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Original Article

Bilateral comparison of the absorbed dose to water in high energy X-ray beams between the KRISS and the NMIJ

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ABSTRACT

The Korea Research Institute of Standards and Science (KRISS) established a new standard of the absorbed dose to water in LINAC X-ray beams. To confirm the equivalence of the new standard with other national metrology institutes (NMIs), a bilateral comparison study of the absorbed dose to water in high energy X-ray beams was performed between the KRISS and the National Metrology Institute of Japan (NMIJ). The comparison was made in-directly. Three transfer chambers were calibrated in the high energy X-ray beams by both laboratories and the calibration coefficients were compared. The average ratios of the calibration coefficients of the three transfer chambers obtained by the KRISS to those obtained by the NMIJ were 1.004, 1.006, 1.006, 1.007 for 6, 10, 15 and 18 MV X-ray beams, respectively. The calibration coefficients obtained at the KRISS were higher than those at the NMIJ but they were in good agreement within the expanded uncertainty of 1.0% ($k = 2$). The results of this study will be used as the evidence for the KRISS standard being comparable with those of other NMIs, temporarily, in the interim period up to finalizing a key comparison study, BIPM.RI(I)–K6 managed by the Consultative Committee for Ionizing Radiation.

1. Introduction

It is important to establish the measurement standard of the absorbed dose to water for the Linear Accelerator (LINAC) high-energy X-ray beams, since the beams have been widely used in radiation therapy and the absorbed dose to water is the basic physical quantity for quality assurance and control of the therapy. A primary standard graphite calorimeter was recently developed at the Korea Research Institute of Standards and Science (KRISS), and a new standard of the absorbed dose to water in LINAC X-ray beams was established with the calorimeter.

Under the CIPM[1] Mutual Recognition Arrangement (CIPM MRA) [1], the measurement standards of the member states need to be compared to confirm that they are equivalent with each other. Within this context, the Consultative Committee for Ionizing Radiation (CCRI) is managing a key comparison (KC), namely, BIPM.RI(I)–K6, in which the standards for absorbed dose to water in LINAC high energy X-ray beams are compared with that of the Bureau of International des Poids et Mesures (BIPM) as the key comparison reference value (KCRV) since 2009 [2]. We have participated in the KC in the end of 2017, and the KC report is under review now. When the KC report is completed, the degree of equivalence of our standard will be published in the BIPM key comparison database (KCDB).

In order to disseminate the new standard under KRISS quality system before KC is completed, it is necessary to estimate the degree of equivalence of the standard in an alternative manner other than KC. We decided to perform a bilateral comparison to validate our value with the National Metrology Institute of Japan (NMIJ) who had just finished the KC in 2015 [3]. Result of this bilateral comparison study is to be used for the evidence of the KRISS standard being comparable to those of other national metrology institute (NMI), temporarily, only in the interim period up to finalizing the KC with BIPM.

The KRISS piloted the present bilateral comparison. The

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[1] CIPM stands for International Committee for Weights and Measures (French: Comité international des poids et mesures).

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comparison was made indirectly. Three transfer chambers were prepared and their calibration coefficients in the high-energy X-ray beams were determined at both the KRISS and the NMIJ, and the results were compared. The measurements were made also in the ^{60}Co gamma-ray beams in order to facilitate the analysis of the comparison results obtained at different beam qualities of both laboratories. Fig. 1 shows the procedure of the comparison study, schematically.

2. Material and methods

2.1. Transfer chambers

Three ionization chambers were prepared as the transfer chambers of the comparison. A brief description of the transfer chambers is given in Table 1. The wall material is C552 Shonka air equivalent plastic for Exradin A2 chambers and graphite with a protective acrylic cover for PTW TN30013 chamber, respectively. All chambers are waterproof.

2.2. Reference conditions, measurement procedure and report of results

The transfer chambers were provided together with acrylic sleeves, an electrometer (Model 6517B, SN 4084329, Keithley) and a piece of triaxial signal cable (approximately 20 m-long) by the KRISS and used in both laboratories.

