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ORIGINAL ARTICLE

Changes in deviation of absorbed dose to water among users by chamber calibration shift

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Abstract

Purpose The JSMP01 dosimetry protocol had adopted the provisional ^{60}Co calibration coefficient N_{D,w,Q_0}, namely, the product of exposure calibration coefficient N_C and conversion coefficient $k_{D,X}$. After that, the absorbed dose to water D_w standard was established, and the JSMP12 protocol adopted the N_{D,w,Q_0} calibration. In this study, the influence of the calibration shift on the measurement of D_w among users was analyzed.

Materials and methods The intercomparison of the D_w using an ionization chamber was annually performed by visiting related hospitals. Intercomparison results before and after the calibration shift were analyzed, the deviation of D_w among users was re-evaluated, and the cause of deviation was estimated.

Results As a result, the stability of LINAC, calibration of the thermometer and barometer, and collection method of ion recombination were confirmed. The statistical significance of standard deviation of D_w was not observed, but that of difference of D_w among users was observed between N_C and N_{D,w,Q_0} calibration.

Conclusion Uncertainty due to chamber-to-chamber variation was reduced by the calibration shift, consequently reducing the uncertainty among users regarding D_w. The result also pointed out uncertainty might be reduced by accurate and detailed instructions on the setup of an ionization chamber.

Keywords Radiotherapy · Standard dosimetry · Absorbed dose to water · Ionization chamber · Uncertainty

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Introduction

Because of the steep dose–response curves, tumor control and normal tissue complications are affected by the dose delivered to the patient in radiation therapy. Overall uncertainty is estimated to be 5% (with coverage factor $k = 1$) at present [1, 2], and 3% should be the goal of the delivered dose in the near future [1]. If 3% were required as the overall uncertainty [1], 1% should be the goal of the absorbed dose to water (D_w) at the calibration point.

To reduce the uncertainty of D_w at the calibration point, the ^{60}Co calibration coefficient N_{D,w,Q_0}, in terms of the absorbed dose to water, has been introduced in the global standard dosimetry protocols [2, 3]. In the protocols, $D_{w,Q}$ for therapy-level megavoltage photons at beam quality Q is given by.

$$D_{w,Q} = M_Q \, N_{D,w,Q_0} \, k_{Q,Q_0}, \qquad (1)$$

where M_Q is the corrected charge reading, and k_{Q,Q_0} is the beam quality conversion factor to correct for the response of the ionization chamber between the reference beam quality ^{60}Co γ-rays and the user beam quality Q. In 2002, the Japan Society of Medical Physics (JSMP) adopted N_{D,w,Q_0} formalism in the dosimetry protocol (JSMP01) [4]. However, the D_w standard had not been established at

Table 1 Uncertainty budget of the D_w comparison between the dosimetry protocols

Quantity or procedure		Relative standard uncertainty (%)		
		TRS398	JSMP01	JSMP12
Calibration at SSDL	N_{D,w,Q_0}	0.6	(1.5)	0.52
Calibration by cobalt exposure	N_C	–	0.74	–
Conversion coefficient (calc.)	$k_{D,X}$	–	1.3	–
Quality conversion (calc.)	k_{Q,Q_0}	1.0	1.0	1.0
Reading	M	0.9	0.9	0.9
Long-term stability		0.3	0.3	0.3
Reference condition		0.4	0.4	0.4
Dosimeter reading		0.6	0.6	0.6
Correction factors		0.4	0.4	0.4
Combined standard uncertainty		1.5	2.0	1.5
Expanded uncertainty ($k = 2$)		3.0	4.0	2.9

that time. For that reason, provisional N_{D,w,Q_0} was given by

$$N_{D,w,Q_0} = N_C\, k_{D,X}, \tag{2}$$

where N_C is the exposure calibration coefficient for ^{60}Co γ-rays and $k_{D,X}$ is the exposure to the absorbed dose conversion coefficient for ^{60}Co γ-rays. Table 1 shows the uncertainty budget of the comparison between dosimetry protocols. Despite the relative standard uncertainty of the N_C being 0.74% [4], the relative standard uncertainty of the $N_C\, k_{D,X}$ (provisional N_{D,w,Q_0}) was estimated to be 1.5% [4] because the $k_{D,X}$ was calculated using nominal dimensions and the material of the ionization chamber rather than individual ones. As a result, the original purpose of JSMP01—namely reduction of D_w uncertainty by adopting the D_w standard, was not achieved until 2012.

