The Comparison of Absolute Dose Measurement for Photon Beam According to JSMP 12, DIN-6800-2, IAEA TRS 398 and AAPM TG-51 Protocols.

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Abstract — In this study, we compared the absorbed dose to water determined at the reference depth for photon beams following the recommendations given in the addendums to TG-51, IAEA TRS-398, DIN 6800-2 and JSMP 12. This study was performed using measurements with flattened photon beams with nominal energies of 6 and 10 MV. Absolute dose measurements were carried out using PTW (30013) Farmer chamber with UNIDOS E electrometer in a 30 x 30 x 30 cm^3 water phantom. Fully corrected charge readings obtained for the chambers according to all four protocols showed maximum percentage of variations like 0.2 % and 0.3 % at 6 and 10 MV, respectively. The values for the beam quality conversion factor k_Q, obtained according to the four protocols agreed to within 0.3 %. The values for the absorbed dose to water obtained for the four protocols agreed to within 0.4 %. The difference in the absorbed dose to water determined by the four protocols depends on the k_Q and correction factor values and the absorbed dose to water obtained according to the four protocols agreed to within the relative uncertainties.

Keywords — Absorbed dose, AAPM TG-51 protocol, DIN 6800-2 protocol, IAEA TRS 398 protocol, JSMP 12 protocol, Photon beam and photon clinical reference dosimetry.

1. INTRODUCTION

Radiation therapy is considered an important step for effective cancer treatment. In radiation therapy, it is necessary to deliver a high dose to the patient for achieving a favourable clinical outcome [1]. In its Report 24 on Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures, the ICRU concluded that certain types of tumour need for an accuracy of ±5 % in the delivery of an absorbed dose to a target volume if the eradication of the primary tumour. ICRU continues that some clinicians have requested even closer limits such as ±2 %, but in the present time (in 1976) it is virtually impossible to achieve such a standard. These statements were given in a context where uncertainties estimated at the 95 % confidence level and had been interpreted as corresponding to approximately two standard deviations (2). Thus, the requirement for 5 % precision in absorbed dose would correspond to a combined uncertainty of 2.5 % the true value.

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The dose delivered to a patient based on this accuracy requirement of today that is 2% considered too strict. Hence the requirement for an accuracy of ±5 % could be interpreted as a tolerance for the deviation between the prescribed dose and the dose delivered to the target volume [3]. Modern radiotherapy has confirmed that in any case, the need for high accuracy in dose delivery if new techniques, including dose escalation in 3D conformal radiotherapy are to be applied. Emerging technologies in radiotherapy includes modern diagnostic tools for determination of target volume. 3D commercial treatment planning systems and advanced linear accelerators for irradiation could be effective if there is high accuracy in dose determination and delivery to patients [4].

During the last two decades, the International Atomic Energy Agency (IAEA), the American Association of Physicists in Medicine (AAPM), and other national organizations from various countries have published clinical reference dosimetry protocols for external beam radiation therapy using high-energy photon and electron beams [5-10]. In this study, we have compared the absorbed dose to water determined at the reference depth for high-energy photon beams following the recommendations given also in JSMP 12. This study was carried out with flattened photon beams with energies of 6 MV and 10 MV using cylindrical (PTW 30013) type ionization chambers.

2. MATERIALS AND METHODS

2.1 Materials

High energy flattened photon beams of 6 MV and 10 MV in Elekta Synergy Agility were used in this study. We performed reproducibility measurements using the dose monitoring system by delivering a series of fixed monitor units. The coefficient of variation was 0.0004 % and 0.00028 % for 6 MV and 10 MV photon beam respectively. Tolerance for coefficient of variance (COV) is less than 0.5 %. Absolute dose measurement and beam quality were carried out using cylindrical (PTW 30013) type ionization chambers in a 30 x 30 x 30 cm^3 water phantom. The electrometer model PTW-UNIDOS E was used to measure the absolute charge. The operating voltage for the cylindrical chamber was kept at 400 V.