For acclimation, the chambers were placed in the laboratory for at least 12 h before the measurements. The electrometer was warmed up for at least 2 h after the signal cable was connected to and the bias voltage was applied to the chambers. The geometrical center of the chambers was placed at the reference point of the measurement in the horizontal beams from the LINACs and ^{60}Co sources. The presumed center of the chambers was marked on the chamber surfaces for visual aid. The chambers were put into the 2 mm-thick acrylic sleeves and immersed in the water phantoms. The temperature, the air pressure and the humidity were monitored during the measurements to make correction for environmental effects. The ionization charge was measured under the irradiation at least ten times to get a measurement set of each chamber. And it was normalized to the reference environmental conditions of 293.15 K, 101.325 kPa and 50% relative humidity.

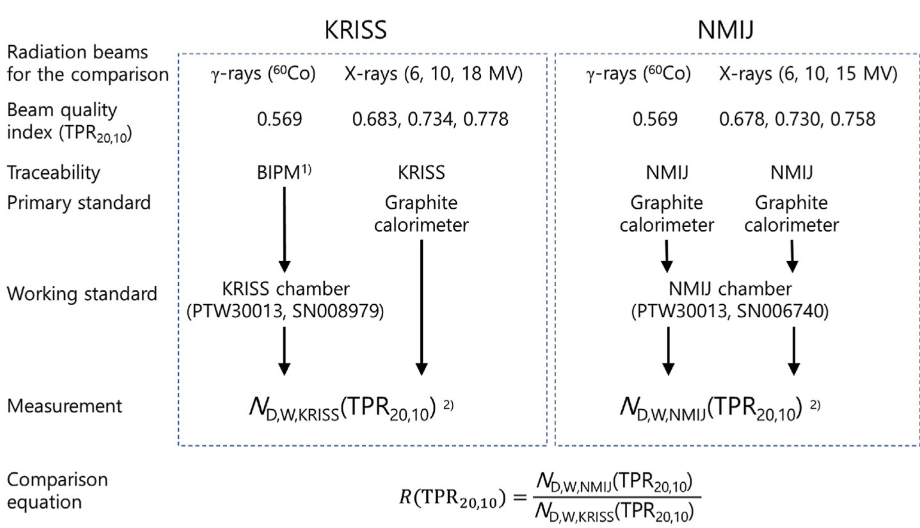
To compare and analyze measurement results, the following information was reported from both laboratories:

(1) Absorbed dose to water calibration coefficient of the transfer chambers (Gy/C)
(2) Measured $TPR_{20,10}$ (tissue phantom ratio at the depths of 20 and 10 cm) and nominal accelerator energy (MV)
(3) Reference depth in water (g/cm^2)
(4) Nominal dose rate at the reference depth
(5) Field size at this reference distance (cm × cm)
(6) Beam profiles on the reference plane
(7) Uncertainty budget of the measurements

2.3. Measurements at the KRISS

The transfer chambers were calibrated at the KRISS for 6 MV, 10 MV and 18 MV X-ray beams and ^{60}Co gamma-ray beams. The high energy X-ray beams were generated by an Elekta synergy® platform and calibrated to the absorbed dose to water with a graphite calorimeter (Model C1505-4) [4]. The ^{60}Co gamma-ray beams were calibrated to the absorbed dose to water with one of the transfer chamber (PTW TN30013, SN008979) which had been calibrated by the BIPM. Then, the transfer chambers were calibrated to the absorbed dose to water under the beams under the same conditions.

The absorbed dose to water of the high energy X-ray beams was determined as



1) BIPM stands for the Bureau of International des Poids et Mesures.

2) $N_{D,W}$ is the absorbed dose to water calibration coefficient given in units of Gy/μC, under the reference environmental conditions of 293.15 K, 101.325 kPa and 50 % relative humidity. The calibration coefficients are determined for three transfer chambers composed of one Farmer chamber, PTW30013 (SN008979) and two thimble chambers, Exradin A2 (XS152643 and XS152644) at both laboratories of KRISS and NMIJ which are denoted additionally in the subscript of $N_{D,W}$.