The D_w standard in ^{60}Co γ-rays was established at the National Metrology Institute of Japan (NMIJ) in 2011 [5] and the N_{D,w,Q_0} calibration service has been provided by the Association for Nuclear Technology in Medicine (ANTM) as an Secondary Standards Dosimetry Laboratories (SSDL) since 2012. The relative standard uncertainty of N_{D,w,Q_0} was estimated as 0.52% by direct N_{D,w,Q_0} calibration. A new standard dosimetry protocol (JSMP12) was issued in 2012 [6]. The combined relative standard uncertainty of D_w was estimated at 1.5%, which was reduced from 2.0% in the case of the JSMP01, and the deviation of D_w among users was expected to become smaller.

The ANTM investigated the deviation of D_w among users by a mailed dose audit with a radiophotoluminescent glass dosimeter (RGD) [7]. Despite a sufficient number of samples, there was no significant difference in the standard deviation of D_w between these two protocols.

The intercomparison of the D_w using an ionization chamber was annually performed by visiting related hospitals. In this study, intercomparison results before and after the calibration shift were analyzed, the deviation of D_w among users was re-evaluated, and the cause of deviation was estimated.

Materials and methods

Intercomparison by visiting related hospitals

The intercomparison of D_w was annually performed for quality assurance of related hospitals (RH) that belong to the Tokyo metropolitan government from 2007 to 2014, except 2012 due to a transition period of the standard dosimetry protocol. The number of hospitals and photon beams in each fiscal year are shown in Table 2. A total of 157 photon beams, including 4 MV ($0.615 \le TPR_{20,10} \le 0.640$), 6 MV ($0.663 \le TPR_{20,10} \le 0.684$), and 10 MV ($0.735 \le TPR_{20,10} \le 0.748$), were investigated.

The combination of LINAC, ionization chamber, and electrometer in the RH is shown in Table 3. The table also shows nominal energy and the beam quality index $TPR_{20,10}$ of each LINAC. The 30013 ionization chamber (PTW, Freiburg) was used at most hospitals in this investigation. Since it occupies about a 78% share of the market in Japan [8], the result in this report represents the current situation. The measurement equipment of our institute (OI), the Tokyo metropolitan university, is shown in Table 4. Other than the ionization chamber and electrometer, a water tank, calibrated barometer and thermometer were also used in the RH. The measurement equipment of RH and OI was completely separated and the setting of equipment was performed by own staff. Besides the D_w at calibration depth, $TPR_{20,10}$, k_{Q,Q_0}, the ion recombination correction factor k_s, and the temperature and pressure correction factor k_{TP} were determined individually. The D_w and factors for D_w determination were recorded, and results were compared using the recording form shown in Fig. 1.

Table 2 Number of institutions and photon beams in each fiscal year

Fiscal year	Institutions	Beams
2007	6	14
2008	12	23
2009	10	23
2010	11	25
2011	11	27
2013	7	25
2014	11	34

Table 3 Combination of LINAC (including nominal energy, $TPR_{20,10}$), ionization chamber, and electrometer in the related hospitals (RH)