Table 1 Characteristics of the chamber used

Chamber type	**Sensitive cavity**			**Wall**		**Central electrode material**
	Volume (cm^3)	**Length (mm)**	**Radius (mm)**	**Material**	**Thickness (mm)**	
PTW 30013	0.6	23.0	3.05	PMMA/Gr	0.335/0.09	Al

2.2 Determining absorbed dose in water

The absorbed dose to water was determined on the basis of recommendations in four protocols (11-13). A comparison of reference conditions for the determination of the absorbed dose to water and formalism in those protocols are shown in Table 2. Only the major differences relevant to this study are described using the notations consistent with the AAPM TG-51 and Addendum to TG-51 protocols (11). In IAEA TRS-398 and JSMP 12 several notations are comparatively different from those in AAPM TG-51, Addendum to TG-51 and DIN 6800 (1-5). However, all quantities can be essentially translated to the quantities in the TRS-398 formalisms without loss of meaning. PTW chambers were calibrated with a Co-60 source to derive a calibration factor (9).

Table 2 Reference conditions for determination of absorbed dose to water for the four protocols.

	AAPM TG-51	**JSMP 12**	**IAEA TRS-398**	**German DIN 6800-2**
Phantom material	water	water	water	Water
Chamber type	cylindrical	cylindrical	cylindrical	Cylindrical
Reference depth	10 g cm^{-2}	10 g cm^{-2}	10 g cm^{-2}	10 g cm^{-2}
Measure point of the chamber	The center of the cavity	The center of cavity	The center of cavity	0.5 r_{cyl} below the measuring depth
SSD/SAD	100 cm	100 cm	100 cm	100 cm
Field size	10×10 cm^2	10×10 cm^2	10×10 cm^2	10×10 cm^2

Clinical reference dosimetry for photon beams was performed in an open beam (i.e., without trays, wedges, lead filters, or blocks) using a cylindrical ionization chamber placed at the reference depth of 10 cm from the surface of the water phantom. The field size was 10 x10 cm^2 defined at the surface of the phantom. We were positioned the ionisation chamber by adjusting the reference point of our chamber to the measuring depth as required in the respective protocol. which was located at the central axis and at the middle point of the chamber cavity (r_{cyl} = internal radius of the chamber cavity).

2.3 Determination of correction factors

For the determination of absorbed dose to water we had taken different correction factors due to compensate the deviation from the calibrating condition and our measuring condition [10,11]. The determination of polarity, ion recombination and beam quality correction were different for different protocols so we followed the respective procedures and formulas to calculate according to the above-mentioned protocols.

2.4 Determination of the Temperature and Pressure correction factor K_{TP}

K_{TP} was calculated from the temperature in the phantom and the absolute pressure at the measuring place as follows:

$$K_{TP} = \frac{P_0(273.2 + T)}{P(273.2 + T_0)} \quad (1)$$

With T = Temperature in the phantom, P = Air pressure in place as well as the corresponding reference values of temperature (T_0 = 20°C) and pressure (P_0 = 1013.25 mbar). To measurements in a water phantom, the chamber waterproof sleeve should be vented to the atmosphere, in order to obtain rapid equilibrium between the ambient air and the air in the chamber cavity [20].

2.5 Determination of the correction factor k_S for the ion recombination

The incomplete collection of charge in an ionization chamber cavity due to the recombination of ions requires the use of a correction factor. k_s can be determined either experimentally by two-voltage-procedure or theoretically by a formula. Based on this, we have applied the experimental method. According to the different protocols, the different methods were used to determine K_P which are shown in Table 3. The difference between the experimental method and theoretical calculation is less than 0.2% for all chambers and energies [3].

Table 3 Determination of ion recombination correction factor K_s by four protocols

Dosimetry protocol	Determination of K_s	
	Theoretical (Formula)	Experimental (U_1,U_2,M_1,M_2)
AAPM TG -51 (10)	(no formula is given)	$P_{ion}(V_H) = \frac{1. - (V_H/V_L)^2}{M_{raw}^H/M_{raw}^L - (V_H/V_L)^2}$.
JSMP 12 (10)		$K_s = a_0 + a_1 \frac{M_1}{M_2} + a_2 \left(\frac{M_1}{M_2}\right)^2$
IAEA TRS 398 (11)		$K_s = a_0 + a_1 \frac{M_1}{M_2} + a_2 \left(\frac{M_1}{M_2}\right)^2$
German DIN 6800-2 (3)	$K_s = 1 + \frac{\gamma + \delta \cdot D}{U_1}$	$Ks = \frac{U_1/U_2 - 1}{U_1/U_2 - [(M - M_0)K_P\ K_\rho]_1 / [(M - M_0)K_P\ K_\rho]_2}$

Here, U1 =normal chamber operating voltage, U2 = lower chamber operating voltage,
M_1 = measured value at U1, M_2 = measured value at U2,
The constants a_0, a_1 and a_2 are listed in the corresponding protocol. The constant γ and δ were taken from the DIN6800-2.