Fig. 1. Schematic diagram of the bilateral comparison study between the KRISS and the NMIJ.

Table 1
Transfer chambers and bias voltage ratings for the comparison.

Model	Serial No.	Chamber type	Nominal volume	Bias voltage[a]	Cable connection
Exradin A2	XS152643	Thimble	0.53 cm^3	300 V	Triaxial
Exradin A2	XS152644	Thimble	0.53 cm^3	300 V	Triaxial
PTW TN30013	SN008979	Farmer	0.60 cm^3	250 V	Triaxial

[a] Positive or negative voltage is to be supplied to the central electrode with respect to the chamber wall being in virtual ground.

$$D_W = \left(C \middle/ m_{eff}\right) \varDelta T \ k_{G\rightarrow W} \tag{1}$$

where D_W is the absorbed dose to water in unit of Gy, C is the temperature calibration to energy or the heat capacity in units of J/K, m_{eff} is the effective mass of the core of the graphite calorimeter in unit of kg, $\varDelta T$ is the temperature rise of the core under the irradiation in unit of K and $k_{G\rightarrow W}$ is the conversion factor of dose to graphite to water.

2.4. Measurements at the NMIJ

The transfer chambers were calibrated at the NMIJ for 6 MV, 10 MV and 15 MV X-ray beams and ^{60}Co gamma-ray beams. The high energy X-ray beams were generated by an Elekta precise treatment system™. All the beams were calibrated with a standard ionization chamber (PTW30013, SN006740) which had been calibrated by using a graphite calorimeter [3,5,6] of the NMIJ. The sleeves provided by the KRISS could not be mounted on a phantom for the high energy X-ray beams in the NMIJ. Thus, all the chambers were irradiated being put in the 1 mm-thick acrylic sleeves of the NMIJ. And the effect of using different sleeves was separately evaluated under the ^{60}Co gamma-ray beams of the NMIJ.

At both laboratories, the following conditions were common. The field size was (10 cm × 10 cm) at source to chamber distance (SCD) = 100 cm. The reference depths in water were 10 g/cm^2 for the high energy X-ray beams and 5 g/cm^2 for the ^{60}Co gamma-ray beams. The temperature and the humidity were kept within 22–24 °C and 30–70% R.H., respectively.

2.5. Analysis of the results

The absorbed dose to water calibration coefficient of the transfer chambers was determined as

$$N_{D,W} = \frac{D_W}{Qk_{el}k_{TP}k_h k_{po} k_s} \tag{2}$$

where $N_{D,W}$ is the absorbed dose to water calibration coefficient given in units of Gy/C, Q is the net ionization charge measured in unit of C at the routinely used polarity of the bias voltage applied to the chamber, k_{el} is calibration coefficient of the electrometer, k_{TP} is the environmental correction factor required to normalize the ionization charge to the reference temperature and pressure, k_h is the humidity correction factor, k_{po} is the polarity correction factor and k_s is the ion recombination correction factor.

The environmental correction factor was obtained by

$$k_{TP} = \frac{T}{T_0}\frac{P_0}{P} \tag{3}$$

where T and P are the temperature in units of K and the air pressure in kPa, respectively. T_0 and P_0 are the reference values of temperature (293.15 K) and pressure (101.325 kPa), respectively. The value of k_s was obtained according to the two voltage method described in IAEA TRS-398 [7]. The polarity correction factor was obtained by

$$k_{po} = \frac{|Q_+| + |Q_-|}{2Q} \tag{4}$$

where Q_+ and Q_- are the net ionization charge measured at positive and negative polarity of the bias voltage supplied to the chamber, respectively.