	LINAC	Nominal energy (MV)	$TPR^{a}_{20,10}$	Ionization chamber	Electrometer	Fiscal year
A	Primus	6	0.676	30013	Ramtec 1000plus	2009–2014
		10	0.742			
B	iX	6	0.669	30013	Ramtec Smart	2010–2014
		10	0.738			
C	2100C	4	0.615	30001	Dosemaster 2590A	2009
		10	0.735			
D	Primus	4	0.627	30013	Ramtec Smart	2009–2014
		10	0.741			
E	Mevatron	6	0.670	30006	Keithley 35040	2009–2014
F	21EX	6	0.665	30013	Ramtec Smart	2010–2014
		10	0.737			
G	Mevatron	6	0.675	23333	Dosemaster 2590A	2009
H	Synergy	4	0.640	30013	Ramtec Smart	2014
		6	0.684			
		10	0.737			
I	EXL-15	4	0.628	30013	Dosemaster 2590A	2009–2011
		10	0.746			
J	iX	6	0.664	30013	Ramtec Smart	2013–2014
		10	0.737			
K	Mevatron	4	0.626	30013	Fluke 35040	2009–2011
		10	0.740			
L	Primus	6	0.676	30013	Fluke 35040	2009–2014
		10	0.742			
M	Primus	4	0.623	30013	Ramtec 1000plus	2009–2014
		10	0.742			
N	21EX	6	0.668	30013	Unidos T10001	2010–2014
		10	0.740			
O	iX	6	0.669	30013	Unidos T10001	2010–2014
		10	0.738			
P	21EX	4	0.619	30013	Unidos webline	2009–2014
		10	0.737			
Q	EXL-15	4	0.625	30013	Unidos webline	2009–2011
		6	0.682			
R	Oncor	6	0.675	30013	Unidos webline	2009–2011
		10	0.744			
S	21EX	6	0.670	30013	Unidos webline	2009
		10	0.738			

[a] The $TPR_{20,10}$ shows the mean from 2009 to 2014

Table 4 Measurement equipment at our institution (OI)

Equipment	Model
Ionization chamber	30013 (PTW)
Electrometer	35040 (Inovision) UNIDOS webline (PTW)
Digital quartz barometer	745-16B (Paroscientific)
Digital thermometer	TL1-A (Thermoprobe)
Water phantom	WP1D (IBA)

Deviation of the D_w and factors for D_w determination

After sufficient pre-irradiation, each measurement was performed on at least five exposures under the same monitor unit and reference conditions: a calibration depth of 10 cm for a 10-cm × 10-cm field and a source-to-chamber distance of 100 cm. D_w had been evaluated by Eq. (1) and provisional N_{D,w,Q_0} by Eq. (2) according to JSMP01 until 2011, or by only Eq. (1) according to JSMP12 since 2013. However, the results in fiscal year 2007 and 2008