2.6 Determination of correction factor K_P for the polarity effect

K_P was experimentally determined by switching the polarity of chamber voltage. According to the different protocols, the different methods were used to determine K_P which are shown in Table 4.

Table 4 Determination of polarity correction factor K_p for four protocols

Dosimetry protocol	Determination of k_p
AAPM TG 51 (10)	$k_{pol} = \frac{\lvert M_+\rvert + \lvert M_-\rvert}{2M}$
JSMP 12 (10)	$k_{pol} = \frac{\lvert M_+\rvert + \lvert M_-\rvert}{2M}$
IAEA TRS 398 (11)	$k_{pol} = \frac{\lvert M_+\rvert + \lvert M_-\rvert}{2M}$
DIN 6800-2 (3)	$K_p = (M_1 + M_2)/M_1/[(M_1 + M_2)/M_1]_{Co}$

M+ and M- are the electrometer readings obtained at positive and negative polarity, M is the electrometer reading obtained with the polarity used routinely (positive or negative), M_1 and M_2 are the electrometer readings obtained at positive and negative polarity.

2.7 Correction factor P_{rp}

P_{rp} was calculated for cylindrical ionization chambers by a dose profile integration (average dose $\langle D_{rel}\rangle$) along the cylinder axis of the ionization chambers' sensitive volume from x=L/2 to x=L/2 as given in the following equation. The P_{rp} is a correction factor to take account of any off-axis variation in the intensity profile of the radiation field over the sensitive volume of the ionization chamber. The correction factor to take in consideration for variation in the radial dose distribution i.e., averaged by the detector. The P_{rp} factors according to the Addendum to TG-51 were 1.002 for 6 MV and 1.003 for 10 MV [4].

$$P_{rp} = \frac{1}{D_{ref}} = \frac{L}{\int_{-L/2}^{L/2} D_{ref}(x)dx} \qquad (2)$$

Here, $D_{rel}(x)$ is defined as the relative dose normalized to the dose at the central axis and L the length of the sensitive volume. The P_{rp} correction factor, introduced in the TG-51 addendum (McEwen et al., 2014), is a radial beam profile correction factor that takes into account the non-uniformity of the beam profile in the axial direction. It is particularly important in peaked FFF beams but can also be on the order of 1-2 % for flat beams. As per the TG-51 addendum we determined P_{rp} in the clinic which was calculated as the average of the radial dose profile over the dimensions of the active part of the chamber.

2.8 Leakage currents P_{leak} correction

P_{leak} is the correction factor defined as any contribution to the measured reading which is not due to ionization released by the radiation beam in the chamber's collecting volume. The leakage current was measured with all the equipment placed and while the accelerator ON with beam OFF. Extra-cameral currents were estimated by shielding the ionization chamber while irradiating the cable as demonstrated method to evaluate such radiation-induced leakage by Campos and Caldas [5]. It was seen that the contributions were from the chamber itself or the ionization chamber cable (e.g., due to damage or long-term radiation induced degradation), or the electrometer. But in such a measurement, extra-cameral currents and radiation-induced leakage (e.g., in the cable) are not evaluated, although the definition of P_{leak} does include those components

Each component of the chamber-cable-electrometer system should be evaluated separately whenever possible. The leakage should contribute less than 0.1% to the charge reading. For any particular system, the value of the leakage current could be significantly larger, and a value greater than 0.5% must be investigated. If the leakage current is ≤ 0.1% level, it is reasonable to set P_{leak}= 1.000 (no correction for leakage) with an associated relative uncertainty of 0.1%.

2.9 Determination of Beam quality $K_{Q, Qo}$ correction factor

For AAPM TG-51 and the Addendum to TG-51 used the Percentage depth dose obtained at 10 cm depth, PDD(10)x, excluding the electron contamination effect. The value of PDD (20-21) X is defined for the field size of 10×10cm^2 at the phantom surface at an SSD of 100 cm. Consequently, for the determination of the dose depth curve 10 MV and above, a lead plate (1 mm) thickness must be positioned between the focus and the measuring chamber. We used 1mm lead filter to remove the contaminating electron. It should be placed about 50 cm (±5 cm) or 30cm (±1 cm) from the phantom surface. Here we kept lead foil in 30 cm from the phantom surface (19).