From the determined calibration coefficients of the transfer chambers, a parameter $R(\mathrm{TPR}_{20,10})$ was obtained, which was given as a ratio of the calibration coefficients at $\mathrm{TPR}_{20,10}$ values as

$$R(\mathrm{TPR}_{20,10}) = \frac{N_{D,W,NMIJ}(\mathrm{TPR}_{20,10})}{N_{D,W,KRISS}(\mathrm{TPR}_{20,10})} \tag{5}$$

where $N_{D,W,NMIJ}$ and $N_{D,W,KRISS}$ are the calibration coefficients determined by the NMIJ and the KRISS, respectively. Beam quality of the high energy X-rays of a laboratory were different from another. Thus, $N_{D,W,NMIJ}$ and $N_{D,W,KRISS}$ were determined by interpolating $N_{D,W}$ values at a given beam quality index value of $\mathrm{TPR}_{20,10}$ and then $R(\mathrm{TPR}_{20,10})$ was calculated.

3. Results and discussions

Nominal dose rates and the $\mathrm{TPR}_{20,10}$ values of the beams at which the measurements were carried out were as shown in Table 2. The high-energy X-ray beams of the KRISS had higher $\mathrm{TPR}_{20,10}$ values relatively than those of the NMIJ at the same nominal X-ray beam energies.

The effect of different sleeves on the transfer chambers tested under the ^{60}Co beams at the NMIJ was as shown in Table 3. The absorbed dose to water rate of the ^{60}Co beams decayed slowly. Thus, the ionization current of the chambers was normalized to the absorbed dose to water rate to be comparable. The results in different sleeves agreed to each other within the standard uncertainty (approximately, 0.1%). Thus it was regarded that the effect by different sleeves was ignorable.

The lateral profiles of the high energy X-ray beams within 10 × 10 cm^2 region on the reference plane were as shown in Fig. 2. Fig. 2 shows the cases of the KRISS only because it is hard to detect the difference between the beams on this scale. In Figs. 3 and 4, the zoomed-in lateral beam profiles of the beams of the KRISS and the NMIJ are displayed.

Table 2
Nominal dose rates and the measured values of $\mathrm{TPR}_{20,10}$ of different beams at the KRISS and the NMIJ.

Beams	KRISS		NMIJ	
	Nominal dose rate	$\mathrm{TPR}_{20,10}$	Nominal dose rate	$\mathrm{TPR}_{20,10}$
^{60}Co	3.51 mGy/s	0.569	4.87 mGy/s	0.569
6 MV	284 MU/min[a]	0.683	300 MU/min	0.678
10 MV	410 MU/min	0.734	300 MU/min	0.730
15 MV	–	–	300 MU/min	0.758
18 MV	350 MU/min	0.778	–	–

[a] MU stands for monitor unit, a measure of machine output from a clinical accelerator.

Table 3
Response of transfer chambers under the ^{60}Co beams in different acrylic sleeves.

Sleeves provided by	Exradin A2 XS152643	Exradin A2 XS152644	PTW TN30013 SN008979
KRISS	57.12 (*3*) Gy/μC	58.37 (*4*) Gy/μC	53.31 (*3*) Gy/μC
NMIJ	57.12 (*4*) Gy/μC	58.54 (*4*) Gy/μC	53.36 (*4*) Gy/μC
NMIJ/KRISS	1.0000 (*10*)	1.0004 (*10*)	1.0009 (*10*)

Note: The number in parentheses is the numerical value of the standard uncertainty referred to the corresponding last digit(s) of the quoted results.

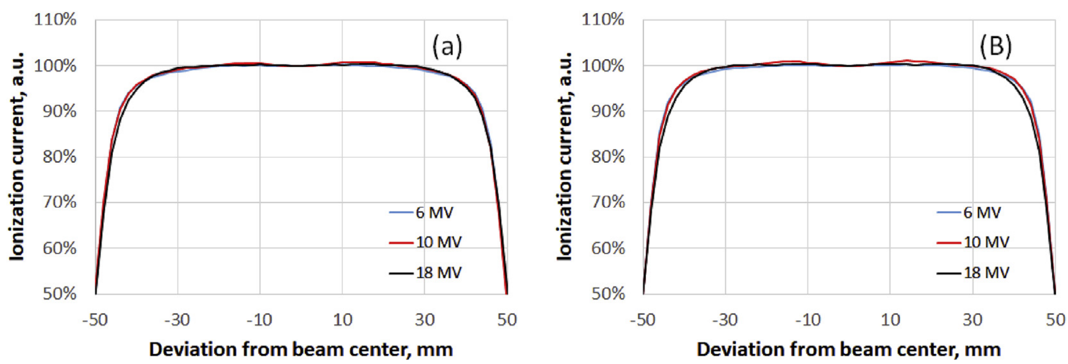


Fig. 2. Lateral profiles of the high energy X-ray beams of the KRISS on the reference plane along the cross-line (a) and the in-line of the beams.

