

The radial non-uniformity correction factors k_{rn} for the transfer instruments were determined by analysis of the measured beam profiles in water in both laboratories. And the results were as shown in Table 4 $k_{\mathrm{rn,IAEA}}$ and $k_{\mathrm{rn,KRISS}}$ are the radial non-uniformity correction factors of the accelerator photon beams at the IAEA and KRISS, respectively. However, no additional radial non-uniformity correction was applied for the transfer instruments in this study. The ionization current was measured using Keysight B2985A electrometer at the IAEA and Keithley K6517B at the KRISS. Chambers were always pre-irradiated for at least 10 min after a collecting voltage was applied.

Table 7
Uncertainties associated with the absorbed dose rate to water at the KRISS, $\dot{D}_{\mathrm{w,KRISS}}$.

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Calibration coefficient of the reference chamber	–	0.40
Ionization current measurement	0.01	0.02
Correction for temperature and pressure	–	0.04
Correction for humidity	–	0.05[a)]
Correction for ion recombination	–	0.05
Stability of the external monitor chamber	–	0.10
Positioning of the reference chamber	–	0.08
Long term stability of the reference chamber	–	0.12
Subtotal	0.01	0.44
Combined relative standard uncertainty	0.44	

[a)] No correction for the humidity was applied, since the humidity is maintained from 30 % to 70 % at the KRISS, but the associated uncertainty was taken into account.

3. Results and discussion

- *Measurement results*

The calibration coefficients determined at both respective laboratories are reported below. In Tables 5 and 6, the number of repetitions of measurements performed by the IAEA before and after the KRISS was different. Thus, the results were weighted based on the number of repetitions to obtain the weighted mean as the final result. The measurement uncertainties of the laboratories were evaluated and presented in Tables 7–10.

- *Calculation of the parameter* $R_{Dw,\mathrm{IAEA}}$

Based on the calibration results of the transfer instruments performed at the IAEA, including the additional three points involving ^{60}Co gamma-ray and two different high energies (8, 15 MV) of the accelerator photon beams, the chamber specific coefficients for the transfer instruments were determined and presented in Table 11. Using the non-linear fitting function as described in equation (4), the $N_{Dw,\mathrm{IAEA},i}(\mathrm{KRISS})$ values were calculated by the IAEA. The calculated

Table 8
Uncertainties associated with the calibration of the transfer instruments at the KRISS, $N_{Dw,\mathrm{KRISS}}$.

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Reference absorbed dose rate to water	–	0.44
Ionization current measurement	0.01	–
Correction for temperature and pressure	–	0.04
Correction for humidity	–	0.05[a)]
Correction for ion recombination	–	0.05
Stability of the external monitor chamber	–	0.10
Positioning of the transfer instrument	–	-[b)]
Subtotal	0.01	0.46
Combined relative standard uncertainty	0.46	

[a)] No correction for the humidity was applied, since the humidity is maintained from 30 % to 70 % at the KRISS, but the associated uncertainty was taken into account.

[b)] This was ignored since a water proof sleeve was used for both the reference chamber and the transfer instruments. The associated uncertainty for the transfer instruments was considered to be included in the uncertainty of the reference absorbed dose determined using the reference chamber placed in the water proof sleeve.

Table 9
Uncertainties associated with the reference absorbed dose rate to water at the IAEA, $\dot{D}_{\mathrm{w,IAEA}}$.

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Calibration coefficient of the reference chamber		0.42
Long term stability of the secondary standard		0.06
Spectral difference PSDL/IAEA		0.06
Current measurement - Ref. Std.	0.05	0.06
Correction for temperature and pressure - Ref. Std.		0.05
Current measurement - Monitor	0.05	0.10
Correction for temperature and pressure - Monitor		0.05
Ion recombination		0.05
Interpolation of N_{Dw}. *vs.* $TPR_{20,10}$		0.08
Subtotal	0.07	0.46
Combined relative standard uncertainty	0.47	

Table 10
Uncertainties associated with the calibration of the transfer instruments at the IAEA, $N_{Dw,\mathrm{IAEA}}$.