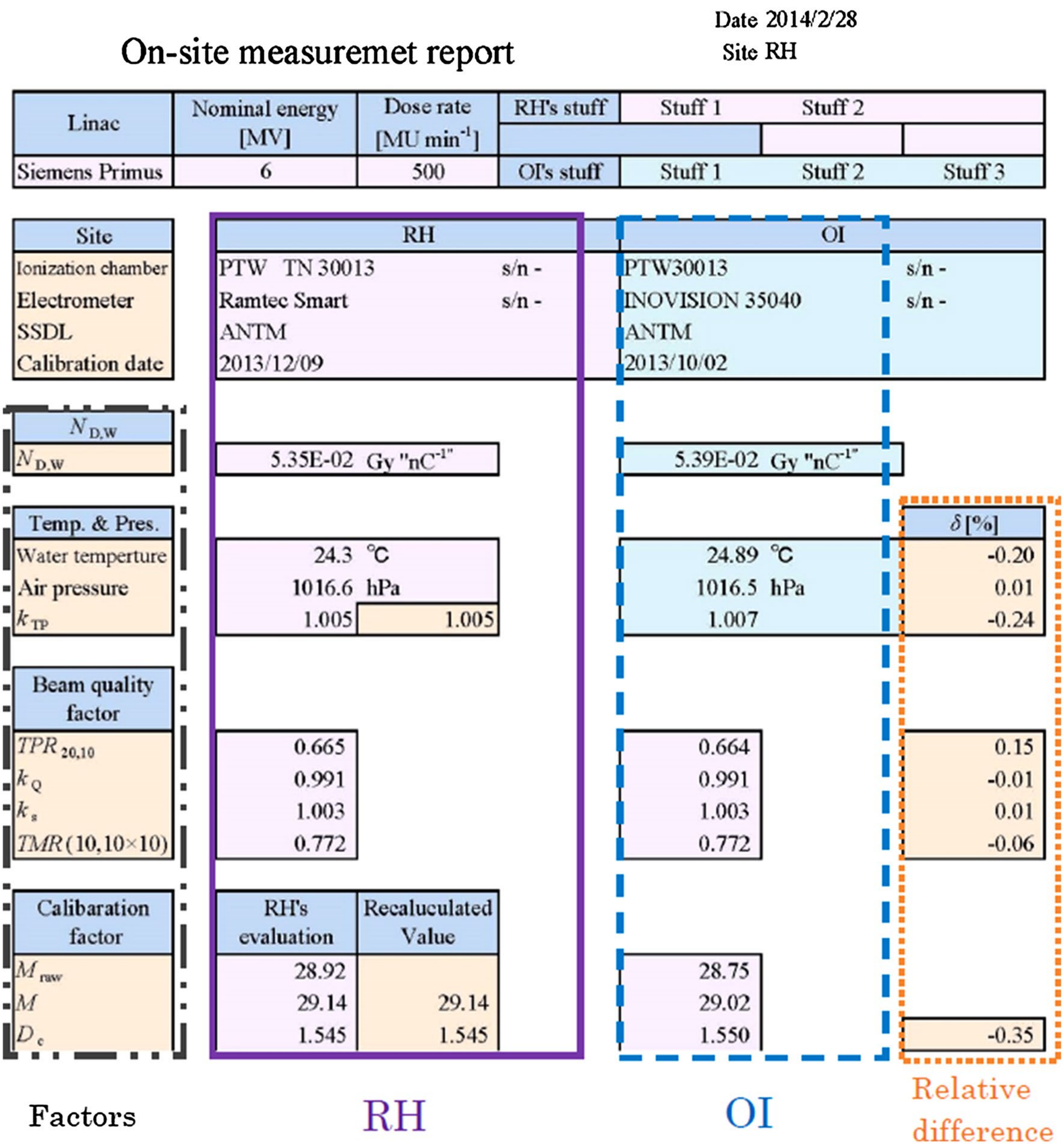

Fig. 1 Recording form for intercomparison

are not included in this report because an uncalibrated barometer was used in some hospitals.

When D_w determined by OI $(D_w)_{OI}$ was assumed to be standard, the relative difference δ (D_w) between $(D_w)_{RH}$ and $(D_w)_{OI}$ was given by:

$$\delta(D_w) = 100\left[\frac{(D_w)_{RH}}{(D_w)_{OI}} - 1\right] (\%) \tag{3}$$

Analogous to Eq. (3), the relative difference δ of k_{TP}, k_s, $TPR_{20,10}$ and k_{Q,Q_0} between RH and OI was analyzed. However, the δ of those factors was derived from whole samples since 2009, because those factors have no relation to calibration shift.

Results

Deviation of the D_w

A histogram for δ (D_w) from 2010 to 2014 is shown in Fig. 2; that for 2009 is not shown because it is almost identical to that for 2010 and 2011. The standard deviations σ of δ (D_w) in 2010, 2011, 2013, and 2014 were 0.57, 0.69, 0.43, and 0.56, respectively. The results of F tests for σ are shown in Table 5. No statistical significance ($P < 0.05$) was observed, except between 2011 and 2013. The cause of the statistical significance may be