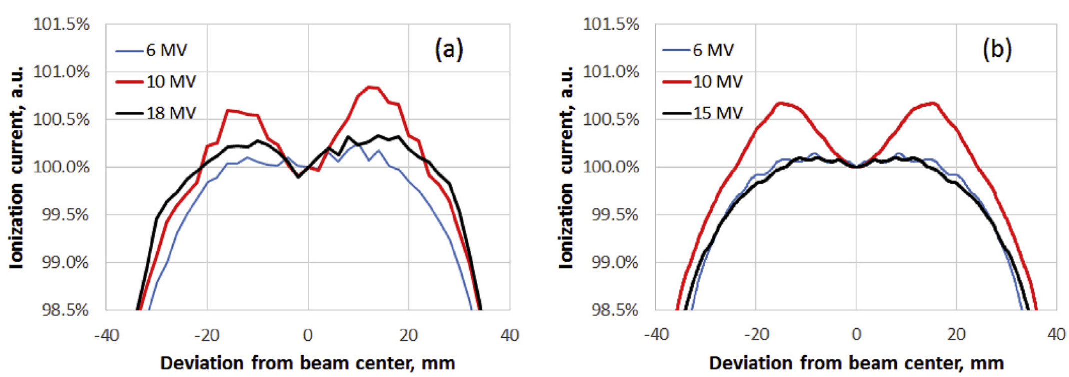


Fig. 3. Cross-line profiles of the beams of the KRISS (a) and the NMIJ (b) on the reference plane.

The calibration coefficients determined in different beams at the KRISS and the NMIJ were as shown in Table 4 and Fig. 5.

The combined relative standard uncertainties of the absorbed dose to water and the calibration coefficients were evaluated as shown in Tables 5 and 6, respectively, at the KRISS.

The $N_{D,W}$ values were fitted in quadratic curves and the $R(TPR_{20,10})$ values were obtained. The results of the fit were as shown in Table 7.

According to equation (5) and the fitted results of Table 7, the $R(TPR_{20,10})$ values and the related uncertainty were determined as shown in Table 8. Uncertainty of the $R(TPR_{20,10})$ values evaluated in the same way as in the previous study [6] was 1% ($k = 2$).

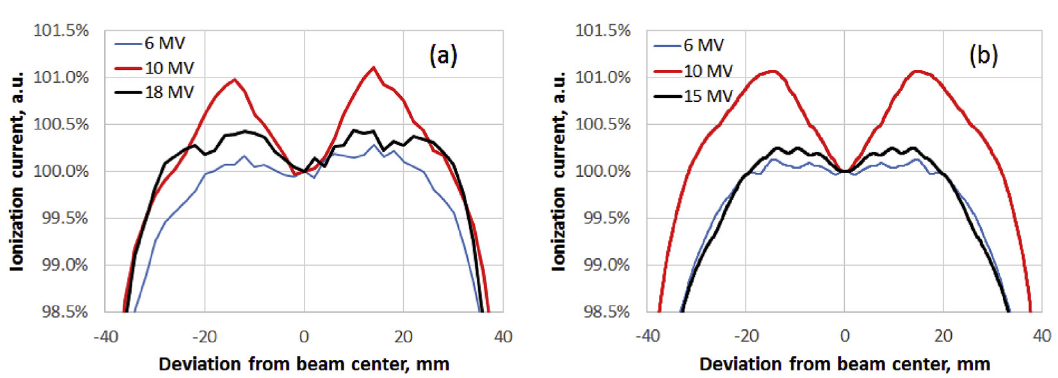


Fig. 4. In-line profiles of the beams of the KRISS (a) and the NMIJ (b) on the reference plane.