Figure.1 Experimental setup for beam quality index

We calculated $K_{Q,Qo}$ factor by the ratio of the absorbed doses at depths of 20 cm and 10 cm in a water phantom, measured with a constant Source-Chamber-Distance of 100 cm and a field size of 10 cm × 10 cm at the plane of the chamber to correct the difference between the response of an ionization chamber in the reference beam quality Q_o which was used for calibrating the chamber and in the actual user beam quality Q. For IAEA TRS-398, DIN 6800-2 and JSMP 12, we used the tissue-phantom ratio ($TPR_{20,10}$) as beam quality index in order to choose the appropriate beam quality conversion factors. TPR can be measured directly according to its definition or by a depth dose measurement:

$$K_{Q,Qo} = 1.2661 \cdot M(20)/M(10) - 0.0595 \quad (3)$$

Where, M (20) and M(10) are the readings at 20 cm and 10 cm depths for a field size of 10 cm × 10 cm defined at the phantom surface with an SSD of 100 cm.

2.10 Determination of the additional correction factor K_r for cylindrical chambers specific to the German DIN 6800-2 protocol

This correction must be included always according to the DIN Protocol for cylindrical chambers (for photon and electron beams). It takes into account about the different positions during the calibration (reference point at measuring depth) and the user's measurement (reference point 0.5 *r* lower than measuring depth) explicitly as a correction factor, in contrast to the other protocols, where this effect is taken into consideration as a perturbation factor to be applied in the calculation of the beam quality correction factor. For the calculation of K_r the following relation is given in DIN 6800-2 (3)

$$K_r = 1 + |\delta|\, r/2 \quad (4)$$

$$\text{Beam quality} = K_{Q,Qo}\, K_r \quad (5)$$

Here, r = inner radius of the chamber cavity and δ = relative gradient of the dose depth curve at the reference depth during the calibration with Co-60 radiation (for Co-60-beam: δ = 0.006 mm^{-1}). For the cylindrical chamber PTW-30013 (r = 3.05 mm), Kr= 1.00915 is obtained.

2.11 Quantification of uncertainties

TG-51 does not provide an estimation of the uncertainties involved in the determination of absorbed dose to water in reference conditions. On the other hand, TRS-398, JSMP 12 and DIN 6800-2 provides a detailed uncertainty estimation for the different steps and factors used in the determination of absorbed dose to water in reference conditions. We can assume that TG-51 will also have similar uncertainty estimates as those given in TRS-398. For photon beams with cylindrical chamber TRS-398 estimates a combined standard uncertainty for D_w to be 1.5% based on a chamber calibration in a Co-60 beam and the total standard uncertainties is estimated according to DIN 6800-2 a maximum of 1.42%. The relative standard uncertainties in $TPR_{20,10}$ for JSMP 12 and IAEA TRS-398 were approximately 0.3% (k =1). The uncertainty was taken from two main sources. The first source was the components associated with setup for the reference conditions and their measurements. The second was the use of ionization ratios in place of ratios of absorbed dose in the determination of $TPR_{20,10}$. By determining the beam quality conversion factor with interpolation, the relative standard uncertainties were 0.05% (k = 1) at the maximum. The Experimental uncertainties in the measurement of photon beam qualities were 0.4 % for AAPM TG-51 PDD (10) X and 0.2 % for IAEA TRS-398 ($TPR_{20,10}$).

3. RESULTS AND DISCUSSION

The Correction factors for meter reading as per four protocols are shown in Table 5 and 6. The temperature-pressure correction and polarity correction factors for the four protocols were calculated using the same formula. The beam quality correction factors based on the four protocols were calculated (22). The correction factors for ionisation collection efficiency by IAEA TRS-398 and JSMP 12 were calculated using the same formula. The correction factors seem to be the same in AAPM TG-51 and JSMP 12 protocol. The ionisation collection efficiency, K_s, was determined based on four protocols and agreed to be within 0.1 %. The P_{rp} factors according to the Addendum to TG-51 were 1.002 at 6 MV and 1.003 at 10 MV.

Table 5 Correction factors obtained using AAPM TG-51 and JSMP 12 protocols.