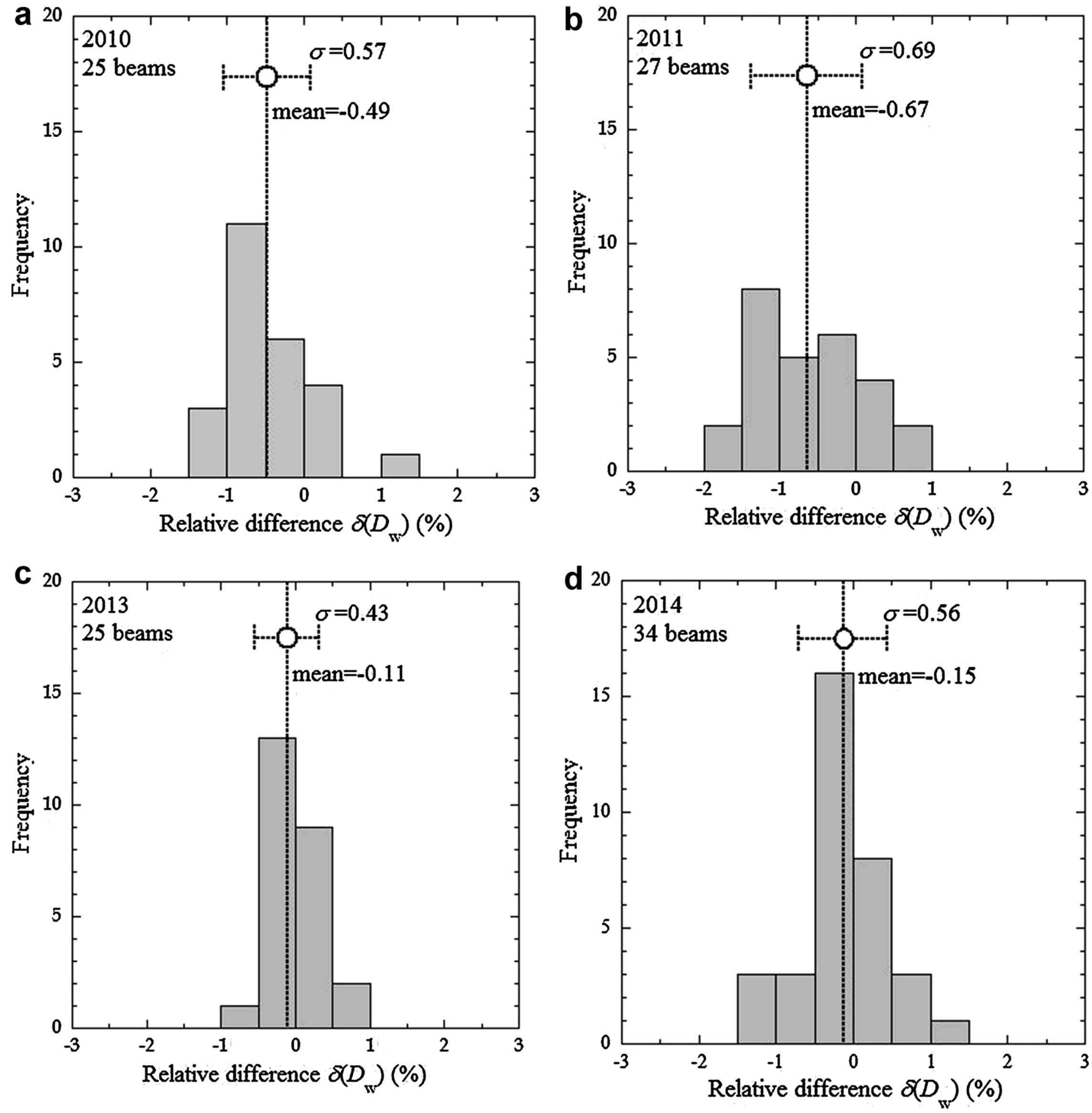

Fig. 2 Temporal change of relative difference of D_w, δ (D_w) from fiscal year 2010 to 2014

Table 5 Probability of *F* test and *t* test for standard deviation (σ) of δ (D_w)

	Fiscal year	*F* test of σ of δ (D_w)				
		2009	2010	2011	2013	2014
t test of mean of δ (D_w)	2009		0.52	0.12	0.46	0.58
	2010	0.61		0.35	0.16	0.90
	2011	0.14	0.30		0.02*	0.25
	2013	0.03*	0.01*	0.00*		0.17
	2014	0.08	0.03*	0.00*	0.75	

* Statistical significance ($P < 0.05$)