Source of component	Relative standard uncertainty (%)	
	Type A	Type B
Reference absorbed dose rate to water		0.47
Ionization current measurement	0.05	0.06
Correction for temperature and pressure		0.05
Current measurement - Monitor	0.05	0.10
Correction for temperature and pressure - Monitor		0.05
Positioning of the transfer instrument		0.01
Ion recombination		0.05
Subtotal	0.07	0.49
Combined relative standard uncertainty	0.50	

Table 11
The chamber specific coefficients of a_{IAEA}, b_{IAEA} and c_{IAEA} of the transfer instruments.

	FC65-G (sn. 1552)	PTW 30013 (sn. 11748)
a_{IAEA}	1.117 ± 0.027	1.189 ± 0.007
b_{IAEA}	−0.099 9 ± 0.008 5	−0.130 8 ± 0.002 6
c_{IAEA}	47.994 ± 0.022	53.743 ± 0.006

values of $N_{Dw,\mathrm{IAEA},i}(\mathrm{KRISS})$, $R_{Dw,i}$ and $R_{Dw,\mathrm{IAEA},i}$ are provided in Table 12. Additionally, the calculations of $R_{Dw,\mathrm{IAEA}}$ and u_{tr} are provided in Table 13.

- Evaluation of the uncertainty, $u_{R,\mathrm{IAEA}}$

The uncertainty arising from the transfer instruments, u_{tr}, was calculated using equation (11) and the results are presented in Table 13. At 6, 10 and 18 MV x-ray energies, u_{tr} was found to be 0.06 %, 0.02 % and 0.02 %, respectively. For the purpose of this study, u_{tr} was conservatively evaluated at 0.06 %.

The uncertainty arising from the linking mechanism, u_{LINK}, was calculated using equation (12). Based on the report of the BIPM.RI(I)–K6 (KRISS 2017) [2], the values of $u_{\mathrm{D,KRISS,\ statistical}}$, $u_{I,\mathrm{KRISS,\ statistical}}$ and $u_{I,\mathrm{BIPM}}$ were calculated to be 0.090 %, 0.08 % and 0.16 %, respectively. For $u_{I,\mathrm{KRISS,\ statistical}}$, various uncertainty components related to chamber positioning, water depth, and the SSD of the water phantom were considered, along with the type An uncertainty of the ionization current measurement. Consequently, u_{LINK} was evaluated to be 0.24 %.

Finally, $u_{R,\mathrm{IAEA}}$ was calculated using equation (10) combining the u_{tr}, u_{LINK}, u_{IAEA} and u_{BIPM}. The value of u_{IAEA} was provided as 0.5 % in Table 10. In the BIPM.RI(I)–K6 (KRISS 2017) report [2], u_{BIPM} was given as 0.41 %. However, given that the IAEA is traceable to the BIPM, all non-statistical components of u_{BIPM} were assumed to be fully correlated ($f_j = 1$) with u_{IAEA}. All components contributing to the type B uncertainty, except for the component related to the water depth, were included in the non-statistical components of u_{BIPM}, which was calculated to be 0.31 %. Therefore $u_{R,\mathrm{IAEA}}$ was calculated to be 0.53 % as provided in Table 14.

- Degree of equivalence of the IAEA

The values of D for the IAEA at different x-ray beam qualities were calculated as provided in Table 15, where D and U are both expressed in mGy/Gy. Degree of equivalence of other national metrology institutes (NMIs) or designated institute (DIs) are available on the KCDB [1].

The results presented in Table 15 indicate that the largest observed discrepancy between the IAEA and the KCRV was 3.4 mGy/Gy, which is significantly smaller than the expanded uncertainty of 10.7 mGy/Gy. This finding demonstrates excellent consistency of the IAEA measurement with the KCRV and suggests that IAEA's standard, which is traceable to the BIPM, is well maintained. The effective operation of calibration procedure at the IAEA, including the non-liner fitting for correction of differences in photon beam quality between the IAEA and the BIPM, is evident from these results.

The relatively large U can be attributed to the complexity of the comparison and the linking mechanism employed in this study, with approximately half of U attributed to the linking mechanism. Despite of this, the calculated U in this study is generally smaller compared to other BIPM.RI(I)–K6 studies. This can be attribute to the direct traceability of the IAEA's standard to the BIPM standard, considering that the BIPM's standard was assigned as the KCRV.