ENERGY (MV)	Chamber	AAPM TG -51						JSMP 12			
		P_{TP}	P_{ion}	P_{pol}	P_{elec}	P_{leak}	P_{rp}	K_{TP}	K_s	K_{pol}	K_{elec}
6	PTW 30013	1.071	1.002	1.001	1.000	1.000	1.002	1.071	1.002	1.001	1.000
10	PTW 30013	1.071	1.000	1.000	1.000	1.000	1.003	1.071	1.004	1.000	1.000

TABLE.6 Correction factors obtained using IAEA TRS-398 and DIN 6800-2 protocols.

ENERGY (MV)	Chamber	IAEA TRS-398				German DIN 6800-2			
		K_{TP}	K_s	K_{pol}	K_{elec}	K_{TP}	K_s	K_{pol}	K_{elec}
6	PTW 30013	1.071	1.002	1.001	1.000	1.071	1.000	1.001	1.000
10	PTW 30013	1.071	1.004	1.000	1.000	1.071	1.000	1.000	1.000

3.1 Beam quality conversion factor for the four protocols

The beam quality conversion factors obtained according to the four protocols are shown in Table 7.

Table 7 Beam quality conversion factor for respective protocols

Chamber	Protocol	6 MV	10 MV
PTW 30013	AAPM TG-51	0.988	0.978
	JSMP 12	0.987	0.978
	IAEA TRS -398	0.989	0.980
	German DIN 6800-2	0.998	0.989

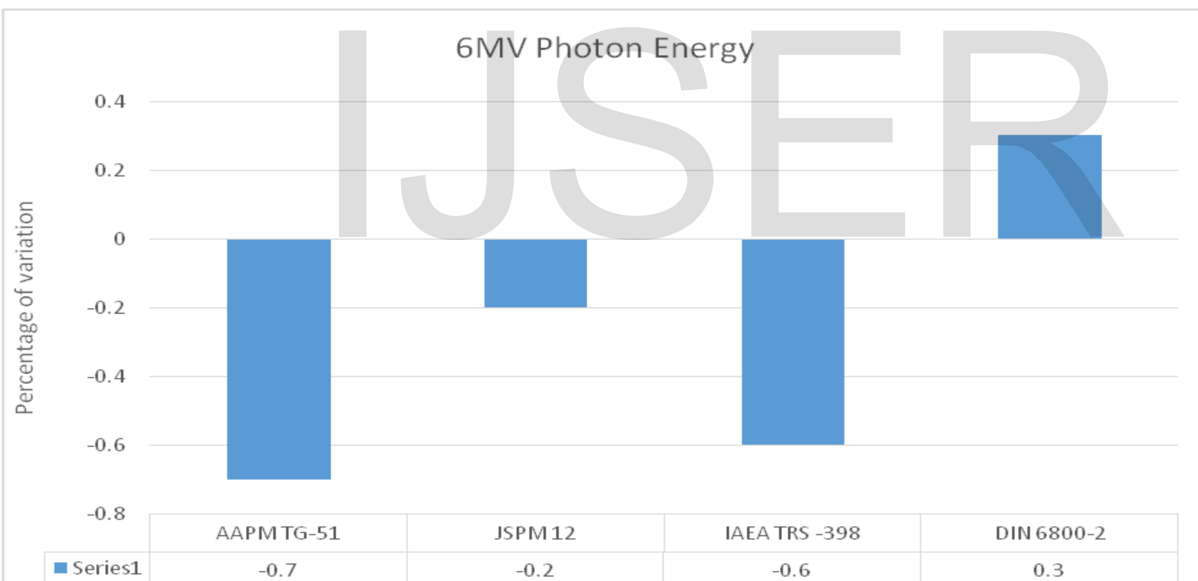

Figure 2 The Comparison of absorbed dose at D_{max} for 6 MV photon beam

Figure.2 shows the deviations for 6MV photon beam for AAPM, JSMP-2, DIN 6800-2 and IAEA protocols.