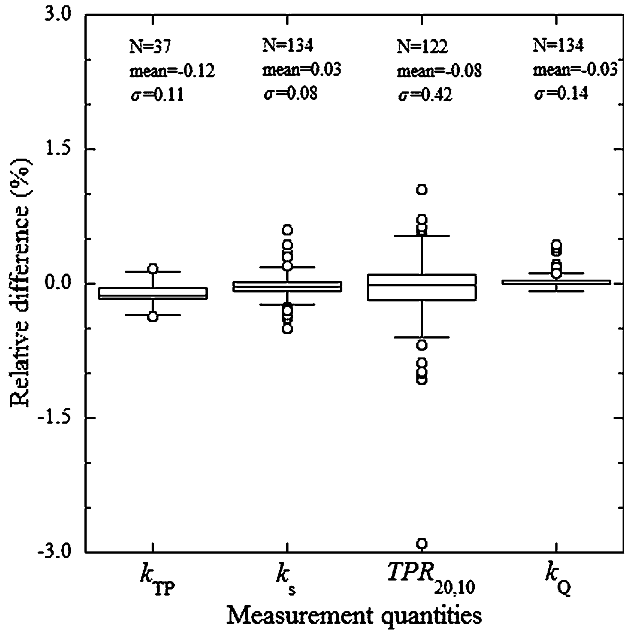

Fig. 3 Relative difference of k_{TP}, k_s, $TPR_{20,10}$, and k_{Q,Q_0} between related hospitals (RH) and our institution (OI)

that the number of hospitals in 2013 was less than that in other fiscal years, because the protocol shift to JSMP12 was not completed in 2013 in some small-scale hospitals.

The means of δ (D_w) in 2010, 2011, 2013, and 2014 were −0.49, −0.67, −0.11, and −0.15, respectively. The results of Student's or Welch's t test are shown in Table 5. Statistical significance ($P < 0.05$) was observed between before and after calibration shift, although the change was within the range of the σ.

Deviation of factors for D_w determination

The relative difference in factors for D_w determination [δ (k_{TP}), δ (k_s), δ (TPR$_{20,10}$) and δ (k_{Q,Q_0})] is shown in Fig. 3; δ was derived from whole samples of the intercomparison, because no difference was observed between fiscal years. The σ of δ (k_{TP}), δ (k_s), and δ (k_{Q,Q_0}) was 0.11, 0.08, and 0.14%, respectively. On the other hand, σ of the δ ($TPR_{20,10}$) was 0.42%.

Discussion

According to JSMP01, the ratio between D_w estimated by RH and OI in Eq. (3) is expanded as follows:

$$\frac{(D_w)_{RH}}{(D_w)_{OI}} = \frac{(M\ N_C\ k_{D,X}\ k_{Q,Q_0})_{RH}}{(M\ N_C\ k_{D,X}\ k_{Q,Q_0})_{OI}}. \tag{4}$$

In a similar fashion, the ratio of D_w according to JSMP12 is expanded as follows:

$$\frac{(D_w)_{RH}}{(D_w)_{OI}} = \frac{(M\ N_{D,w,Q_0}\ k_{Q,Q_0})_{RH}}{(M\ N_{D,w,Q_0}\ k_{Q,Q_0})_{OI}}. \tag{5}$$

These quantities have items of uncertainty, as shown in Table 6, and can be separated into two categories: dependent or independent between the numerator and denominator. When items are dependent, they have the same quantity and direction of uncertainty, so that they could cancel each other out and do not contribute to the uncertainty of δ (D_w). N_C and N_{D,w,Q_0}, except the item "measurement by the user electrometer and ionization chamber" at the calibration, are dependent because the entire ionization chamber was calibrated by the ANTM. The $k_{D,X}$ and k_{Q,Q_0}, except the item chamber-to-chamber variation of perturbation correction, are also dependent, because they are calculated using nominal dimensions and material for each model.

On the other hand, M in the numerator and denominator are independent, because the measurement by RH and OI was completely separated. The variation of δ (D_w) was caused mainly by the variation of M. Therefore, items of uncertainty of M were analyzed. The coefficient of variation of electrometer readings M_{raw}, δ (k_{TP}), and δ (k_s) were within 0.1%, so that the stability of LINAC, calibration of the thermometer and barometer, and collection method of ion recombination were confirmed.

The variation of $TPR_{20,10}$ is insensitive to k_{Q,Q_0} [2]. However, it represents variation of ionization chamber positioning so that it might involve the variation of D_w. The σ of ($TPR_{20,10}$) was larger than other factors: 0.42% is equivalent to ± 1.6 mm of water depth displacement for 10 MV X-rays and corresponds to 0.4% of dose difference. Figure 4 shows the relative difference distribution between $TPR_{20,10}$ in the fiscal year concerned $(TPR_{20,10})_{con}$ and that in the preceding fiscal year $(TPR_{20,10})_{pre}$ by (a) RH and (b) OI. The σ of the relative difference by RH and OI was 0.31% and 0.22%, respectively. The σ is smaller than the estimated uncertainty of the "Reference condition" (0.4%) by IAEA and JSMP as shown in Table 1. However, by the F tests of σ, statistical significance ($P < 0.05$) was observed between RH and OI. This may be because the OI owns a measurement procedure manual with step-by-step description and a specified person managed the measurement. Therefore, uncertainty could be reduced by detailed documentation on how to set up an ionization chamber with reference conditions accurately for every measurement. As an example, the instruction of checking if the cylinder chamber and its reflection in water image form a perfect circle with the eye at the same level as the water level needs to be added to a condition of setting the center of the chamber at the water surface [9].