Table 4
Calibration coefficients of the transfer chambers at different beam quality index measured by the KRISS and the NMIJ.

	Beams	$TPR_{20,10}$	$N_{D,W}$, Gy/μC		
			Exradin A2 XS152643	Exradin A2 XS152644	PTW TN30013 SN008979
KRISS	^{60}Co	0.569	57.36 ± 0.18	58.59 ± 0.19	53.59 ± 0.17
	6 MV	0.683	57.07 ± 0.23	58.28 ± 0.24	53.03 ± 0.22
	10 MV	0.734	56.73 ± 0.23	57.91 ± 0.24	52.60 ± 0.22
	18 MV	0.778	56.27 ± 0.23	57.49 ± 0.24	52.08 ± 0.21
NMIJ	^{60}Co	0.569	57.19 ± 0.18	58.54 ± 0.18	53.27 ± 0.16
	6 MV	0.678	56.83 ± 0.18	58.08 ± 0.18	52.84 ± 0.16
	10 MV	0.730	56.52 ± 0.18	57.73 ± 0.18	52.45 ± 0.16
	15 MV	0.758	56.15 ± 0.18	57.35 ± 0.18	52.03 ± 0.16

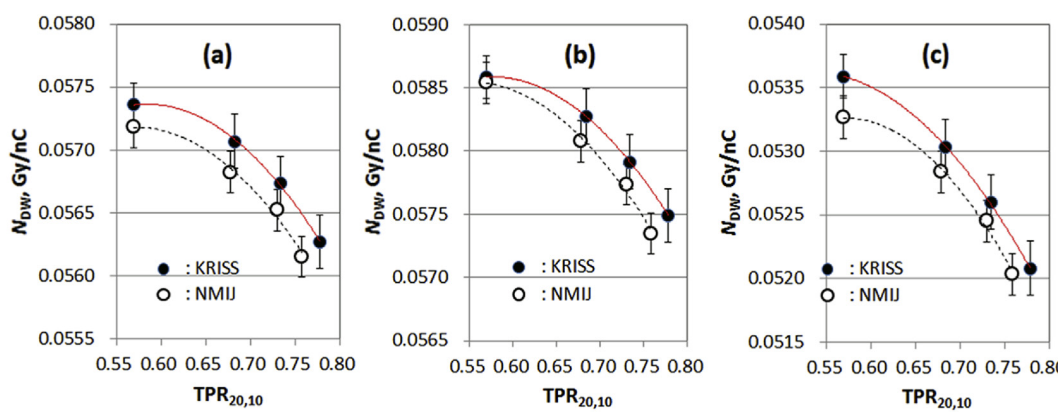


Fig. 5. Calibration coefficient of the transfer chambers of (a) Exradin A2 (XS152643), (b) Exradin A2 (XS152644) and (c) PTW TN30013 (SN008979).

Table 5
Uncertainties associated with the determination of D_W by using the graphite calorimeter of the KRISS.

Uncertainty components	Relative standard uncertainty	
	Type A	Type B
Temperature rise, ΔT (K)	0.02%	0.06% [a]
Temperature calibration to energy, C (J/K)	0.09%	0.24%
Effective mass of the core, m_{eff} (kg)	–	0.05%
Conversion of dose to graphite to water, $k_{G\rightarrow W}$	–	0.19%
Other correction factors		
- Calorimeter positioning, $k_{pos,g}$	–	0.07%
- Graphite depth, $k_{depth,g}$	–	0.06%
- Beam homogeneity, $k_{rn,g}$	–	0.10%
- Backscattering to external beam monitoring chamber, k_{BK}	–	0.05%
Subtotal	0.09%	0.35%
Combined relative standard uncertainty	0.36%	

[a] Uncertainty of the thermometer calibration is ignored since it gets canceled when ΔT is multiplied by C.