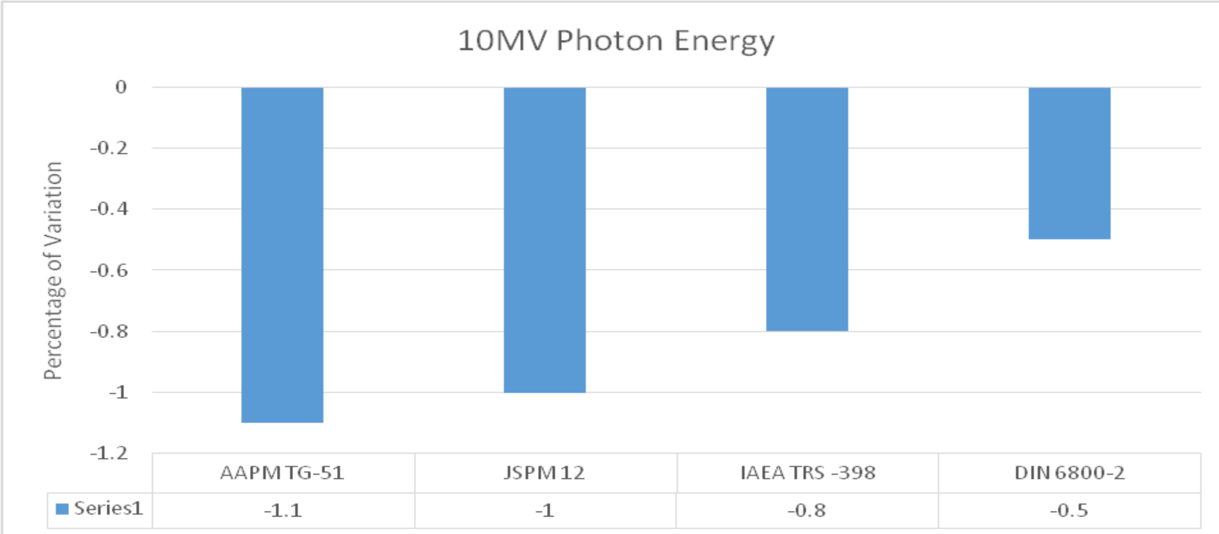

Figure 3 The Comparison of absorbed dose at D_{max} for 10 MV photon beam

Figure.3 shows the deviations for 6 MV photon beams for four protocols According to AAPM, JSMP-2, DIN 6800-2 and IAEA protocols. The deviations may be as much as 0.6 %. The greatest deviation from this study was about 1.0 %.

The correction factors for charge readings obtained in ionization chamber using the four protocols for 6 MV and 10 MV photon beams and the maximum deviation for 6 MV photon was 0.7 % and the maximum deviation for 10 MV photon was 1.1 % which is in permissible tolerance of 1.1% as shown in Figure 2 and 3. The beam quality correction factors based on the four protocols were calculated, the maximum deviation for 6 MV photons was 0.9 % and the maximum deviation for 10 MV photons was 1.1 %. The correction factors for ionisation collection efficiency according to IAEA TRS-398 and JSMP 12 were calculated using the same formula, and the ionisation collection efficiency (K_s) was determined by the four protocols and agreed to within 0.1 %. The P_{rp} factors according to the Addendum to TG-51 were 1.002 at 6 MV and 1.003 at 10 MV. The discrepancies in the determination of absorbed dose to water for photon beams were within 1.0 % as shown in Figure 2 and 3. For the determination of dose by photon beams with cylindrical chambers, the total standard uncertainties are estimated according to TRS 398 a maximum of 1.25 %, and a maximum of 1.42 % according to DIN 6800-2 (2008 March).

4 CONCLUSIONS

From our study, we observed that the time required for the clinical dosimetry is almost the same for each of the four protocols. Advantages of TRS 398 Code of Practice based on standards of absorbed dose to water is obtained with reduced uncertainty and the setup is very simple. So it tends to very less man manmade error, a more robust system of primary standards because of use of a simple formalism. DIN 6800-2 and JSMP-2 protocols were almost adapted to the IAEA TRS-398. But practical difficulties and inconveniences are raised in TG-51 protocol at the time of measurement of PDD (10) X as a lead filter needs to be used to remove electron contamination (high photon energies only). The discrepancies in the determination of absorbed dose to water for 6 MV and 10 MV photon beams using the recommendations in the four protocols were within 1.0 % tolerance specified by respective protocols. The absorbed dose to water using the ionization chamber showed good agreement within the relative uncertainty in the absorbed dose to water given in the four protocols. Because of the use of cylindrical ionization chamber with the same Co-60-based calibration factors, the major discrepancy is likely due to the difference in the P_{rp}, $K_{Q,Q0}$ and correction factors values found among the four protocols. The P_{rp} and $K_{Q,Q0}$ values may depend on the linear accelerator and cylindrical ionization chamber used, respectively. Thus, the absorbed dose to water determined for high-energy photon beams according to the four protocols agreed to within the relative uncertainties.

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Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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