Table 6 Items of uncertainty to evaluate difference of D_w and dependency in intercomparison

Quantity	Item	Dependence
N_C	Calibration by specified standard instruments	Yes
	Determination of exposure in ^{60}Co γ-ray by specified secondary standard instruments	Yes
	Measurement by user electrometer and ionization chamber	No
N_{D,w,Q_0}	Calibration by specified standard instruments	Yes
	Determination of D_w in ^{60}Co γ-ray by specified secondary standard instruments	Yes
	Measurement by user electrometer and ionization chamber	No
$k_{D,X}$	Restricted mass collision stopping power of water to air	Yes
	Average energy lost per Coulomb of charge released by electrons in air	Yes
	Part of the theoretical formula of perturbation correction	Yes
	Chamber-to-chamber variation of perturbation correction	No
k_{Q,Q_0}	Restricted mass collision stopping power of water to air	Yes
	Average energy lost per Coulomb of charge released by electrons in air	Yes
	Part of the theoretical formula of perturbation correction	Yes
	Chamber-to-chamber variation of perturbation correction	No
M	Long-term stability of ionization chamber	No
	Setting of field-size	No
	Setting of water depth	No
	Setting of source-to-surface distance	No
	Stability of LINAC	No
	Long-term stability of electrometer	No
	Humidity	No
	Leakage current	No
	Polarity correction	No
	Ion recombination correction	No
	Temperature and pressure correction	No
	Pre-irradiation	No

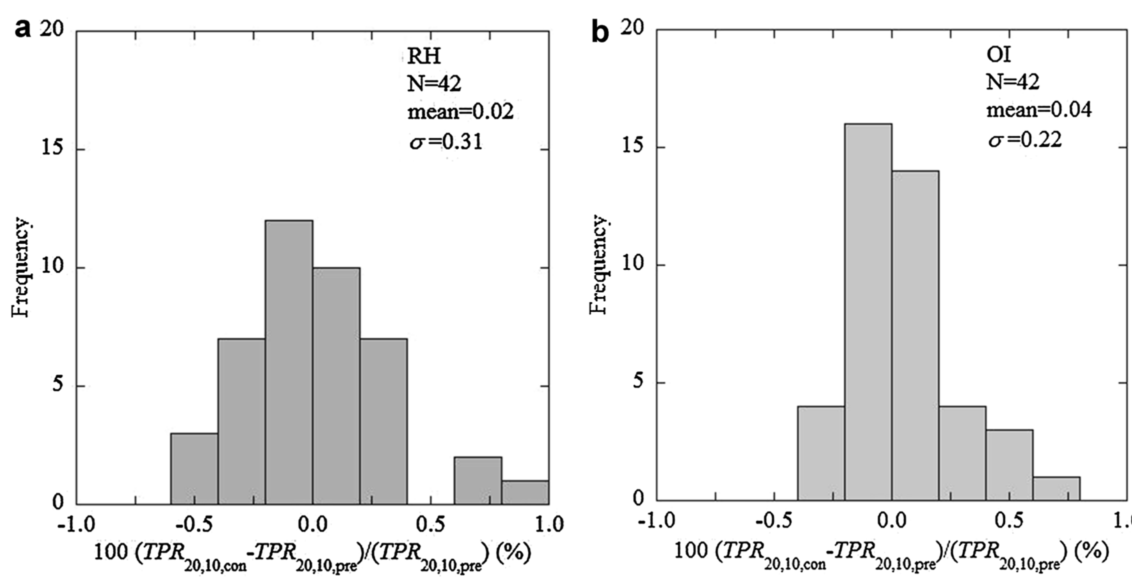

Fig. 4 Relative difference between $TPR_{20,10}$ of the current and preceding fiscal year