Table 6
Uncertainties associated with the determination of $N_{D,W}$ of transfer chambers at the KRISS.

Uncertainty components	Relative standard uncertainty	
	Type A	Type B
Absorbed dose to water, D_W (Gy)	–	0.36%
Net ionization charge measured, Q (C)	0.02%	0.04%
Calibration coefficient of the electrometer, k_{el}	–	0.05%
Environmental correction factor, k_{TP}	–	0.04%
Humidity correction factor, k_h	–	0% [a]
Polarity correction factor, k_{po}	–	0.02%
Ion recombination correction factor, k_s	–	0.05%
Other correction factors		
- Transfer chamber positioning, k_{pos}	–	0.07%
- Water depth, k_{depth}	–	0.05%
- Beam homogeneity, k_{rn}	–	0.15%
Subtotal	0.02%	0.41%
Combined relative standard uncertainty	0.41%	

[a] The effects of the humidity was ignored (k_h=1), since the humidity was kept within a range 30–70% R.H [7]. Thus the uncertainty of k_h was also ignored.

For all beams, the calibration coefficients of all chambers obtained at the KRISS were bigger than those obtained at the NMIJ, and they got bigger at the higher values of $TPR_{20,10}$. But the calibration coefficients from the KRISS and the NMIJ were in good agreement within the expanded uncertainty of 1.0% ($k = 2$).

The degree of equivalent of the KRISS's new standard of absorbed dose to water to KCRV can be predictable based on the previous KC result of the NMIJ [8] included in BIPM.RI(I)–K6 which was approved in CCRI in 2015. It is then expected that the KRISS new standard will be in good agreement satisfactorily with KCRV within the measurement uncertainty, too.

4. Conclusion

The new absorbed dose to water standards for high energy X-ray beams of the KRISS were compared with those of the NMIJ indirectly by using the transfer chambers. The calibration coefficients of the ionization chambers determined by the KRISS were slightly higher than the NMIJ's but they were in good agreement within the expanded uncertainty of 1.0% ($k = 2$). And it is expected that they will be in good agreement with the key comparison reference value when reevaluating the comparison based on the previous result of the NMIJ [8] included in BIPM.RI(I)–K6. Therefore, it is confirmed that the Gy unit of the

Table 7
Results of quadratic curve fit[a] of $N_{D,W}$ values with respect to the $TPR_{20,10}$ value as an indepenent variable.

Transfer chamber	KRISS				NMIJ			
	a ($\times 10^2$)	b ($\times 10^2$)	c ($\times 10^2$)	%RMS deviation[b]	a ($\times 10^2$)	b ($\times 10^2$)	c ($\times 10^2$)	%RMS deviation
PTW TN30013 SN008979	−2.55	2.71	4.64	0.05	−3.42	3.90	4.22	0.14
Exradin A2 XS152643	−2.90	3.39	4.75	0.05	−2.85	3.25	4.79	0.13
Exradin A2 XS152644	−2.66	3.06	4.98	0.05	−2.71	2.98	5.03	0.13

[a] Equation form of the quadratic fit was $y = ax^2 + bx + c$, where x is the $TPR_{20,10}$ value.
[b] %RMS deviation means percentage root mean square deviation.

Table 8
Results of the bilateral comparison study between the KRISS and the NMIJ.

Beams	$TPR_{20,10}$	$R(TPR_{20,10})$			Mean	Standard uncertainty
		Exradin A2 XS152643	Exradin A2 XS152644	PTW TN30013 SN008979		
^{60}Co	0.569	0.997	0.999	0.994	0.997	0.005
6 MV	0.678–0.683	0.996	0.997	0.996	0.996	0.005
10 MV	0.730–0.734	0.995	0.995	0.996	0.995	0.005
15 MV	0.758	0.995	0.995	0.995	0.995	0.005
18 MV	0.778	0.994	0.994	0.994	0.994	0.005

absorbed dose to water in the high-energy X-ray beams used in the radiation therapy range has been successfully realized at the KRISS independently by means of the graphite calorimetry recently developed by the KRISS.

Declaration of competing interest

None.

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