The small discrepancy observed in this study indicates that the IAEA's standard and calibration capability are equivalent to the BIPM and other standard dosimetry laboratories participated in the BIPM.RI (I)–K6.

4. Conclusion

In this study, a bilateral comparison was conducted between the

Table 13
Obtained $R_{Dw,\mathrm{IAEA}}$ from the measurements in the sleeve.

Nominal energy ($TPR_{20,10}$)	6 MV (0.684)	10 MV (0.734)	18 MV (0.778)
$R_{Dw,\mathrm{IAEA},1}$ (FC65-G, sn.1552)	1.002 9	0.999 9	0.999 4
$R_{Dw,\mathrm{IAEA},2}$ (PTW-30013, sn.11748)	1.003 8	1.000 2	0.999 7
$R_{Dw,\mathrm{IAEA}}$	1.003 4	1.000 1	0.999 6
u_{tr}	0.06 %	0.02 %	0.02 %

Table 12
Calibration of $N_{Dw,\mathrm{IAEA},i}(\mathrm{KRISS})$, $R_{Dw,i}$ and $R_{Dw,\mathrm{IAEA},i}$ of the transfer instruments.

$TPR_{20,10,}$	FC65-G (sn.1552)				PTW-30013 (sn.11748)			
	$N_{Dw,\mathrm{IAEA}}$	$N_{Dw,\mathrm{KRISS}}$	$R_{Dw,i}$	$R_{Dw,\mathrm{IAEA},i}$	$N_{Dw,\mathrm{IAEA}}$	$N_{Dw,\mathrm{KRISS}}$	$R_{Dw,i}$	$R_{Dw,\mathrm{IAEA},i}$
0.684	47.58	47.82	0.995 1	1.002 9	53.11	53.32	0.996 1	1.003 8
0.734	47.18	47.45	0.994 3	0.999 9	52.60	52.89	0.994 6	1.000 2
0.778	46.64	47.06	0.991 0	0.999 4	51.98	52.44	0.991 3	0.999 7

Table 14
Calculation of $u_{R,\mathrm{IAEA}}$.

Components	u_{IAEA}	u_{BIPM}	$\sqrt{\sum f_j^2(u_{\mathrm{IAEA},j}^2 + u_{\mathrm{BIPM},j}^2)}$	u_{tr}	u_{LINK}	$u_{R,\mathrm{IAEA}}$
Value	0.5 %	0.41 %	$\sqrt{2}\times$ 0.31%	0.06 %	0.24 %	0.53 %

Table 15
Degrees of equivalence and expanded uncertainty ($k = 2$) of the IAEA for absorbed dose to water measurement in high-energy photon beams.

$TPR_{20,10}$	D/(mGy/Gy)	U/(mGy/Gy)
	(mGy/Gy)	
(0.63–0.71)	3.4	10.7
(0.71–0.77)	0.1	10.7
(0.77–0.81)	−0.4	10.7

IAEA and the KRISS for the measurement of absorbed dose to water for accelerator photon beams. The comparison was performed indirectly by utilizing two transfer instruments provided by the IAEA, which were sent to the KRISS for the measurements and then returned back to the IAEA.

Calibration of the transfer instruments was conducted against the absorbed dose to water standards of both the IAEA and KRISS. The calibration coefficients determined separately by the IAEA and KRISS were compared as a ratio, and the degree of equivalence of the IAEA to the KCRV of the BIPM.RI(I)–K6 comparison program was evaluated, utilizing the previous results obtained by KRISS from their participation in the BIPM.RI(I)–K6 (KRISS 2017) comparison in 2017.

The results of this comparison demonstrated excellent consistency of the IAEA measurement and the KCRV. The largest observed discrepancy between the IAEA and the KCRV was 3.4 mGy/Gy, which is significantly smaller than the evaluated expanded uncertainty ($k = 2$, at a 95 % level of confidence) of 10.7 mGy/Gy.

This study enhances the confidence in absorbed dose to water measurements for accelerator photon beams and validates the traceability of the IAEA standard. The findings contribute to the overall improvement of patient safety and the harmonization of dosimetry practices in radiotherapy on a global scale.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used [ChatGPT May24 Version/OpenAI] in order to improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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