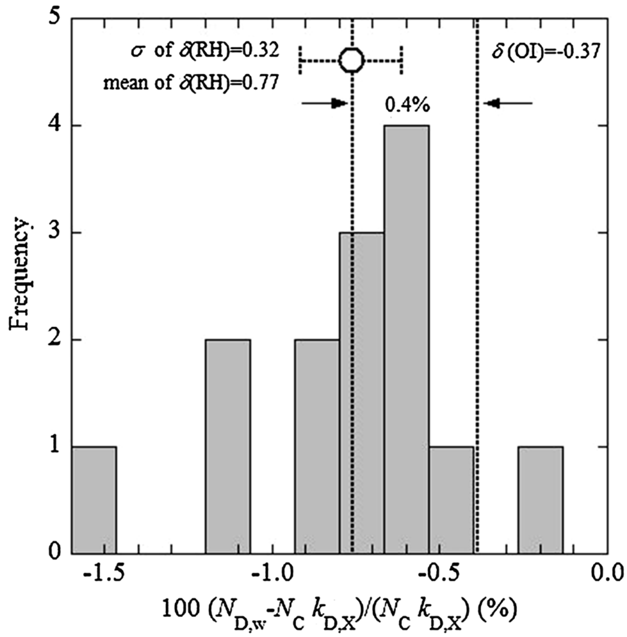

Fig. 5 Relative difference between N_C, $k_{D,X}$, and N_{D,w,Q_0} δ ($k_{D,X}$) for 30013 Farmer-type chamber

The uncertainty of M between JSMP01 and JSMP12 was identical, and chamber-to-chamber variation of k_{Q,Q_0} was within 0.1% [10]. Consequently, the difference of the δ (D_w) in the two protocols might be mainly caused by reduced chamber-to-chamber variation of $k_{D,X}$. Analogous to Eq. (3), frequency distribution of the relative difference between N_C $k_{D,X}$ and N_{D,w,Q_0}, δ ($k_{D,X}$) for 14 Farmer-type chambers (30013) is shown in Fig. 5. Mean and σ were −0.77% and 0.32%, respectively. Sakata et al. [8] reported the mean was −0.64% and the σ was 0.41% with 30013 ionization chambers (n = 866). δ ($k_{D,X}$) in this study shows good agreement with findings of the previous study. Although $N_{D,w}$ was determined 1 year later than N_C calibration, change of response between calibration years could be ignored, because the δ ($k_{D,X}$) of OI's chamber (−0.37%) was comparable to the δ ($k_{D,X}$) (−0.43%) determined by the pilot study of $N_{D,w}$ calibration performed 1 year prior by the ANTM and OI [11].

No statistical significance of σ of δ (D_w) between JSMP01 and JSMP12 was observed by intercomparison. In contrast, statistical significance of the mean of the δ (D_w) between JSMP01 and JSMP12 was observed. Mean of δ (D_w) −0.67% in 2011 decreased to −0.15% in 2014. This 0.42% decrease coincides with the difference between mean of δ ($k_{D,X}$) of RH −0.77% and δ ($k_{D,X}$) of OI −0.37%, as shown in Fig. 5. Therefore, uncertainty due to chamber-to-chamber variation was reduced by the calibration shift from N_C to N_{D,w,Q_0}, and uncertainty of D_w in users was consequently reduced.

Conclusion

To evaluate influence of the calibration shift from N_C to N_{D,w,Q_0}, the results of a intercomparison before and after the calibration shift were analyzed. The deviation of D_w among users was re-evaluated, and the cause of deviation was estimated.

As a result, we confirmed the stability of LINAC, calibration of the thermometer and barometer, and collection method of ion recombination in user hospitals. The statistical significance of D_w was not observed, but that of difference of D_w among users was observed between N_C and N_{D,w,Q_0} calibration. Therefore, uncertainty due to chamber-to-chamber variation was reduced by the calibration shift and the uncertainty of D_w among users was consequently reduced. The result also pointed out the uncertainty among users regarding D_w might be reduced by accurate and detailed instructions on the setup of an ionization chamber for reference condition.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest associated with this manuscript.

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